J. Integr. Sci. Technol. 2024, 12(5), 823

Journal of Integrated
SCIENCE & TECHNOLOGY

Improving the methodology for calculating the thrust force during underwater crossing by directional drilling method

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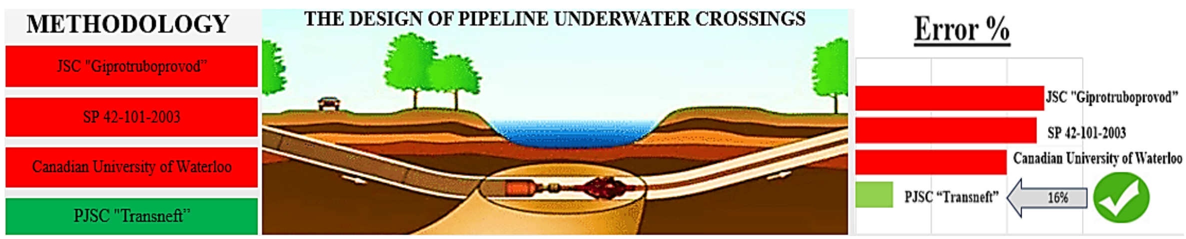
Received on: 10-Jan-2024, Accepted and Published on: 02-May-2024

Article

ABSTRACT



This study aimed to enhance the methodology for determining pulling force when designing pipeline crossings. The authors thoroughly analyzed three existing methods for calculating pipeline pulling force during the construction of transitions via directional drilling, namely JSC "Giprotruboprovod" method, the Canadian University of Waterloo method, and SP 42-101-2003 method. Through comparing the calculation results of each method with actual pulling force values, the authors identified the pros and cons of each method that impact the accuracy of the final calculation. Consequently, they formulated proposals that enable the improvement of calculating pipeline pulling force methodology used by domestic companies (PJSC "Transneft") during facility design and construction. The proposed (improved) method achieved an average calculation error of 16%, which was the most precise among all existing methods, as confirmed by the comparison with actual force values of previously constructed transitions.

Keywords: Horizontal Drilling; Directional Drilling; Pipeline; Pulling Force; Modelling; Underwater Crossings.

INTRODUCTION

The transportation of oil and gas through pipelines is of highest importance to the Russian fuel and energy complex.[1] Despite the many natural and artificial obstacles that pipelines encounter, they remain a reliable means of transportation. The main part of these intersections is made up of underwater pipeline crossings. About 94% of all underwater crossings are laid using trench technology. However, at the present stage of construction, closed-hole drilling technologies are increasingly common, in particular the method of directional drilling.[2,3]

The process of pulling the pipe into the well is one of the most important technological operations of the entire construction. Stopping pulling due to the collapse of the well walls, a sharp increase in forces, and a break in the string can lead to complex emergency operations.[4,5]

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Cite as: *J. Integr. Sci. Technol., 2024, 12(5), 823.*
URN:NBN:sciencein.jist.2024.v12.823

The problems of determining the effort of dragging the pipeline into the well are mainly related to the inaccuracy of the calculation models used. However, an assessment of the actual construction conditions leads to the fact that in 10% of cases of construction of the crossings, difficulties arise with dragging the pipeline.[6]

TASK STATEMENT

Calculation of the design effort of pipeline dragging during the construction of crosswalks by the directional drilling method, with the smallest error to the actual value of the force, is an urgent task for pipeline transport.[7]

In order to increase reliability and reduce the risk of increasing the cost of construction of the crossing, the authors propose to improve the existing methodology for calculating the pipeline pulling force applied in the design and construction of facilities in the system of PJSC "Transneft" – the methodology of JSC "Giprotruboprovod".

COMPARATIVE ANALYSIS OF EXISTING METHODOLOGIES

Existing calculation methods for determining the pulling force have significant differences in modelling the behaviour of the pipeline. As a result, the values of the pulling forces obtained during calculations for the same transition construction conditions (pipeline and well diameter, well geometry, etc.) differ significantly.[8,9] It is necessary to analyse the methods for calculating the pulling force and find out the advantages and disadvantages of the methods under consideration.

In Russia, two main methods for determining the pulling force are used:

1) calculation method according to SP 42-101-2003,[10];

2) method of JSC "Giprotruboprovod".[11]

Abroad, the most common method for calculating the pipeline pulling force into the well is National Library of the Canadian University of Waterloo.

In order to conduct a comparative analysis between the three existing methods, calculations were performed for the already constructed transition of the oil and gas collection steel pipeline of the "Priobskoye" field across the river "Evyakha" by the directional drilling method (530x10 mm, L -844.5 m, actual pulling force-450 kN).

The calculation results are shown on the graph of the dependence of the value of the dragging force on the length of the transition see Figure 1.

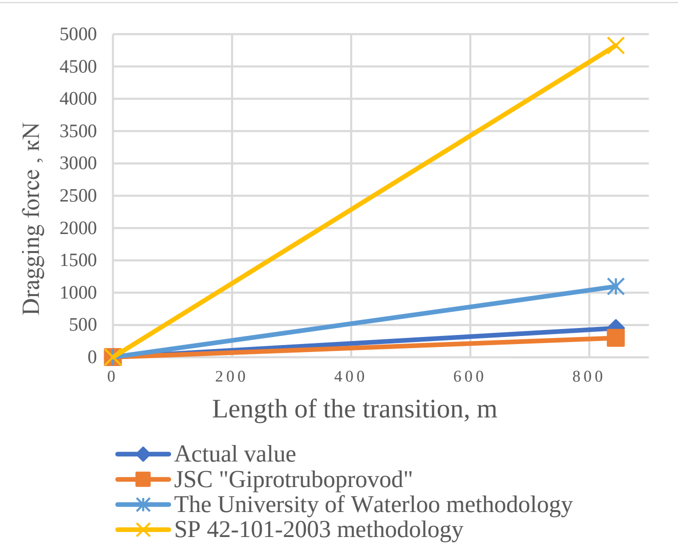

Figure 1. Dependence of the value of the dragging force on the length of the transition (river Evyakha)

A comparison of the pulling force calculations shows significant discrepancies due to fundamental differences in the calculation models used.

Pros and cons of SP 42-101-2003 methodology

As per the calculation, it follows that the methodology of SP 42-101-2003 (4824 kN) gives the largest error in comparison with the actual value. One of the decisive factors in the high error of this method is the consideration of natural collapse in the calculation model of the arch, according to the theory of M. M. Protodyakonov for favourable and unfavourable conditions [7,12]. Its presence leads to an abnormally large increase in the friction force. For more accurate calculations, you need reliable data from engineering and geological surveys.[13]

Pros and cons of the Canadian University of Waterloo methodology

The Canadian University of Waterloo has proposed an approach that is considered to be highly favourable in this regard.[14] This is because their calculation model involves simplifying the borehole profile and replacing curved portions with straight ones that have known angles of inclination. While this method poses some challenges in accurately determining the pipeline's geometric features as it navigates through the angular sections of the borehole that are necessary for computation, it still remains a highly effective and reliable solution.

The calculated value according to the method of the University of Waterloo was 1096.5 kN, which is significantly more than the actual value. However, the method of the University of Waterloo gives an error of 14.4% in this case, and the result for SP 42-101-2003 is 972%.

However, the high margin of error according to the method of the University of Waterloo is also explicable. The bending stiffness of the pipeline, its weight, and changes in the direction of the wellbore create forces that bring the pipeline into contact with the ground, which in turn leads to frictional forces. The values of contact stresses depend on the geometric characteristics of the well, the size of the inter-wall space between the pipe and the well, the ability of the soil to deform, and the weight of the pipe in the drilling fluid. In addition, according to the calculation model, the technique simplifies the profile to straight sections with certain angles of inclination, thereby simulating conditions that are more severe than in reality. The use of this technique always leads to a higher calculated effort than the full-scale one.[15]

Pros and cons of JSC «Giprotruboprovod» methodology

A relatively small error in the calculation was shown by the method of JSC "Giprotruboprovod" (33.67%) with a pulling force of 298.5 kN. The calculation model for straight sections takes into account the efforts to overcome the friction of the pipeline against the walls of the well as well as against the drilling fluid. For curved sections, the impact of contact forces from pressing the pipeline against the walls of the well is additionally taken into account, but active and passive force factors are not taken into account, as well as how their value changes depending on the change in the angle of inclination of the pipeline whip being dragged along the length of the curved section.

Specified Dependencies

The study of methods for calculating the drag force showed the dependence of the calculated drag force on the presence and number of rectilinear and curved segments of the wellbore[16]. Therefore, the method of calculation should be chosen based on the projected wellbore profile.[17]

Due to the features of the currently accepted technology for drilling directional wells, each transition profile is characterized by the presence of rectilinear sections at the entrance and exit of the well from the soil mass, as well as the presence of one or more curved sections (elastic bending radius: $R \geq 1200 \times DN$).[18]

Depending on the transition parameters (plan length, pipeline depth), there are two types of drilling paths:

view-a profile consisting of two straight border sections and a central section curved along the radius (3 sections, Figure 2).

View a profile consisting of two straight border sections, two curved border sections, and a central straight section (5 sections, Figure 3).

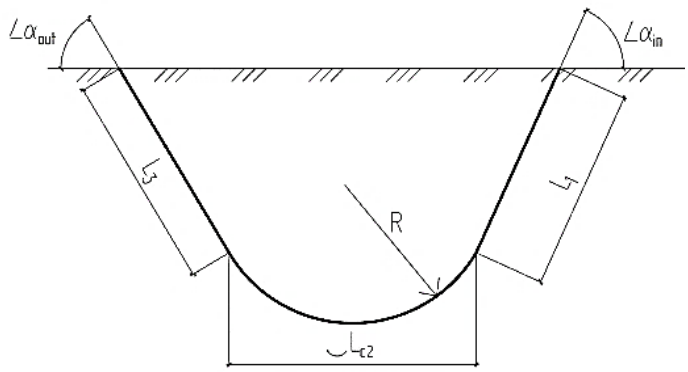

Figure 2. Diagram of the longitudinal profile of the directional drilling well (1 view)

Where L_1 – length of rectilinear section at the well inlet, m; L_3 – length of rectilinear section at the well outlet, m; L_{c2} – length of the central curved section of the well, m; R – radius of curvature, m; α_{in} – angle of the well axis entrance, relative to the horizon; α_{out}– angle of the well axis exit

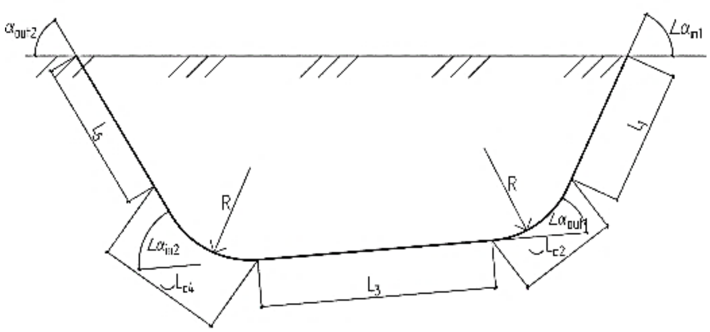

Figure 3. Diagram of the longitudinal profile of the directional drilling well (2 view)

L_1 – length of the straight section at the well inlet, m; L_3 – length of the central straight section, m; L_5 – length of the straight section at the well outlet, m;

L_{c2}, L_{c4} – lengths of curved sections of the well, m;

R – radius of curvature, m;

α_{in1} – angle of entry of the well axis (relative to the horizon), deg;

$\alpha_{out1}=\alpha_{in2}$ – angle of inclination of the axis of the central rectilinear section of the well, deg;

α_{out2} – angle of exit of the well axis.

The shape of the directional drilling well trajectory will affect the final result of calculating the pull-through force.

DESIGNED METHODOLOGY

In our proposed method for calculating the pulling force, the well trajectory is considered not as a sequence of straight and curved sections but as a curved line differentiated into segments of elementary length that have a different slope to the horizon line without breaking the continuity of the line itself. As an assumption, it is assumed that the reaction forces during the interaction of the pipeline with the well wall do not affect the value of the pulling force (i.e., there is no thrust force between the pipe and the well)[19].

Dividing the curve of the line into many segments allows us to more fully assess the effect of the well geometry (entry angle, exit angle, and elastic bend in the vertical plane) on the terms of the pulling force, taking into account for each specific section the factors that increase (passive) and decrease (active) the pulling force.

The proposed analytical method for calculating the pipeline pulling force is based on a model similar to the method of JSC "Giprotruboprovod," which is based on the interaction of the pipeline with curved surfaces of the wellbore, pipe friction caused by its weight, jet resistance of the drilling mud, and changes in direction in the angular sections of the wellbore. The axial pulling force (T_i) that occurs on the drilling rig during dragging consists of the forces to overcome the friction forces between: the pipeline and the well walls; the pipeline and the jet resistance of the drilling fluid flowing in the free cavity of the borehole; the drill rods and the well walls; the drill rods and the jet resistance of the drilling fluid flowing in the free cavity of the wellbore; the expander and the well walls; the drill string locks and the well walls (Figure 4).

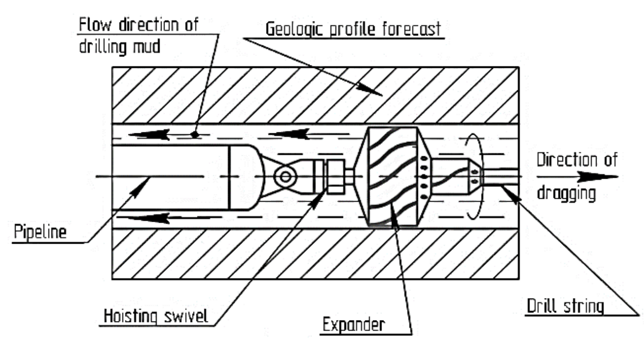

Figure 4. Scheme of dragging the pipeline into the well in case of directional drilling

The proposed methodology makes the following assumptions:

- The wellbore comprises of precisely angled straight sections.
- The ground is considered to be an inflexible medium, and it does not undergo any deformation or collapse while interacting with the pipeline.
- The interaction between the pipeline and the wellbore leads to the development of thrust forces.

As the operation of differentiating the well path into segments of a certain length with an eigenvalue of the angle of inclination to the horizon is performed, the operation of summing up the elementary dragging forces on individual segments along the length of the entire transition is performed.[20]

Calculations use the equivalent weight per unit length of the pipeline. This characteristic takes into account the filling of the pipeline with liquid ballast and the action of buoyant forces when the pipeline is submerged [21] in liquid (Figure 5). The calculation method allows you to calculate the pulling forces of both hollow pipelines and those filled with water.

The pull-through point for the final moment of pipeline stretching is determined simultaneously, that is, when the entire pipeline is located in the well and the string of drilling rods is on the shore (pulling the pipeline using the drilling rig based on the "on yourself method" company proceduces method).

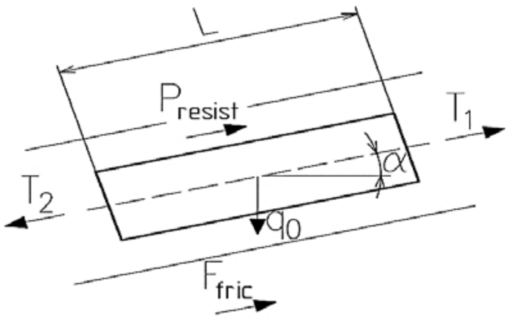

Figure 5. Design diagram of the pipeline section in the well during dragging

T_2 is the tension at the left end of the section required to overcome the friction resistance,

T_1 – tension at the right end of the segment, can be zero or determined by the resistance to movement of the pipe remaining on the rollers; F_{fric}– the friction force between the pipe and the ground; P_{resist} is the hydraulic resistance between the pipe and the viscous drilling mud; q_0 is the equivalent weight of the unit length of the pipeline; α is the angle of inclination of the axis of the rectilinear segment relative to the horizontal; L is the length of the section.[22]

BASIC FORMULAS FOR CALCULATION

In general, the formula for determining the total pulling force is written as:

$$T = \sum_{c_i=0}^{L}(T_i) + T_0 + Q_{lock,pcs} + T_{tens}, \quad (1)$$

where T_0 is the force required to be applied at the initial stage of pulling to the pipeline located outside the well. It is determined by the resistance to movement of the pipe remaining on the rollers of the downhill track or on the downhill dirt track; $Q_{lock,pcs}$ is a contact force on the lock of the drill string, N; T_{tens} – tensile force that occurs on the expander as a result of the unbalanced pressure of drilling mud on the expander holes,[23] H; L– the length of the transition along the longitudinal profile, m; T_i – the pulling force on each elementary section (segment) c_i, N.

$$T_i = T_{i.fric.pipe} + P_{i.dm.pipe} + T_{i.fric.dr} + P_{i.dm.dr}, \quad (2)$$

where $T_{i.fric.pipe}$ is the friction force between the pipe and the ground on each elementary section (segment) c_i, N.[24] It is determined by the formula:

$$T_{i.fric.pipe} = f \cdot |q_{0.pipe}| \cdot \cos\alpha \pm q_{0.pipe} \cdot c_i \cdot \sin\alpha, \quad (3)$$

where f is the coefficient of friction of the pipeline against the well walls moistened with drilling mud [25]; $q_{0.pipe}$ is the effective (submerged) running weight of one meter of the pipeline and the internal contents (if the pipeline is filled with water) located in the drilling mud, N/m; α is the angle of inclination of the segment axis relative to the horizontal (α_{in} – angle of entry of the pipeline into the well; α_{out}-angle of exit of the pipeline from the well), deg.

Before the term with the sign"±", "minus" is placed when the force vector is directed down the well (active force factor), and "plus" when it is directed up the well (passive force factor). This is due to the fact that in the area of dragging downhill, the projection of gravity is directed in the direction of the applied pulling force, which partially compensates for the friction force of the pipeline against the well walls.

$P_{i.dm.pipe}$ is the resistance force to movement of the pipeline in viscoelastic drilling mud per unit length (c_i) [26], N. It is determined by the formula:

$$P_{i.dm.pipe} = \pi \cdot d \cdot \tau_0, \quad (4)$$

where τ_0 is the dynamic shear stress of the drilling mud, Pa (the parameter is determined by laboratory tests); d is the outer diameter of the pipeline, taking into account the thickness of the insulation coating, m.

$T_{i.fric.dr}$ – the friction force between the drill rod and the ground on each elementary section (segment) c_i [27], N is determined by the formula:

$$T_{i.fric.dr} = f_{dr} \cdot |q_{0.dr}| \cdot \cos\alpha \pm q_{0.dr} \cdot c_i \cdot \sin\alpha, \quad (5)$$

where f_{dr} is the coefficient of friction of drilling rods against the well walls; $q_{0.dr}$ is the effective (submerged) running weight of one meter of drilling rods, N/m.

$P_{i.dm.dr}$ – the force of resistance to the movement of drilling rods in visco-plastic drilling mud per unit length (c_i), N.

$$Pi.dm.dr = \pi \cdot ddm.dr \cdot \tau 0\ , \quad (6)$$

where $d_{dm.dr}$ is outer diameter of drilling rods, m.

c_i is the length of the elementary section of the partition (for a curved section, the length of the chord of the partition), m.

In order to determine the value of c_i, we consider the curved section L_{c2} for the "1 type" profile. Section L_{c2}-represents a section of the arc of a circle with a central angle equal to the sum of α_{in} and α_{out} (similarly for the profile "2 types": L_{c2} – the sum of the angles α_{in1} and α_{out1}; L_{c4} – the sum of the angles α_{in2} and α_{out2}), as presented segment of a circle with radius R (Fig. 6)

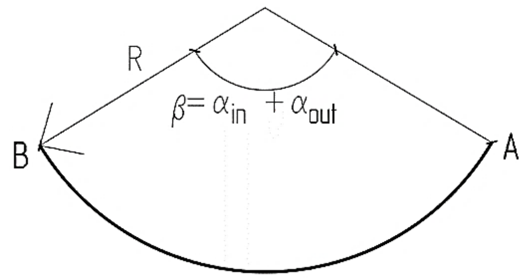

Figure 6. Arc of a circle with radius R

We divide the arc AB into equal segments with elementary central angles β_i and chords c_i (Figure 7). The chord length of the partition will be determined by the formula:

$$c_i = \frac{L_{AB}}{n} \quad (7)$$

where L_{AB} is the arc length AB:

$$L_{AB} = \frac{2 \cdot \pi \cdot R \cdot \beta}{360°}. \quad (8)$$

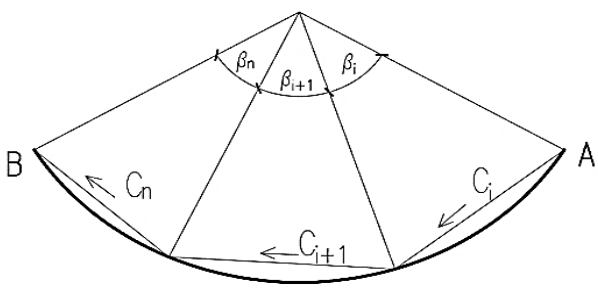

Figure 7. Splitting the AB arc into segments

n is the number of chords of the division of arcs AB;

c_i is the length of the chord i

As the pipeline is dragged through the AB section from chord i to chord i+1, the trajectory will rotate by an angle corresponding to the value of the elementary central angle β_i, determined by the formula:

$$\beta_i = \frac{\beta}{n}. \quad (9)$$

The calculation using the proposed method involves dividing the curved section (AB arcs) – into chords in the amount of n (Figure 7).

When the pipeline is pulled through the bending sections of the well, all forces acting on the pipe cause longitudinal and transverse deformations in it [28], while being in dynamic equilibrium, without disturbing the continuity of the pipe (Figure 8).

The previously accepted formulations and assumptions allow us to estimate bending deformations as a result of pipeline movement through the angular sections of the wellbore[29]. After determining the deformations, the friction forces that occur between the pipeline and the walls of the underground well, as well as the required pulling force, can be calculated.[30]

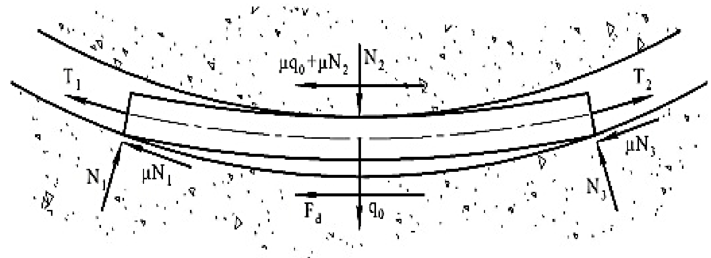

Figure 8. Forces exerted on the pipe section during dragging

N_1, N_2 and N_3 are the reaction forces that occur between the pipe and the ground, directed along the normal to the pipe;

q_0 is the weight of the pipe immersed in drilling mud;

F_d is the force that occurs due to the jet drag of the drilling mud;

T_1 and T_2 are the tension forces at the left and right ends of the pipe, respectively;

μ – coefficient of friction of the pipe on the ground surface.

In the corner section, the pipe and well walls will have three points of contact (Figure 9). In this case, the force with which the pipe will act on the ground is transmitted through these points and will be equal to the reaction force of the pipe at the contact point. Within each section of the wellbore, the pipeline profile is considered as a simple beam supported at points B_1 and B_2 with a concentrated load at point B.

Taking into account the location of the pipeline inside the wellbore, the following relations are obtained [30]:

$$y_{max} + c' = l \cdot \mathrm{tg}\psi, \quad (10)$$

where c' is the gap between the pipe and the wellbore at the angular point, m;

ψ – half of the angle between two lines of the wellbore segments, rad;

l – half the distance between the fulcrum B_1 and B_2, m.

$$c' = \left(\frac{d + c''}{\cos\psi} - d\right), \quad (11)$$

where c'' is the distance between the pipe and the well wall, m.

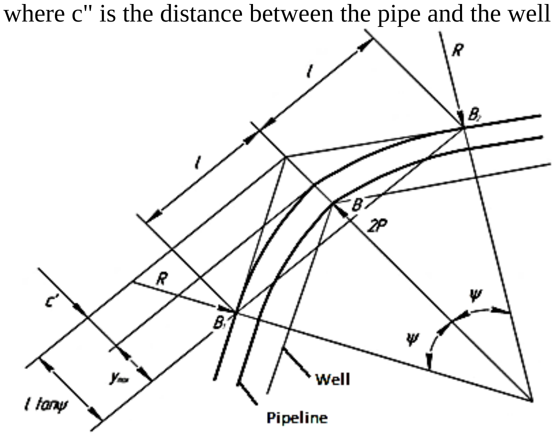

Figure 9. Calculation scheme for determining bending forces arising from the contact of the pipe with the walls of the well

c ' is the gap between the pipe and the wellbore at the angular point;
ψ – half of the angle between two lines of the wellbore segments;
l – half the distance between the fulcrum B_1 and B_2;
P – normal force;
R – support response.
From equations (10) and (11) we obtain:

$$l = \frac{c'/\cos\psi}{tg\psi - y_{max}/l}. \quad (12)$$

In equation (12), y_{max}/l is determined using the following expression:

$$\frac{y_{max}}{l} = \frac{[\sqrt{2}\sin\psi\cos\phi_0 - \cos\psi\cdot\Phi(p,\phi_0)]}{[\sqrt{2}\cos\psi\cos\phi_0 + \sin\psi\cdot\Phi(p,\phi_0)]}. \quad (13)$$

Having obtained the value l, the normal force P is calculated by the equation:

$$P = \frac{EI}{l^2}\cdot\cos\psi_0\cdot[\sqrt{2}\cos\psi_0\cos\phi_0 + \sin\psi_0\Phi(p,\phi_0)], \quad (14)$$

where the parameters are defined as:

$$p = \frac{1}{\sqrt{2}}, \quad \phi_0 = \sqrt{[sin\psi_0]}, \Phi(p,\phi_0) = 0{,}8472 + F(p,\phi_0) - 2\cdot E(p,\phi_0). \quad (15)$$

The functions F(p, ϕ_0) and E(p, ϕ_0) are elliptic integrals [30] defined as:

$$F(P,\phi_0) = \int_0^p \frac{1}{\sqrt{1-\phi_0 2.\sin\theta^2}}d\theta, \quad (16)$$

$$E(P,\phi_0) = \int_0^p \sqrt{1-\phi_0{}^2.\sin\theta^2}\,d\theta. \quad (17)$$

Figure 10 shows a section of the ABC pipe that changes its direction tangentially to the curvilinear section under consideration, which leads to the appearance of an equalizing force acting on the ground at the point of angle B. Stretching forces at a point C and point A do not act on a straight line. There is an equalizing force acting on the ground at the point of angle B.[31]

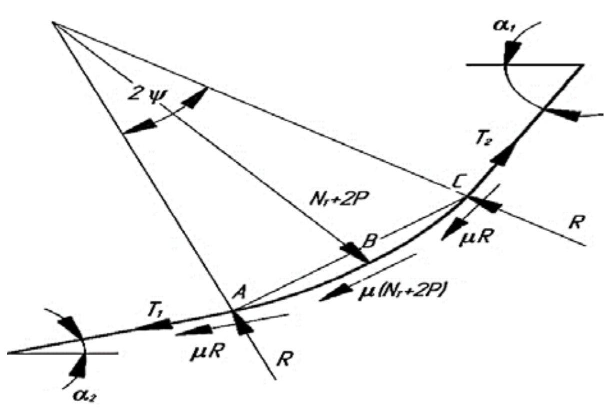

Figure 10. Forces, acting on the pipe at the corner point of the well

T_1, T_2 – axial tensile forces;
N_T – equilibrium force in the direction normal to the AC;
ψ – half of the angle between two lines of the wellbore segments;
P and R are forces due to the bending stiffness of the pipe.

The equation of equilibrium in the AC direction.[30]:

$$T_2\cdot\cos\psi = (T_1 + 2\cdot R\cdot\mu_b)\cdot\cos\psi + 2\cdot P\mu_b + N_T\cdot\mu_b, \quad (18)$$

where μ_b is the coefficient of friction between the pipe and the wellbore;
P and R are forces that occur due to the bending stiffness of the pipe (the pipe's resistance to bending). Equilibrium in the direction normal to the AC:

$$N_T = (T_1 + T_2)\cdot\sin\psi. \quad (19)$$

Given that R = P / cosψ, the equation of force change in the AC section ($\Delta T = T_2 - T_1$) will have the form [30]:

$$\Delta T = T_1\times\left(\frac{\cos\psi + \mu_b\times\sin\psi}{\cos\psi - \mu_b\times\sin\psi} - 1\right) + 4\times P\times\mu_b\left(\frac{1}{\cos\psi - \mu_b\times\sin\psi}\right), \quad (20)$$

Or

$$\Delta T = T_1\cdot C_1(\psi) + P\cdot C_2(\psi), \quad (21)$$

$$C_1(\psi) = \left(\frac{\cos\psi + \mu_b\cdot\sin\psi}{\cos\psi - \mu_b\cdot\sin\psi} - 1\right), \quad (22)$$

$$C_2(\psi) = 4\cdot\mu_b\left(\frac{1}{\cos\psi - \mu_b\cdot\sin\psi}\right). \quad (23)$$

To calculate the force applied to a pipeline with bending stiffness EI when it is pulled through a curved section of length L_c and bending radius R, apply the formula [32]:

$$P = \frac{3EI(R - \sqrt{R^2 - L_c^2})}{L_c^3}. \quad (24)$$

Comparison of the Proposed Methodology with Existing Ones

For a detailed comparison of the theoretical values of the pulling forces obtained by the proposed method with the results obtained by existing calculation methods, we selected a number of profiles of pipeline transitions with different diameters and lengths inherent in the transitions of main pipelines (Table 1). The outer diameters of theoretical junctions vary from 219 to 1420 mm, and the length ranges from 200 to 2500 m, in addition to the following considerations:

- Soil Sandy loam; coefficient of friction of the pipe against the walls of the well f = 0.4;
- Drilling flushing fluid characteristics: Dynamic shear stress of drilling mud τo = 100 MPa; density of drilling mud ρdm = 1100 kg / m33.

Table 1. Initial data of pipeline crossings (theoretical)

Pipe parameters	**Transition geometry**

1) Outer diameter D_{out} = 219 mm;
wall thickness δ = 8 mm;
insulation thickness δ_{ins}= 3.5 mm;
length in plan L = 200 m;
ballasting (filling the pipe cavity with water)
W = 100%
	Profile consisting of three sections: rectilinear length L_1= 80.5 m; curvilinear length L_{2c} = 80.1 m;
	rectilinear length L_3 = 40.4 m; entrance angle α_{in1} = 6°,
	α_{in2} = 0°; exit angle α_{out2} = 0°, α_{out2} =9°; radius of curvature of the profile R = 307 m; well diameter D_w = 400 mm; depth of the lowest point h = 10.1 m

2) D_{out}= 325 mm; δ = 10 mm; δ_{ins}= 3.5 mm; L = 600 m; W = 100%	The profile of five sections: L_1 = 33,6 m; L_{2c} = 47.6 m; L_3 = 445,4 m; L_{4c} = 71,4 m; L_5 = 2.6 m; α_{in1} = 6°, α_{in2} = 0°; α_{out2} = 0°, α_{out2} =9°; R = 455 m; D_w = 500 mm; h = 6 m
3) D_{out}= 426 mm; δ = 11 mm; δ_{ins}= 3,5 mm; L = 900 m; W = 100%	L_1 = 54,5 m; L_{2c} = 62,4 m; L_3 = 600 m; L_{4c} = 93,5 m; L_5 = 10.4 m; α_{in1} = 6°, α_{in2} = 0°; α_{out2} = 0°, α_{out2} =9°; R = 596 m; D_w = 600 mm; h = 9 m
4) D_{out}= 530 mm; δ = 12 mm; δ_{ins}= 3,5 mm; L = 1100 m; W = 100%	L_1 = 75,9 m; L_{2c} = 77,7 m; L_3 = 812,8 m; L_{4c}= 116,4 m; L_5 = 18.3 m; α_{in1} = 6°, α_{in2} = 0°; α_{out2} = 0°, α_{out2} =9°; R = 742м; D_w= 700 mm; h = 12 m
5) D_{out}= 720 mm; δ = 14 mm; δ_{ins}= 3,5 mm; L = 1300 m; W = 100%	L_1 = 71,5 m; L_{2c} = 105,5 m; L_3 = 962,1 m; L_{4c} = 158,2 m; L_5 = 3.8 m; α_{in1} = 6°, α_{in2} = 0°; α_{out2} = 0°, α_{out2} =9°; R = 1008 m; D_w = 900 mm; h = 13 m
6) D_{out}= 820 mm; δ = 16 mm; δ_{ins}= 3,5 mm; L = 1600 m; W = 100%	L_1 = 83,3 m; L_{2c} = is 120.2 m; L_3 = 1212,1 m; L_{4c} = 180,1 m; L_5 = 5.5 m; α_{in1} = 6°, α_{in2} = 0°; α_{out2} = 0°, α_{out2} =9°; R = 1148 m; D_w= 1000 mm; h = 15 m
7) D_{out}= 1020 mm; δ = 18 mm; δ_{ins}= 3,5 mm; L = 1900 m; W = 100%	L_1 = 112,0 m; L_{2c}= is 120.2 m; L_3 = 1464,6 m; L_{4c} = 180,1 m; L_5 = 24.7 m; α_{in1} = 6°, α_{in2} = 0°; α_{out2} = 0°, α_{out2} =9°; R = 1428 m; D_w = 1250 mm; h = 18 m
8) D_{out}= 1220 mm; δ = 20 mm; δ_{ins}= 3,5 mm; L = 2200 m; W = 100%	L_1 = 150,3 m; L_{2c} = is 120.2 m; L_3 = 1701,3 m; L_{4c} = 180,1 m; L_5 = 50,3 m; α_{in1} = 6°, α_{in2} = 0°; α_{out2}= 0°, α_{out2} =9°; R = 1708 m; D_w = 1500 mm; h = 22 m
9) D_{out}= 1420 mm; δ = 26 mm; δ_{ins}= 3,5 mm; L = 2500 m; W = 100%	L_1 = of 144.6 m; L_{2c} = 208,1 m; L_3 = 1827,8 m; L_{4c} = 311,9 m; L_5 = 9.8 m; α_{in1} = 6°, α_{in2} = 0°; α_{out2}= 0°, α_{out2} =9°; R = 1988 m; D_w = 1750 mm; h = 26 m

Due to the fact that when using these theoretical profiles, it is not possible to rely on the actual values of pulling forces, the results of calculations using the proposed method, the method of the University of Waterloo, and the method of SP 42-101-2003 are compared with the results of calculations using the method of JSC "Giprotruboprovod".

The relationship between the value of the pipeline diameter and the error of the calculation method for a series of theoretical profiles of pipeline junctions, the parameters of which are given in Table 1, is shown in Figure11.

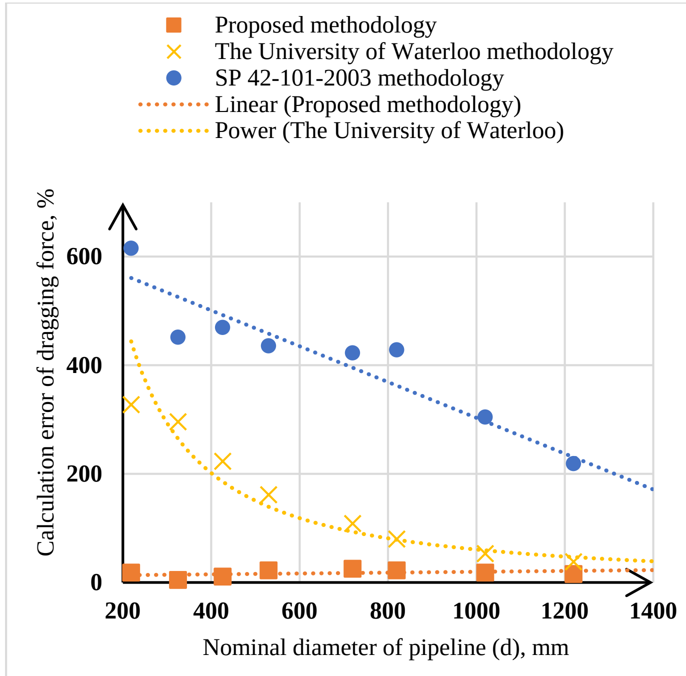

Figure 11. Dependence of the error value of the calculation method from the pipeline diameter (theoretical)

From the graph shown in Figure 11, it follows that the best convergence with the results of the calculation of the method JSC "Giprotruboprovod" shows the results determined by the proposed method (the error varies from 4 % to 25 %).

Due to the underestimation of the JSC "Giprotruboprovod" methodology of the factors mentioned earlier and affecting the final value of the pipeline pulling force, the trend line of the results obtained by this method is lower than the trend line of the results obtained by the method proposed by us. The proposed method gives the value with a margin, in relation to the result according to the method of JSC "Giprotruboprovod". However, the stock is very moderate.

In order to increase the accuracy of calculating the design value of the dragging force, the dependence of the total dragging force on the properties of the drilling mud should also be taken into account [33]. For this purpose, the drag forces were calculated according to the proposed method with different parameters of the density and dynamic shear stress of the flushing drilling mud.

It should be noted that changes in the parameters of the drilling mud may be due to both deliberate actions of the construction contractor, and changes in the properties of the drilling mud due to an increase in hydraulic pressure and the deposition of large rock fractions at the bottom of the well. A sharp increase in the density of drilling mud at the bottom point of the well will lead to an increase in the buoyancy of the pipeline, its ascent and pressing against the well arch.[34]

Practical experience shows that the requirements for the rheological properties of drilling fluids also change depending on the number of stages in the construction of underwater passages and expander structures. The average density of drilling mud is from 1060 kg /m3 to 1200 kg/m3.

Depending on the properties of the soils composing the geological section (the size of particles held in solution), the dynamic shear stress (structural strength) in solution averages from 90 Pa to 130 Pa.[35]

An increase in the density of the flushing mud by 10 % and a decrease in the dynamic shear stress by 10 % result in a 23% reduction in the total force. A 10% reduction in the flushing mud density and a 30% increase in the dynamic shear stress result in a 28% increase in the total force. All this once again confirms that the change in the drilling mud parameters has a significant impact on the value of the total pipeline pulling force.

Table 2. Results of calculations of dragging forces for various n-chords

Crossings	Actual pulling force, kN	Calculation of the pulling force according to the proposed method for n-chords, kN								
		n=4000	n=3000	n=2000	n=1000	n=400	n=200	n=100	n=50	n=25
Crossing the river Evyakha (530x10 mm; L= 844.5 m)	450	556,20	546,75	534,51	539,10	542,70	546,30	558,27	563,17	573,07
Crossing the Singapayskaya channel (720x12 mm; L= 451.6 m)	399	349,32	361,81	367,20	352,96	336,56	320,80	307,63	304,84	296,14
Crossing the river Kama (426x10 mm; L= 1654 m)	686	855,37	837,26	826,01	825,33	836,65	841,72	860,11	898,87	906,49

Nevertheless, the calculation results obtained by the method of JSC "Giprotruboprovod" are not an absolute standard. To correctly assess the results of the calculated effort obtained by the proposed method, it is proposed to compare them with the actual (full-scale) values of the effort.

Calculations are performed based on the field data of three constructed underwater crossings:

1. Passage of the Priobskoye field's oil and gas collection steel pipeline across the river evyakha by the directional drilling method;
2. Passage of the Solkinskoye field steel water pipeline through the singapayskaya channel by the directional drilling method;
3. Passage of the steel oil pipeline from the elnikovskoye field through the river Kama by directional drilling.

To justify the choice of n-number of chords for dividing curved sections of the well, it is necessary to calculate the pulling forces according to the proposed method for three existing transitions with different values of n (table 2).

In accordance with the calculated data in Table 2, the dependence of the error in determining the calculated force on the number of split chords is shown in Figure 12.

According to the diagram in Figure 12, the number of chords n = 2000 is the most preferred for calculations. Therefore, it gives the lowest value of the error in calculating the pulling force.

The results of calculations of dragging forces using the proposed and three existing methods are shown in Table 3.

The calculation error based on four methods for crossing the river Evyakha, the channel Singapayskaya, and the river Kama is shown in Figure 13.

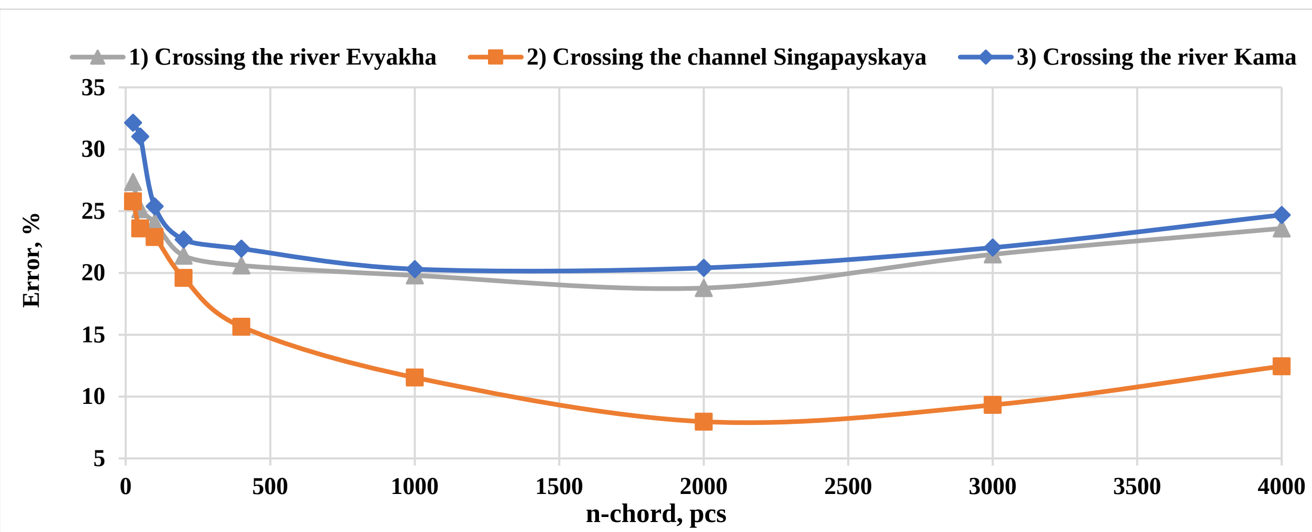

Figure 12. Dependence of the error in determining the calculated force on n-chord

In accordance with the data (Figures 13–15), in all three calculated cases, the proposed method gives the most accurate value of the pulling force.

In order to determine the relationship between the values of the dragging force of one linear meter (lin. m) of the transition and the value of the diameter of the pipeline being dragged using the three most accurate methods (the proposed method, the method of JSC "Giprotruboprovod," and the methodology of the University of Waterloo), we present the results of the calculation in the form of graphs.

In all three calculated cases, the results of calculations based on the proposed method and methodology converge on JSC "Giprotruboprovod." This fact is due to the fact that the calculation model of the proposed method practically coincides with the model of JSC "Giprotruboprovod," except for the addition associated with taking into account additional passive and active force factors on curved sections of the profile.

Table 3. Results of calculations of dragging forces

Area	Calculation method	Parameter	
		Actual pulling force, kN	Estimated pulling force, kN
Crossing the river Evyakha (530x10 mm; L= 844.5 m)	Proposed methodology	450	534.5
	JSC "Giprotruboprovod"		298.5%
	The University of Waterloo		1096.5
	SP 42-101-2003		4824
Crossing the Singapayskaya channel (720x12 mm; L= 451.6 m)	Proposed methodology	399	367.2
	JSC "Giprotruboprovod"		351.4%
	The University of Waterloo		799
	SP 42-101-2003		6580
Crossing the river Kama (426x10 mm L= 1654 m)	Proposed methodology	686,826	826
	JSC "Giprotruboprovod"		536.7%
	The University of Waterloo		1919
	SP 42-101-2003		7217

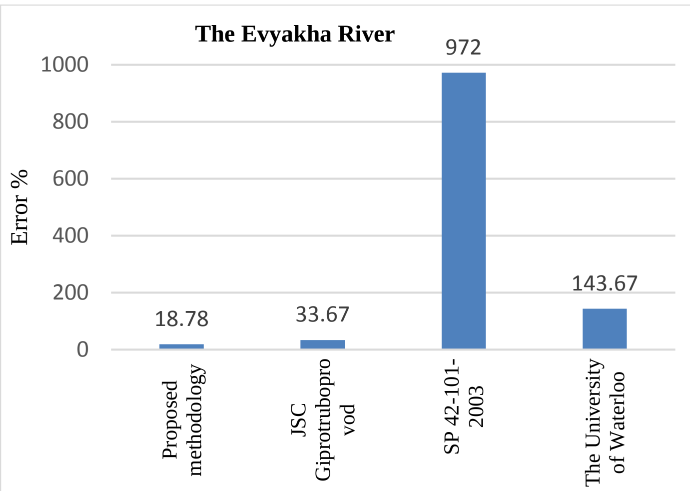

Figure 13. The error of the calculated force determined by various methods, River Evyakha

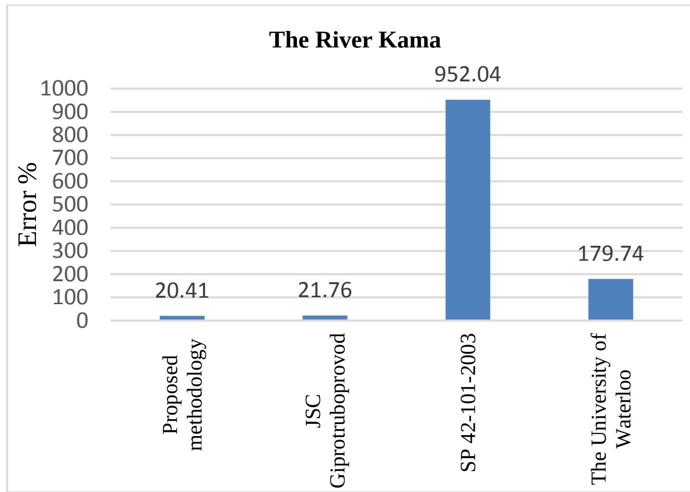

Figure 15. The error of the calculated force determined by various methods, River Kama

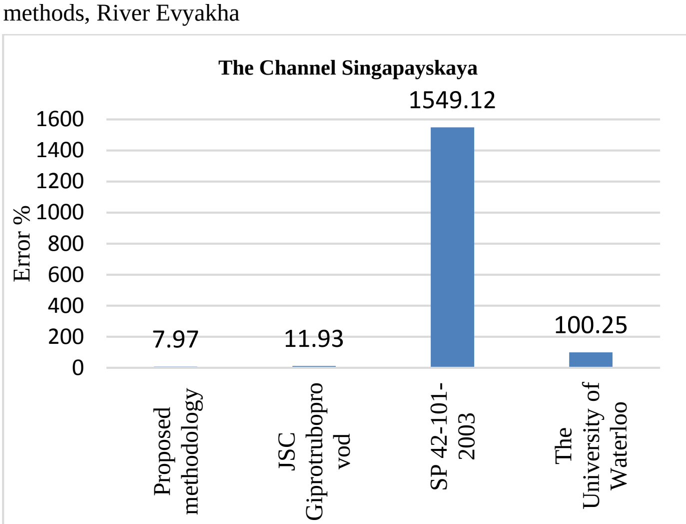

Figure 14. The error of the calculated force determined by various methods, Channel Singapayskaya

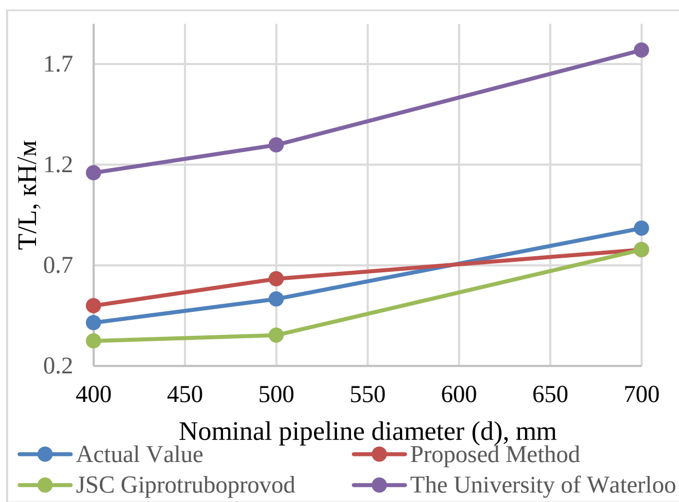

Figure 16. Dependence of the amount of dragging force 1 lin. m. of transition from the pipeline diameter

From Figure 16, it can also be determined that the amount of force calculated according to the proposed method for a diameter of 630 mm corresponds to the actual value. When the diameter is less than 630 mm, the calculation method gives an overestimated result, and with an increase in the diameter from 630 to 700 mm, the calculated force decreases due to underestimation of force factors.

The accuracy of the calculation according to the proposed method is on average 7% higher than that of the proposed method, JSC "Giprotruboprovod." The average error of the proposed method in relation to the actual value is 16%. The average error according to the method of JSC "Giprotruboprovod" in relation to the actual value is 23%.

To optimize the calculated pipeline pulling force according to the calculation method proposed by us under various construction conditions, various transition configurations for the subsequent optimal selection of the well profile, drilling fluid characteristics, and ballasting parameters, as well as to assess the stress-strain state of the pipeline, the Pull Force-HDD v1.0 software package was developed in the programming language "Java.".

Conclusion

The paper analyzes the existing methods for calculating the effort of dragging the pipeline into the well at low pressure. When comparing the results of calculations using existing methods with the actual values of pulling forces, the advantages and disadvantages of existing methods that affect the final result of the calculation are revealed, which form the basis of the updated methodology proposed by the authors. Recommendations were made to increase the accuracy of calculating the pulling force, including on curved sections. Further work on improving the calculation model should be carried out by identifying the dependence of the drag force on the rheological properties of the drilling mud. By the theoretical provisions of the method proposed by the authors, the calculations of dragging forces for three existing transitions constructed by the directional drilling method are complete. The obtained theoretical results are characterized by excellent convergence with field data (the margin is from 8 to 20%). The proposed method for determining the pulling force gives values that exceed those obtained by the method of JSC "Giprotruboprovod," which increases, on average, by 7–25%, which allows for minimizing risks in the implementation of the pipeline transition project by directional drilling.

Acknowledgments

Author (MP) acknowledges the department staff for their support to this project. Their support, dedication, and expertise have been instrumental in its success.

Conflict of Interest Statement

The authors of this article declare no conflicts of interest related to the research, authorship, or publication of this article. We affirm that the research presented in this article has been conducted objectively and without any financial or personal biases that could influence the findings or conclusions.

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