Reduction of movement resistance force of pipeline in horizontal curved well at stage of designing underground passage

V S Toropov and S Yu Toropov

Industrial University of Tyumen, 38 Volodarskogo St., Tyumen, 625000, Russia

E-mail: vladimir.s.toropov@gmail.com

Abstract. A method has been developed to reduce the resistance to movement of a pipeline in a horizontal curved well in the construction of underground passages using trenchless technologies. The method can be applied at the design stage. The idea of the proposed method consists in approximating the trajectory of the designed trenchless passage to the equilibrium profile. It has been proved that in order to reduce the resistance to movement of the pipeline arising from contact with the borehole wall, the profile of its initial and final sections must correspond, depending on the initial conditions, to the parabola or hyperbolic cosine equation. Analytical dependences are obtained which allow supplementing the methods of calculation of traction effort in trenchless construction for the case when the profile of the well is given by an arbitrary function.

1. Introduction

The use of trenchless technologies for the construction of pipeline passages requires careful attention to the design of the well profile in which one or another form of communication is to be laid. Parameters of the profile of trenchless pipeline passages are closely related to the relief of the terrain, the ground conditions in the longitudinal section, the location of the boundary of the zone of possible channel changes, and of course the technology of production.

The key parameters of the passage itself are usually the length of a trenchless pass and the greatest depth of the pipeline section, especially if one constructs a passage under a water obstacle.

The listed parameters are obtained by calculation at the design stage, and as a rule, they are specified at the place of construction of the underground or underwater passage during technological design.

Erroneous methods of calculation and design have to be compensated in practice by the capabilities of drilling rigs and auxiliary equipment [1]. Statistics of emergency situations in trenchless construction indicates that the design and construction methods for passages are far from perfect [2]. In Russia, each industry sector develops standard documentation on this issue separately.

Obviously, in this situation, there is an industry demand for improving trenchless technologies, including methods of calculation and design. This potential is not fully realized, and improvement of modern design methods can well provide significant savings in resources and production capacity [3].

2. Materials and methods

Unlike steel pipelines, the buoyancy of which depends on the diameter and wall thickness, plastic pipes always have positive buoyancy. This fact does not allow optimizing the profile of the well by the
criterion of weight or distributed load [4]. At the same time, the main force component of the pipeline movement resistance in a curved well is the normal force acting on the borehole wall from buoyancy forces [5].

When ballasting with water or drilling mud, the small values of the rigidity of plastic pipes and the relatively large areas of the pipeline burial, both during drilling wells and when entering the day surface, in these areas allow us to consider a ballasted plastic pipeline as a flexible thread of the third form of sagging. In this case, the point of access to the day surface and the point of conjugation of curvilinear and horizontal sections of the borehole are considered suspension supports. In the absence of a horizontal section, the pipeline can be considered as a thread of the first form of sagging.

![Figure 1](image)

**Figure 1.** Load distribution along the length of the pipeline: $KL$ – the considered section of the curved well; $MN$ – the infinitesimal section of the well; $dl$ – the infinitesimal increment of the trajectory along the length of the profile; $dx$ – the infinitesimal increment of the trajectory along the horizontal projection of the profile; $qdl$ – the magnitude of unit load applied to an infinitesimal section of the profile length; $F$ – the pipeline pulling force; $dF$ – the pulling force of an infinitesimal section of the pipeline; $a$ – the slope angle of an infinitesimal section of the profile to the horizontal at the given point of the profile.

Such assumption allows the well to be profiled from the condition of sagging of the pipeline pulled along the axial well, without touching the walls. Obviously, in real conditions, because of the uncertainty of the “suspension” conditions, complete alignment of the well and pipeline cannot be achieved. Therefore, the task of profiling involves reducing the component of frictional forces on the side walls by approximating the shape of the borehole profile to the equilibrium profile [6, 7].

When calculating the well trajectory for the equilibrium profile depending on the adopted scheme, two variants of load distribution are possible [8]:

1. Load distribution along the length of the pipeline.
2. Load distribution along the pipeline projection.

In the first case, according to the calculation scheme shown in Figure 1, let us obtain the equation of the well trajectory in the form:
\[ y = \frac{H_h}{2q} \left( e^{\frac{q}{H_h}} x + e^{\frac{-q}{H_h}} x \right) \]  

(1)

where \( H_h \) - horizontal component of the pipeline tension force; 
\( q \) - unit load distributed along the length of the pipeline; 
\( x \) – current coordinate of the passage profile; 
\( y \) – elevation mark of the current coordinate of the passage profile.

Let us take into account that the ratio of the horizontal component of the pipeline tension force to the unit load will be equal to the slope angle of the infinitesimal section of the profile to the horizontal at the given point of the profile:

\[ a = \frac{H_h}{q}. \]  

(2)

Then, (1) has the form:

\[ y = \frac{a}{2} \left( e^a x + e^{-a} x \right) = a \cdot \cosh \frac{x}{a}. \]  

(3)

Thus, let us obtain the well-known equation of catenary. That is, from the point of view of load distribution along the length of the pipeline, the well profile corresponding to the hyperbolic cosine equation will be optimal to minimize the resistance to pipe movement [9].

In the other case, if one distributes the load along the horizontal projection of the borehole profile, it is possible to use the calculation scheme shown in Figure 2 and compose the following equation:

\[ \frac{d^2 y}{dx^2} = \frac{q}{H_h}. \]  

(4)

Solving this equation, one gets:

\[ y = \frac{1}{H_h} \int dx \left[ \int q \cdot dx \right] + C_1 x + C_2 \]  

(5)

where \( C_1 \) and \( C_2 \) – constant values.

Let us introduce the notation:

\[ \varphi(x) = \frac{1}{H_h} \int dx \left( \int q \cdot dx \right). \]  

(6)

And let us reduce equation (5) to the form:

\[ y = \varphi(x) + C_1 x + C_2. \]  

(7)

In equation (6), let us denote the integral by \( \varphi(x) \) and keep in mind that the profile of the well must pass through points \( K \) and \( L \). Then one obtains the limiting conditions:

\[ \begin{cases} \varphi(x_0) + C_1 x_0 + C_2 = y_0 \\ \varphi(x_1) + C_1 x_1 + C_2 = y_1. \end{cases} \]  

(8)

From these conditions, one can determine both constants.

In a particular case, with a constant load along the projection of the well, the profile will have the form of a parabola.
Figure 2. Distribution of load along the horizontal projection of the pipeline: $ADEBB'E'D'A'$ – distributed load diagram for the pipeline.

Thus, in order to reduce the resistance force from contact with the borehole wall, the profile of its initial and final sections must correspond, depending on the initial conditions, to the parabola or hyperbolic cosine equation.

For practical application of the obtained dependences, it is necessary to supplement the method of calculation of the resistance force for the case when the well profile is given by an arbitrary function:

$$y = F_{bh}(x).$$

Figure 3 shows the profile of such well.

Drawing a tangent to the profile at point $B$, let us obtain the angle of inclination $\alpha$ of the profile at a given point to axis $Ox$, i.e. to the day surface. This angle will be:

$$\alpha = \arctg\left(F_{bh}'(x)\right).$$

For further calculations, it is necessary to set the accuracy value. Since the profile of the well is given by an arbitrary function, the radius of curvature can vary continuously throughout the entire length of the passage. So it usually happens in practice. Just as the process of drilling and expanding the pilot well, the process of pulling the working pipeline has a cyclic character [10], since the string consists of separate drill pipes connected to each other. They have the property of bending within certain limits, but the most significant change in the radius of curvature of the profile occurs just at the junction of two adjacent drill pipes.
This fact allows us to set the calculation accuracy in the case of an arbitrary curvature function in two ways:
1. For extended passages, let us take this value divisible by the linear dimension of one drill pipe.
2. For short-range passages, let us take the accuracy value divisible by a certain fraction of the linear dimension of the drill pipe used.

Thus, by setting calculation accuracy $t_c$ in one way or another, let us calculate angle $a$ through every $t_c$ of the values of function (9). The difference between the current and previous values of $a$ gives us angle $a_w$:

$$a_w = a_i - a_{(i-1)}$$  \hspace{1cm} (11)

where $a_i$ - current value of the angle of inclination of the well profile at a given point to the day surface;
$a_{(i-1)}$ - previous value of the angle of inclination of the well profile at distance $t_c$ from the current value.

Whence, the current radius of curvature of the profile will be:

$$r = \frac{t_c}{2 \sin \frac{a_w}{2}}.$$  \hspace{1cm} (12)

This dependence of the variable radius of the curvature of the profile on the current coordinate with a given accuracy can be used to calculate any components of the resistance force to movement of the pipeline in a horizontal well. Movement can be carried out by pulling or pushing [11], or using a combination of basic and auxiliary machines and mechanisms.

3. Results and Discussion
As a result of the study, a designer using any specific technique for designing trenchless pipeline passages has the opportunity to use the obtained analytical dependences to minimize the calculated pulling force of the working pipeline into the well [12].

In horizontal directional drilling, the overall result is formed taking into account a combination of various factors, both minor and major [13]. And the first thing to do when designing a passage is to approach the profile building responsibly.

With due consideration of all details and a careful approach to designing and planning of operations, it is possible to obtain such design effort of pulling a working pipeline at the design stage that will allow using a less powerful and therefore cheaper installation from the existing standard size range [14]. Thus, there is a possibility of a situation in which there will be a particular case of the implementation of the law of transition of quantity to quality. This, naturally, will mean a significant
reduction in the cost of the pipeline passage construction and an increase in the overall economic efficiency of construction.

4. Conclusion
The methods discussed in the paper can be used in the design of underwater and underground trenchless pipeline passages through any kinds of obstacles.

Any model of the pipeline pulling process used to calculate horizontally directed wells is provided in addition to taking into account properties of soils and the rheological model of the drilling mud, also taking into account the curvature of the profile and its effect on the amount of force for pulling the pipeline into the well. And the effect is negative [15].

The obtained dependences allow minimizing the negative effect of the very fact of the well curvature in the construction of the passage. Moreover, the use of this approach is not limited to wells having only curved areas.

Various special cases of designing a passage profile can be, for example, the following. The profile can have a central horizontal section and two curved sections of the entrance and exit. In another case, the central section of the profile can be curved, and the entrance and exit areas - rectilinear.

The breakdown of the profile into sections, in general, is typical for the majority of calculation and design methods, but this does not prevent the use of the dependences obtained in the work to reduce the resistance to movement of the pipeline from contact with the walls of the well. The results of the work can be applied to individual sections of the profile.

As shown in the paper, the profile of such sections, depending on the loading conditions, must correspond to the parabola or hyperbolic cosine equation.

The methods proposed in the work can also calculate the pulling force of the pipeline in the event that the profile of the well is specified by an arbitrary function, which is important for the practical implementation of the results of minimizing the pulling force.

References
[1] Toropov V S, Toropov E S, Podorozhnikov S Yu, Seroshtanov I V 2015 The use of additional equipment in horizontal directional drilling technology. *Mining information and analytical bulletin*. 36 36-44
[2] Seroshtanov I V, Toropov V S, Toropov S Yu 2015 Accidents and complications in trenchless construction of pipelines. Oil and gas of Western Siberia Materials of the International scientific and technical conference dedicated to the 90th anniversary of the birth of Anatoly Nikolaevich Kosukhin. pp. 98-102
[3] Zemenkova M Yu, Shipovalov A N, Dudin S M, Zemenkov Yu D 2007 System analysis of oil and gas facilities monitoring and control processes. *News of Higher Schools. Oil and gas*. 5 116-119
[4] Toropov V S, Tamer O S, Toropov S Yu and Nikiforov N A 2016 Dynamics of pipeline pulling process by horizontal directional drilling. *IOP Conf. Series: Materials Science and Engineering* 154
[5] Zemenkov Yu D 2008 *Monitoring of hydrodynamic and technical characteristics of pipeline systems: instructional aid.* (Tyumen: publishing house “Vector Book”)
[6] Voronin K S, Ogudova E V 2016 The Effect of Dynamic Processes in the System “Pipe-Soil” on the Pipeline Deviation from Design Position. Transport and Storage of Hydrocarbons. *IOP Conf. Series: Materials Science and Engineering* 154 012019 doi:10.1088/1757-899X/154/1/012019
[7] Voronin K S 2016 Forecasting and Evaluation of Gas Pipelines Geometric Forms Breach Hazard. Transport and Storage of Hydrocarbons. *IOP Conf. Series: Materials Science and Engineering* 154 012020 doi:10.1088/1757-899X/154/1/012020
[8] Toropov V S, Ponomareva T G, Toropov S Yu, Toropov E S 2016 Quantitative assessment of changes in the pipeline - wellbore system in the event of an emergency situation in horizontal
directional drilling. *News of higher educational institutions. Oil and gas* **5** 71-77

[9] Dudin S, Bahmat G, Zemenkov Y, Voronin K, Shipovalov A 2017 Strategy for monitoring and ensuring safe operation of Russian gas transportation system. *MATEC Web of Conferences* **106** DOI: 10.1051/matecconf/201710606004

[10] Shalay V, Zemenkova M, Zemenkov Y, et al. 2016 Modeling Parameters of Reliability of Technological Processes of Hydrocarbon Pipeline Transportation. *MATEC Web of Conferences* **73** 01029 DOI: 10.1051/matecconf/20167301029

[11] Zemenkov Y D, Shalay V V, Zemenkova M Y 2015 Expert systems of multivariable predictive control of oil and gas facilities reliability *Oil and Gas Engineering Procedia Engineering* **113** 312-315 DOI: 10.1016/j.proeng.2015.07.271

[12] Zemenkova M, Shalay V, Zemenkov Y, Kurushina E 2016 Improving the Efficiency of Administrative Decision-Making when Monitoring Reliability and Safety of Oil and Gas Equipment *MATEC Web of Conferences* **73** DOI: 10.1051/matecconf/20167307001

[13] A A Ibragimov, C Yu Podorozhnikov, A B Shabarov, M V Medvedev, M Yu Zemenkova. Calculation model and algorithm for determining residual resource of the pipeline under the periodic variations of stress and corrosion. *Mining informational and analytical bulletin* **S4** 199-206

[14] Zemenkov Yu D 2008 *Technique and technologic processes at transport of energy resources: two volume instructional aid.* (Tyumen: publishing house "Vector Book")

[15] Smirnov V V, Zemenkov Yu D 2013 Using the finite element method for calculation of intense deformed condition of above ground pipelines constructed on permafrost soil. *Pipeline transport: theory and practice.* **4** 18-23