Methodology for reducing energy and resource costs in construction of trenchless crossover of pipelines

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Abstract. The paper suggests a set of measures to select the equipment and its components in order to reduce energy costs in the process of pulling the pipeline into the well in the constructing the trenchless pipeline crossings of various materials using horizontal directional drilling technology. A methodology for reducing energy costs has been developed by regulating the operation modes of equipment during the process of pulling the working pipeline into a drilled and pre-expanded well. Since the power of the drilling rig is the most important criterion in the selection of equipment for the construction of a trenchless crossover, an algorithm is proposed for calculating the required capacity of the rig when operating in different modes in the process of pulling the pipeline into the well.

1. Introduction
Today the method of horizontal directional drilling for the construction of pipelines is one of the most common as it has many advantages and extensive positive experience in the application of laying the utilities [1]. Horizontal directional drilling units have a high cost, and their operation modes are such that machines and equipment involved in construction can quickly fail [2].

A cost-efficient approach to the operation of this equipment can significantly reduce the cost of construction, which is quite high, compared with other trenchless methods of laying pipelines.

2. Materials and methods
The first step in reducing the costs of constructing the communication transitions using horizontal directional drilling technology is selection of the most appropriate equipment and components for the work performance.

The right choice of equipment and components can save energy due to:

1. The use of a less powerful drilling rig that can develop the required pulling force when laying a pipeline on this technology [3].

2. The use of drill pipes with a smaller diameter and, as a consequence, with a less mass and a more flexibility for drilling and pulling, reduces the bending radius of the well as well as the weight of the drilling string and the required effort to move it, which ultimately results in less earthwork [4].

Hardness coefficient of the rock is the main criterion for choosing the drilling equipment, in particular, the rock cutting tool.

The amount of rock extracted from the well during pilot drilling and expansion, which directly depends on the coefficient of soil softening, determines not only the consumption of drilling mud for removal of cuttings, but also the costs and volumes of earthwork for equipping the pits at the working
site for the waste drilling mud.

Thus, this indicator influences the cost of constructing the pipeline crossover through several items of expenditure.

The amount of soil to be extracted from the well will be equal to:

$$V_{gr} = \frac{k_d \cdot L_{bh} \cdot \pi \cdot D_{bh}^2}{4}$$

where $L_{bh}$ – well length;

$D_{bh}$ – well diameter;

$k_d$ – coefficient of soil softening where drilling is performed

Dependence of the soil volume that must be removed from the drilled well on the well diameter with a well length of 200 m for different soil types is shown in Figure 1

\[\text{Figure 1. Dependence of the soil volume, which must be removed from the drilled well, on the well diameter with a well length of 200 m for different soil types: 1 – the initial well volume; 2 – sand, sandclay; 3 – vegetative soil, clay, loam, gravel; 4 – half-rocks; 5 – rocks of moderate strength; 6 – hard rocks; 7 – very hard rocks; }\]

The dependence shows that, all other things being equal, the soil volume can differ significantly from the initial volume of the well for different soil types. In addition, stronger soils tend to have a higher soil softening coefficient, which is an additional argument in favor of a thorough study of the ground conditions in the crossover section, and, if possible, the choice of a ground crossing path with a lower soil softening coefficient.

Measures for the selection of equipment and its components can be carried out after calculating the geometric parameters of the profile of the projected well, starting from the parameters of the pipeline being laid, as well as calculating the operating modes of the equipment during the pipeline pulling operation, in order to determine the necessary power characteristics of the drilling rig [5, 6].

To calculate the basic parameters of the pulling process, it is necessary to determine the geometric parameters of the profile of the projected pulling.
The main parameters of the well profile are:
1. The well length in the plan (over the day surface).
2. The burial depths at the lowest point of the profile.
3. Well length.
4. Well diameter.
5. Spudding angle.

The calculation of the profile can be made in several variants, depending on the initial data.

The profile, the length of the horizontal crossover, the maximum burial depths and the
diameter of the working pipeline are determined as the initial data for construction. Then the bend
radius of the transition profile and the pipeline depth at each point of the profile are calculated.

The actual well length is calculated by equation:

$$L = R_c \alpha_x = R_c \left( \arcsin \left( \frac{L_h}{2R_c} \right) - \arcsin \left( \frac{L_h - x}{R_c} \right) \right)$$  \hspace{1cm} (2)$$

where $R_c$ – bend radius of the well profile;
$x$ – horizontal coordinate;
$L_h$ – well length in the plan;
$\alpha_x$ – central angle of the well profile section.

In equation (2), variable $x$ is assumed to be equal to the total well length in the plan.

The bend radius must be compared with the minimum allowable bending radius of the pipeline
being laid for steel pipelines and with the minimum allowable bend radius of the drilling string for
polyethylene pipelines. And, if necessary, the radius must be increased by changing the crossing
length or the maximum burial depths in the plan.

It is expedient to select the spudding angle from the working range of the drilling rig angles, when
calculating the bending radius of the profile.

Next, the maximum operating rate of pulling the pipeline must be set. Its value for a specific
drilling rig will be limited by the maximum rate of carriage movement.

Due to the fact that the process of pulling the pipeline has a cyclical pattern, the calculation of the
process power characteristics must be carried out separately for each cycle, choosing a cycle of
pipeline movement, for which initializing the rig will require the greatest power [7].

Therefore in future, having received the value of the average power needed to disperse the drilling
string within one cycle at different profile points while pulling the pipeline of the developed diameter,
it is necessary to compare the result with the maximum power of the drilling rig. If the required power
is too high, the maximum operating rate must be reduced while the pulling process.

Calculation of the resistance force at the beginning of the braking section is made using equation
[8]:

$$\sum F_{res} = \lambda \cdot \rho_f \left( L_{bh} - L - x \right) \frac{\pi \left( D_{bh}^2 - D_{dr}^2 \right)}{8D_{bh}} \left( \frac{dx}{dt} \right)^2 + \frac{L_p - L - x}{L_p} \cdot m_p \cdot g \cdot k_{res} +$$

$$+ \frac{\pi}{4} \left( D_{bh}^2 - D_{dr}^2 \right) \left( \sqrt{R_c^2 - x^2 + H_{max} - R_c} \right) \rho_f \cdot g,$$

where $\lambda$ - coefficient of the hydraulic resistance;
$\rho_f$ – mud density;
$D_{bh}$ – well diameter;
$D_{dr}$ – drill pipe diameter;
$L_{bh}$ – well length;
$R_c$ – well profile curvature radius;
$H_{max}$ – maximum burial depths of the well profile relative to the earth’s surface.
Thus, the values of the sum of the resistance forces are obtained, which must be overcome when the pipeline moves at a given maximum operating rate at each particular point in the well profile as the pipeline and the drilling string enter it [9].

After this, the acceleration in the braking section and the length of the braking section are calculated.

Next, it is necessary to determine the version of the cycle, that is, the presence or absence of a uniform motion section.

In the case when a uniform motion section is present, it is necessary to specify its length and calculate the amount of the drilling rig operation related to moving the pipeline on the uniform motion section.

The length of the acceleration section is found as follows:

\[ l_I = l_{dr} - l_{III} - l_H. \] (4)

Further, it is necessary to calculate the amount of operation of the drilling rig for moving the pipeline in the acceleration section.

In the case when the uniform motion section is absent, the length of the acceleration section will be equal to:

\[ l_I = l_{dr} - l_{III}. \] (5)

And after that, the work of the drilling rig in the acceleration section is determined.

Then, in the case of the presence of a uniform motion section, the propagation time for the speeding up and uniform motion sections will be:

\[ t_I + t_{II} = \frac{2l_I}{a_I} + \frac{l_H}{v_{max}}. \] (6)

And in the case of absence of a uniform motion section, the propagation time for the acceleration section will be equal to:

\[ t_I = \frac{2l_I}{a_I}. \] (7)

After that, the required capacity of the installation is calculated to move the pipeline to a length equal to that of the drill pipe, according to the calculation methodology presented in [10].

The pulling mode is determined by a combination of such parameters as maximum working speed, speeding up in the acceleration section, the presence or absence of a uniform motion section and its length [11]. The length of the used drill pipes is also significant.

Using the above described calculation sequence, it is possible to select the pulling mode, most profitable in terms of power, the maximum back pull force of the rig or the time of work performance.

Selecting the equipment according to peak values of tractive power calculated for the entire well profile, it is possible to select the pulling mode with the least energy costs that occur when pulling the pipeline and the drilling string during the pulling process [12].

3. Results and Discussion
Calculation of the parameters of the pulling process at various operating modes of the drilling rig requires a fairly large amount of calculations, in connection with the need to take into account a variety of factors that affect the amount of tractive power and the required drilling rig power [13].

Therefore, for calculations using the methodology described in this paper, an algorithm was developed that allows selecting the most cost-effective mode of pulling the pipeline.
Figure 2. A flow-chart of the algorithm for calculating the required power of the rig when operating in different modes

The algorithm allows solving the following problems:
1. Determination of the geometric parameters of the well profile in accordance with the tasks facing the designer and the capabilities of the drilling rig.
2. Calculation of the instantaneous value of the traction power for the rig, which is necessary for pulling, at all points of the well profile, at different operating modes of the rig.
3. Calculation of the value of the rig power, which is necessary to perform the work of pulling the pipeline into the well, in this or that mode of operation.

The flow-chart of the algorithm is shown in Figure 2. Calculation using this algorithm requires the following data:
1. Geometrical parameters of the transition profile:
   1.1. The transition length over the day surface.
   1.2. Maximum burial depths.
2. Parameters of the laid pipeline:
   2.1. Pipeline diameter.
   2.2. Material of the pipeline.
   2.3. Weight of lineal meter of pipeline.
3. Drilling pipes parameters:
   3.1. Drilling pipe weight.
3.2. Length of the drilling pipe.
3.3. Diameter of the drilling pipe.
4. Drilling mud parameters:
   4.1. Drilling mud density.
   4.2. Tangential shear stress of the drilling mud.
   4.3. Coefficient of plastic viscosity of the drilling mud.
5. The parameters of the pulling process:
   5.1. Maximum working speed of the pipeline during the pulling process.
   5.2. The current coordinate of the well profile.
6. Characteristics of the used auxiliary equipment:
   6.1. Coefficient of roller friction against the pipeline wall for a section of the pipeline located outside the well.

The calculation results are:
1. The instantaneous value of the thrust force of the rig, which is necessary for pulling, at all points of the well profile, at different operating modes of the rig.
2. The value of the rig power, which is necessary to perform the work on pulling the pipeline into the well, in this or that mode of operation.

4. Conclusion
The calculation results for the algorithm given in the work are the obtained values of the parameters of the pulling process at various operating modes of the drilling rig. They can be the basis for a reasoned choice of a drilling rig for work performance, and can also serve as indicators when taking decisions on the choice of operating modes of the used rig for horizontal directional drilling [14].

Thus, the developed set of measures for selection of the equipment and its components for pulling the pipeline is very relevant in a situation where the bulk of the work performers make crossings mainly on low-power rigs [15].

The rig possibilities can be expanded also by applying the proposed methodology of reducing the energy costs in terms of regulating the operating modes of the rig while pulling the working pipeline.

For the practical application of the proposed methodology, the algorithm for calculating the required power, proposed in the paper, can be used.

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