

Force of resistance to pipeline pulling in plane and volumetrically curved wells

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Abstract. A method has been developed for calculating the component of the pulling force of a pipeline, arising from the well curvature in one or several planes, with the assumption that the pipeline is ballasted by filling with water or otherwise until zero buoyancy in the drilling mud is reached. This paper shows that when calculating this force, one can neglect the effect of sections with zero curvature. In the other case, if buoyancy of the pipeline is other than zero, the resistance force in the curvilinear sections should be calculated taking into account the difference between the normal components of the buoyancy force and weight. In the paper, it is proved that without taking into account resistance forces from the viscosity of the drilling mud, if buoyancy of the pipeline is zero, the total resistance force is independent of the length of the pipe and is determined by the angle equal to the sum of the entry angle and the exit angle of the pipeline to the day surface. For the case of the well curvature in several planes, it is proposed to perform the calculation of such volumetrically curved well by the central angle of the well profile. Analytical dependences are obtained that allow calculating the pulling force for well profiles with a variable curvature radius, i.e. at different angles of deviation between the drill pipes along the well profile.

1. Introduction

The technology of horizontal directional drilling, which is increasingly used in the construction of pipeline passages, includes three main stages [1]. The most energy-intensive and difficult from the technical point of view is the stage of pulling the working pipeline [2]. It is the parameters of the pulling process that are the criteria for choosing the equipment for construction.

During pulling, the pipeline gradually enters the well at the point where the drill string exits and moves along the well to the spudding point [3]. It is obvious that the pulling force will vary, depending on the length of the pipeline that has entered the well. As the pipeline enters the well, the pulling force will increase. The maximum force will be observed when the pipeline enters the well with its full length [4].

Since the maximum force required to pull the pipeline is of the main interest, let us limit ourselves to the case when the pipeline has completely entered the well. The force required at this stage of pulling will be the criterion for choosing the drilling equipment for the construction of this passage [5].

2. Materials and methods

The profile of the pipeline passage can have both rectilinear and curved sections [6]. In these sections, various pull-resistant forces will act.



In general, the resistance force to pulling a pipeline into a well depends on several components:

$$F_{res} = F_{res}(F_{cur}, F_{dm}, F_{gr}) \quad (1)$$

where F_{cur} - resistance force to pulling from the well curvature;

F_{dm} - resistance force from drilling mud weight;

F_{gr} - resistance force from friction against the ground.

At the curved sections, the pipeline will be pressed against the wall of the well due to the tension of the pipeline [7]. Figure 1 shows a section of the pipeline in a curved well with a constant curvature (shown in dotted lines). Let us study a pipeline moving in a well filled with drilling mud and ballasted until it reaches zero buoyancy.

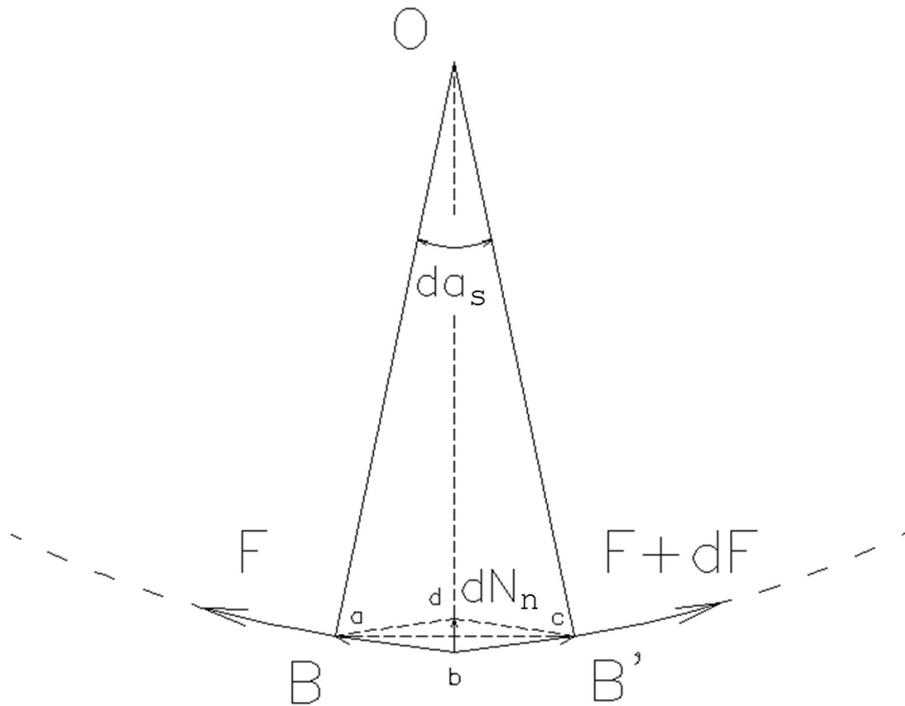


Figure 1. A design scheme for determining the force that presses the pipeline against the wall of the well in the process of pulling: BB' - infinitesimal element of the pipeline; dN_n – normal component of the force of pressing the pipeline against the wall of the well; F – force of pipeline tension; dF – force of tension of an infinitesimal pipeline element; da_s – central angle of the profile section.

If one considers the equilibrium of an infinitesimal element of pipeline BB' limited by central angle da_s , it is possible to obtain a component of total pressing force dN from pulling force dF :

$$dN_n = 2F \sin \frac{d\alpha_s}{2} + dF \sin \frac{d\alpha_s}{2}. \quad (2)$$

We discard infinitesimals of higher orders:

$$dN_n = F d\alpha_s. \quad (3)$$

When deriving the equation for the component from the tension force of the pipeline without taking into account other forces of resistance, the solution is reduced to the Euler formula that is used in a number of standard documents for the design of trenchless pipeline passages by the method of horizontally directed drilling. With this approach, there is no need to divide the well profile into sections of different curvatures, as well as calculate for each section the component of the resistance force from the well curvature [8]. This approach only complicates calculations and introduces significant errors.

The following computations can serve as the basis for this provision.

Figure 2 shows a well of length L_s with the entry angle of the pipeline when pulling α_1 at point A and the exit angle to the day surface of α_2 at point C . The day surface is represented by straight line O_1O_2 . Dotted lines indicate the tangents to the well profile at the points from which the radii of curvature are restored. Let us assume that the curvature of the well profile in the accepted coordinates is positive and does not change sign throughout its length.

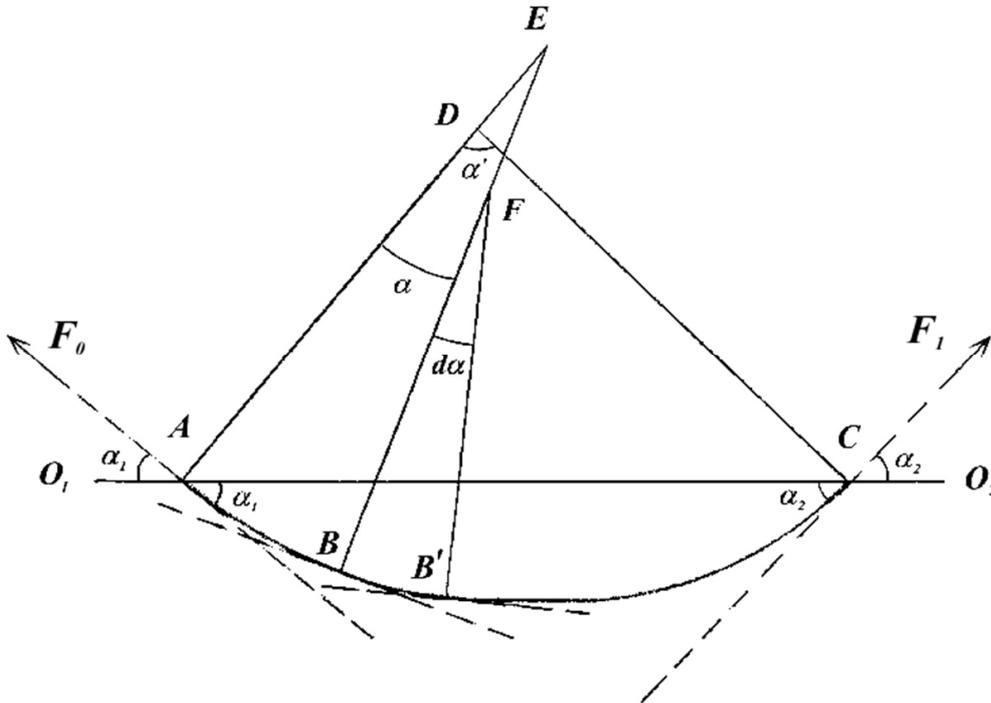


Figure 2. A design scheme for determining the component of the resistance force from the well curvature with a variable curvature radius: F_1 – pipeline pulling force, F_0 – pulling resistance force; O_1O_2 – earth's surface, A, C – entry and exit points of the pipeline.

At a well section, let us fix point B , the position of which is determined by current angle a between the radii of curvature recovered from the pipeline entry point A and point B . Moreover, well section AB can have variable curvature. In Figure 1, element BB' of the pipeline is presented in an enlarged form. The forces acting on element BB' of the pipeline corresponding to angle da are determined for point B as:

$$F = F(\alpha) \quad (4)$$

and for point B' as:

$$F + dF = F(\alpha + d\alpha). \quad (5)$$

Both forces are directed tangentially to the well trajectory. The normal force of pressure on wellbore roof N is defined as the total parallelogram force built on forces F and $F+dF$ neglecting the change in the radius of curvature and the displacement of the center of curvature.

Since determining angle da is not connected with the change in the position of the center and the radius of curvature, the corresponding changes in the resultant force can be neglected, considering the parallelogram as a rhombus. Discarding infinitesimals of a higher order, let us obtain equation (3).

As the friction force of the pipeline against the wellbore roof is proportional to the normal force, one obtains:

$$dR = \mu \cdot dN_n = \mu \cdot F \cdot d\alpha. \quad (6)$$

where μ – coefficient of friction of the pipeline against the wall of the well.

Friction counteracts the beginning movement of the pipe, so that force dR together with pulling force F at point B must counterbalance force $F+dF$ at point B' , whence:

$$dF = \mu \cdot F \cdot d\alpha. \quad (7)$$

Solving this differential equation for the entire borehole profile, which is determined by central angle a' , one obtains the well-known Euler equation:

$$F_0 = F_1 e^{-\mu\alpha'}. \quad (8)$$

Returning to Figure 2, let us note that from a simple geometric calculation, angle a' turns out to be equal to the sum of angles a_1 and a_2 .

In actual pipeline laying conditions, especially in urban areas, the well profile can have a volumetric curvature. In this case, an additional component appears from the curvature of the profile in the horizontal plane.

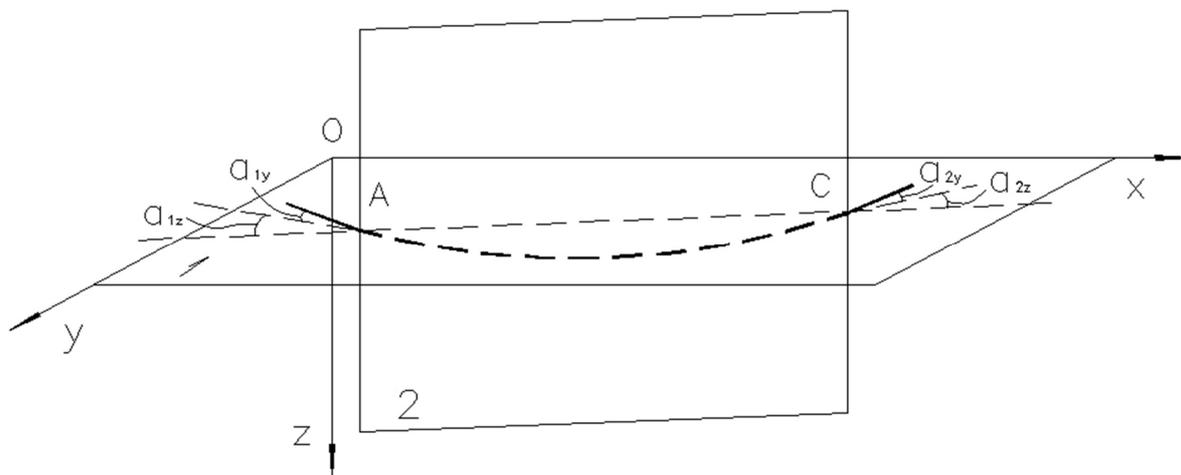


Figure 3. A design scheme of a well curved in two planes: A, C - entry and exit points of the well, 1 - plane of the earth's surface; 2 - plane perpendicular to the earth's surface; a_{1y} , a_{1z} , a_{2y} , a_{2z} - angles of entry and exit of the well relative to the corresponding planes.

Figure 3 shows a volumetrically curved well of length L_s . Straight line AC travels through the entry and exit points of the pipeline to the day surface, which is represented by plane 1. Plane 2 intersects plane 1 along straight line AC and perpendicular to the day surface. At point A, the angle of the pipeline entry into the well with respect to plane 1 is denoted by a_{1y} , and relative to plane 2 - by a_{1z} , and at point C, the exit angle of the pipeline relative to 1 and 2 will be denoted by a_{2y} and a_{2z} , respectively.

In this case, the side force will have two components: dN_z - in plane 1 and dN_y - in plane 2. They will give two components of the resistance forces, respectively, dF_z and dF_y , acting along the borehole axis. Adding these two components and solving the resulting differential equation, one obtains equation (8), in which:

$$\alpha' = \alpha_{1y} + \alpha_{2y} + \alpha_{1z} + \alpha_{2z} \quad (9)$$

where a_{1y} , a_{1z} , a_{2y} , a_{2z} - angles of entry and exit of the well relative to the corresponding planes.

Therefore, the volumetrically curved well can also be calculated from the central angle of the well profile.

Angle a' , which defines F_{cur} in (8), when the well is curved only in the vertical plane (the plane problem), is numerically equal to the sum of angles a_{1y} and a_{2y} . When the borehole is also curved in the horizontal plane, the sum of angles a_{1z} and a_{2z} is added to angle a' .

In fact, it is not always possible to drill a borehole section along one radius of curvature, i.e. ensure the same angle of deviation between drill pipes [9]. In particular, this can happen due to the fact that in order to strictly ensure the design radius of curvature in this section, it will be necessary to deflect drill

pipes with respect to each other by fractional angles (in degrees), which cannot be realized in practice, because the drill head navigation system and the rig itself can only work with angles that are multiples of one degree [10]. The solutions obtained earlier make it possible to calculate the pulling force for well profiles with a variable radius of curvature, i.e. at different angles of deviation between the drill pipes along the well profile.

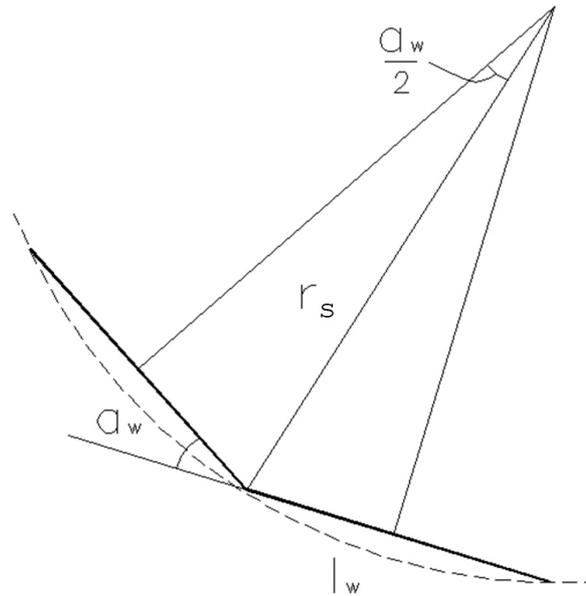


Figure 4. Finding the radius of curvature of the section of the profile from the angle of deviation of the drill pipes relative to each other in the general case: a_w - angle of deviation; l_w - drill pipe length; r_s - radius of curvature of the examined section of the well.

Figure 4 depicts a curved section of the well profile (shown in dotted lines), equal in length to two drill pipes. Perpendiculars are recovered from the centers of the drill pipes, the intersection of which gives the central angle of the profile section on the current drill pipe [11]. Radius r_s of curvature of the well profile in this section will depend on length l_w of the drill pipe and deviation angle a_w of this drill pipe, relative to the previous one.

Thus, if one uses the value of the current radius of curvature in this section when searching for the resistance force, one may find the pulling force in a section of one drill pipe length [12]. When summing these forces along the entire length of the profile, one gets a total pulling force for the entire profile. In this calculation, provided that a_w is zero, i.e. in a rectilinear section, it is necessary to neglect the curvature of the section in which this drill pipe is located.

3. Conclusion

Thus, the solutions obtained make it possible to draw the following conclusions:

1. When calculating the component of the frictional force from the curvature of the borehole, the effect of the sections having zero curvature can be neglected. In this case, this conclusion applies only to pipelines that have zero buoyancy [13]. With buoyancy other than zero, friction in curvilinear sections is calculated taking into account the difference between the normal components of the buoyancy force and weight.

2. With zero buoyancy of the pipeline, the total resistance to pulling, excluding the pulling forces from the viscosity of the drilling mud, is independent of the pipe length and is determined by the angle equal to the sum of the entry angle and the exit angle of the pipeline to the day surface.

Thus, finding the component of the resistance force from the curvature of the well can be reduced to finding the force of resistance according to the Euler formula (for the entire profile at once) using the angle numerically equal to the sum of the entry and exit angles of the pipeline.

Such calculation can be carried out for a profile of a well of any shape, since before drilling a well in this profile, a table is always compiled, in one form or another, indicating the deviation angles for each drill pipe relative to the previous one [14].

In addition, if the well is curved in several planes, one can calculate this volumetric curved well along the central angle of the well profile, taking into account the angles of the well entry and exit relative to the corresponding planes [15].

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