AGH DRILLING, OIL, GAS • Vol. 36 • No. 4 • 2019

http://doi.org/10.7494/drill.2019.36.4.5

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CALCULATION OF CRITICAL FORCES ACCOMPANYING THE INSTALLATION OF A HIGH-PRESSURE GAS PIPELINE IN MRZYGŁÓD, WITH TRENCHLESS HDD TECHNOLOGY

Abstract: The basic element providing the safety of HDD drilling jobs is properly selected pull force and torque. They also have an effect on the time of the realization of the wellbore and the cost of the investment. The professional literature offers a number of algorithms according to which the theoretically maximal installation force can be calculated. The calculated installation force values are presented in this paper, referring to some of the procedures used globally, and compared with the actual force encountered in practice. Real geological and drilling conditions are accounted for in the calculations. They are juxtaposed with the real forces recorded while installing a DN 1000, MOP 8.4 MPa gas pipeline. The discrepancies in the analytical results are explained. The paper closes with some conclusions and recommendations.

Keywords: trenchless technology, Horizontal Directional Drilling

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1. INTRODUCTION

Natural gas and oil have undoubtedly been the most important global energy minerals for decades. Unfortunately, the occurrence of oil deposits does not coincide with the main areas of their consumption, therefore they have to be transported over long distances, sometimes hundreds of kilometers. The building of pipelines is a very costly and logistically difficult engineering task, with most gas pipelines being placed in an open trench. Sometimes this cannot be realized or the difficulties are considerable, e.g. when passing across broad water courses, highways, protected areas or swamps. In such cases, more advanced solutions should be applied, i.e. trenchless technologies such as HDD, Microtunelling or Direct Pipe.

The most common technology presently applied in Poland is HDD (Horizontal Directional Drilling).

2. HDD TECHNOLOGY

The HDD technology dates back to the 1960s and is associated with AT&T Bell Laboratories in the USA. This R&D institution developed the first percussion rig driven with compressed air. In 1971 the first project was realized with this new technology by Titan Construction, before being implemented in Europe in 1981. In ca. 1991 the first such borehole was created in Poland [2].

Advantages of horizontal boreholes

With the development of HDD technology, the applicability of this method has also considerably extended. This is connected with the increasing length and diameter of the boreholes, e.g. the World's longest borehole of 5,205 m (as of 2018) was constructed in Hongkong.

Among the most important advantages of HDD technology are, e.g. [1, 2, 6, 7]

- minimized environmental impact,
- the installation can be realized at great depths (even dozens of meters under river beds, lakes or swamps),
- such a deep installation reduces the negative impact of large on-surface objects,
- it has zero impact on the existing utilities and traffic in a compact urban setting,
- lower cost and short time of works as compared to the trench method in difficult field conditions,
- works can be performed under watered and swampy areas,
- works can be performed in unstable soil conditions,
- underground utilities can be bypassed,
- works can be performed in natural reserves areas,
- works connecting land with marine objects can realized.

The first, and often overlooked stage in HDD technology lies in designing the concept, profile and trajectory. This stage should begin with establishing parameters of the linear object to be placed in the ground. Then the local field vision should be performed to check for any objects in the ground which may hinder the realization of trench methods. These can be water reservoirs and courses, swamps, developed urban areas, surface infrastructure, roads, railways forests or natural protected areas. After defining obstacles and passage sites with the trenchless method, a suitable trenchless method is selected. Among the most frequently applied ones are usually: pipe ramming, microtunelling and HDD and also Direct Pipe (first installation in USA in 2010) [3].

After selecting HDD technology, the transition site has to be designed. Typically, the HDD technology consists of three stages:

1. Drilling of a pilot borehole.
2. Reaming (Fig. 1).
3. Installation of a pipe.

For large boreholes, with a Hole Difficulty Index (HDI) greater than 20,000 and realized in difficult ground conditions, this standard should be extended by two phases, i.e. cleaning/flushing of the borehole (i.e. cleaning cycles) and obligatory calibration of the pipeline before the pipeline is installed (Fig. 2).

Fig. 1. Roll reamer (Hole Opener) before tripping to the borehole [collection of J. Janicki]

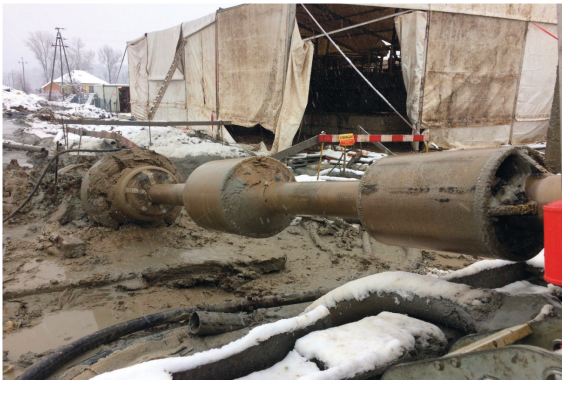

Fig. 2. Reamer kit [collection of J. Janicki]

In the calibration cycle a subdimensional closed-body tool, i.e. barrel reamer of smaller diameter than the one used in the last reaming cycle by ca. 2–4 inches (50.8 mm to 101.6 mm), is introduced to the borehole. By constantly monitoring the forces and properly selecting the procedure according to which a tool or tools are driven through the borehole, we can clearly specify the quality of the borehole and its readiness for the pipeline. Only after calibration can the pipeline be installed.

In the process of pipeline installation, certain amounts of water are introduced to the borehole in line with the applied method to outbalance the buoyancy of the pipeline and reduce the forces generated during the installation.

3. CALCULATION OF MAXIMAL, THEORETICAL FORCE NEEDED TO INSTALL PIPELINE

The expected maximal force of pipeline installation was calculated on the basis of three methods: estimated installation force calculated according to DCA in line with *Technical Guidelines* 4th edition, 2015 [8], described in a book by David A. Willoughby *Horizontal Directional Drilling utility and pipeline applications*, 2005 [4], and according to the below procedure. Special Microsoft Excel calculation sheets were worked out for them. The obtained results (Tab. 3) were compared with force measured in the course of the DN 700 pipeline installation in Mrzygłód, Poland (Fig. 3).

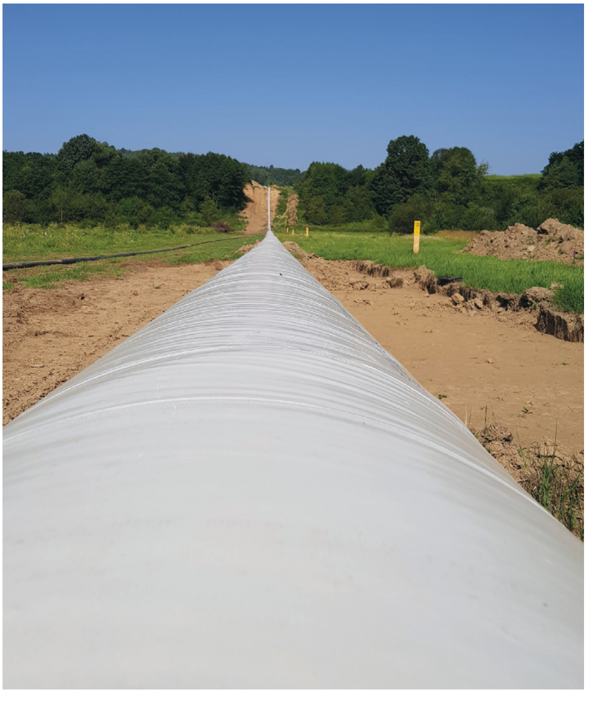

Fig. 3. Welded pipeline DN 700 979 m long with a protective layer [collection of J. Janicki]

Figure 4 shows the installation kit passing through the Pipe Truster on the pipe side.

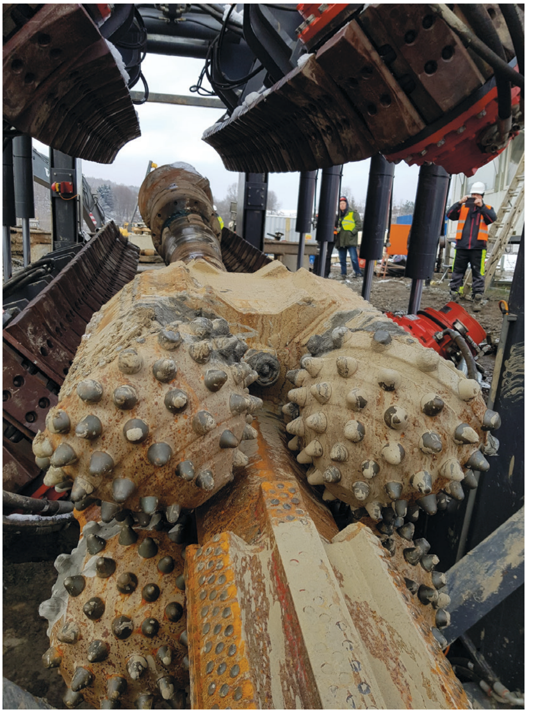

Fig. 4. Roll reamer inside the pusher pipe [collection of J. Janicki]

The procedure of calculating the theoretical maximal force needed for pipeline installation encompasses [5, 6]:

– Resistance from the buoyancy force acting on the pipeline sunk in the mud:

$$T_{wi} = L_i \cdot F'_w \cdot \mu \cdot \cos\alpha_i \text{ [kN]}$$

– Component of buoyancy force along the borehole axis:

$$T_{wsi} = L_i \cdot F'_w \cdot \sin\alpha_i \text{ [kN]}$$

– Resistance from fluid (mud) consistency:

$$F_{osi} = L_i \cdot f_{tp} \text{ [kN]}$$

– Tension acting on the end of the arc:

$$F'_{ni} = T_{wi} + T_{wsi} + F_{osi} \text{ [kN]}$$

– Resistance on arcs in the tendon theory:

$$F_{ci} = F_{ni} \cdot \left(e^{\mu \cdot \alpha} - 1\right) \text{ [kN]}$$

– Summaric tension in particular sections:

$$T_i' = T_{wi} + T_{wsi} + F_{osi} + F_{ci} \text{ [kN]}$$

– Resistance (from friction) of pipeline in the borehole:

$$T_i = \sum T_i' \text{ [kN]}$$

– Resistance of pipeline placed on rolls:

$$T_{rol} = f_{rol} \cdot (L - L_i) \text{ [kN]}$$

– Resistance of the tool kit:

$$T_z = t_z \cdot (L - L_i) \text{ [kN]}$$

– Summaric resistance at the end of each pipeline section:

$$T_k = \sum T_i \text{ [kN]}$$

– Maximal tension at the end of each pipeline section:

$$T_m = T_i + T_{rol} \text{ [kN]}$$

where:

F_w' – resultant buoyancy [kN],
T_{wi} – component buoyancy along borehole axis [kN],
f_{rol} – friction coefficient of pipeline placed on rolls (0.1 in the calculations) [according to standard NEN 3650],
L_k – total length of pipeline [m],
L_i – particular sections of pipeline [m],
F_r – weight of pipeline [kN/m],
i – number of particular section $i = 1, ..., 5$,
L_i – length of particular pipeline sections [m],
μ – friction coefficient in the borehole between the casing and pipeline wall [–],
α – inclination of the trajectory [rad],
α_i – inclination of the trajectory [°],
f_{tp} – consistency resistance in the borehole per unit of length according to standard NEN 3650 (assumed value equaled to 0.3),
t_z – estimated value of resistance of drilling tool (assumed value equaled to 0.25) [kN/m].

Calculation of installation force based on the DCA procedure

The expected installation forces in the pipeline can be calculated with a much easier method, making use of an equation proposed by Drilling Contractors Association (DCA) in the form [8]:

$$F_{max\ inst} = \pi \cdot D_r \cdot L \cdot f \text{ [kN]}$$

where:

- $F_{max\ inst}$ – installation force [kN],
- L – length to be covered by the pipeline [m],
- D_r – diameter of the pipeline [m],
- $\pi = 3.14$,
- f – average value of proportionality coefficients calculated as an arithmetic sum of coefficients in Table 1.

Value of particular components of coefficient f was selected from Table 1.

Table 1

Value of particular components of coefficient f

Parameter	Coefficient	Scope (description)		Assumed values
Material of the pipe	f_m	0.3 (HDPE)	0.4 (steel)	0.4
Diameter of the borehole	f_r	0.5 (small)	0.3 (large)	0.3
Sum of angles	f_w	0.3 (<15 degree)	0.5 (>30 degree)	0.4
Underground obstacles	f_h	0.5 (very probable)	0.3 (little probable)	0.5
Ballasting	f_b	0.3 (optimal)	0.5 (non-optimal)	0.3
Conditions of friction in construction ground	f_μ	0.5 (difficult)	0.3 (standard)	0.5
			Average value:	0.4

Calculated value of force in this method equaled to $F_{max\ inst} = 894.39$ [kN].

4. INDUSTRIAL EXAMPLE

The above method was used for making calculations for an industrial case, i.e. the crossing of the San River with a high pressure DN700 MOP 8.4 MPa steel pipeline. Data assumed for the calculation of the maximal installation force was presented in Table 2.

Table 2

Data assumed when calculating the maximal installation force of a pipeline

Parameter	Denotation	Value	Unit
Outer diameter of a pipe with insulation and a protective layer	d'_z	0.727	[M]
Outer diameter of a steel pipeline	d_z	0.711	[M]
Thickness of the pipe wall	g_r	0.0175	[M]
Inner diameter of a pipe	d_w	0.676	[m]
Cross-sectional area of a pipe	A	0.0381	[m^2]
Thickness of insulation	g_i	0.003	[m]
Thickness of protective layer	g_o	0.005	[m]
Density of steel	ρ_s	7850	[kg/m^3]
Density of insulation	ρ_i	1100	[kg/m^3]
Density of protective layer	ρ_o	1360	[kg/m^3]
Density of mud	ρ_{pl}	1280	[kg/m^3]
Geometrical parameters of borehole trajectory			
Length of straight-line section – entry	L_1	130	[m]
Angle of entry	β_1	10	[°]
Length of arc on entry	L_2	170	[m]
Radius of arc on entry	R_1	960	[m]
Length of straight-line section before the obstacle	L_3	410	[m]
Length of arc on exit	L_4	120	[m]
Radius of arc on exit	R_4	900	[m]
Length of straight-line section – exit	L_5	149	[m]
Angle of exit	β_2	8	[°]

Based on real data obtained from the realized crossing, Microsoft Excel calculations were performed, as presented in Table 3.

Table 3

Comparison of calculated results with recorded real, maximal installation force of the pipeline

	DCA method	David A. Willoughby's method	Proposed method
Maximal calculated installation force [kN]	894.39	1515.90	531.99
Maximal installation force recorded on the machine [kN]	490.5		
Change as compared to the real force [%]	182.3	308.8	108.5

5. CONCLUSIONS

1. One of the most important criteria of planning and realizing HDD projects is properly and safely determining the force of the pipeline installation. For this purpose, suitable calculations should be made, and a proper, rational safety coefficient assumed. On this basis can the proper class of rig be selected.
2. The following conclusions can be drawn on the basis of calculations and their comparison with real values:
   - The DCA method did not account for precise ballasting pipelines during their installation. Only two coefficients were assumed: 0.3 – optimal ballasting or 0.5 – non-optimal ballasting. According to the authors, this parameter should be treated as providing an approximate value – order of magnitude.
   - According to D.A. Wiloughby's method, the safety coefficients were included in the formula. However, only ballasting realized by filling the entire pipeline with water was taken into account. The result can be treated as a demand for the maximum power of the machine.
   - In the presented method, real force could only be approached very closely if the borehole was performed ideally and the ballasting was selective. In this case, the calculations were performed for the DN 700 ballasting steel pipe with a DN 450 PE HD 100 SDR17 pipe, as being realized in the construction field. When selecting the machine, one should account for the margin of pull force of the machine, assuming an appropriate safety coefficient. According to DCA recommendations, the force of the machine should be 2 to 3 times bigger than the calculated value. The authors recommend safety coefficient equal to ca. 2.0 and selective ballasting.
3. It must be remembered that the size of the machine itself does not guarantee that the installation will be performed. The quality of the performance and preparation of the borehole and ballasting of the pipeline are very important elements.

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