The calculation of the thrust force for pipeline installation using the Direct Pipe method

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Abstract

The Direct Pipe method enables to lay a prefabricated pipeline in one single, continuous working operation into the ground with the aid of the thrust unit "Pipe Thruster". As with Pipe Jacking, earth excavation is executed by means of a navigable microtunnelling machine, which is directly coupled with the pipeline The tunnel face is slurry supported and often uses a bentonite suspension for controlled excavation of the soil. Due to the success of the new method several other projects have been carried out. The magnitude of the thrust force generated by the Pipe Thruster is an important topic of the design of a Direct Pipe project. The thrust force is required to push the pipeline into the borehole and was investigated by means of Finite element calculations using the ABAQUS software package. The analysis of the Finite element calculation results shows several mechanisms, which contribute to the thrust force. The mechanisms have a strong interaction with each other. Formulas for the calculation of the Thrust Force were deduced per mechanism and per section of the drilling line. The measurement results of the thrust force from several projects, which have been carried out recently, were compared with the calculated thrust forces using the new set of formulas. The results are quite promising. The effect of a higher friction after a standstill period is currently still a research topic. Soon a decision will be made whether the time dependent standstill effect can be calculated based on physical processes in the bore hole, or whether a practical approach should be applied to estimate the time dependent standstill effects.

1. Introduction

The so-called trenchless techniques such as horizontal directional drilling, microtunnelling and other pipe jacking methods are applied on a large scale since the eighties. On one hand they provide a logical alternative when pipelines need to cross roads, railways, dikes, wetlands, rivers and other structures that have to remain intact. On the other hand these techniques minimize the impact of installation activities in densely populated and economical sensitive areas.

Since a few years a new trenchless technique developed by Herrenknecht exists (figure 1). In October 2007 the world premiere for the new Direct Pipe technology took place. This technique was used for the installation of a 464 m (1,522 ft) long culvert underneath the Rhine River near Worms in Germany. The Direct Pipe technique uses a Pipe Thruster, which pushes the pipe through the borehole [1].

Due to the success of the new method several other projects have been carried out. However the results of all the Direct Pipe projects were positive, design rules are not yet available. The magnitude of the thrust force generated by the Pipe Thruster is an important topic of the design of a Direct Pipe project [2]. The predicted thrust force (by calculation) and the comparison of the force with the capacity of the Pipe Thruster, should be one of the engineering works carried out before the installation of the pipeline.
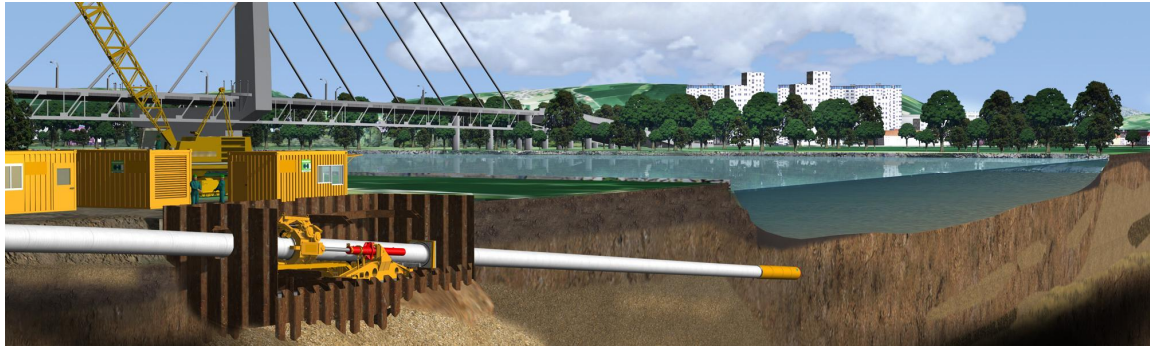
Figure 1. The Direct pipe method for pipeline installation

2.   *Background*

The Direct Pipe method enables to lay a prefabricated pipeline in one single, continuous working operation into the ground with the aid of the thrust unit "Pipe Thruster". As with Pipe Jacking, earth excavation is executed by means of a navigable microtunnelling machine, which is directly coupled with the pipeline (figure 2). The tunnel face is slurry supported and often uses a bentonite suspension for controlled excavation of the soil.

The Pipe Thruster is fixed horizontally and vertically in the launch pit and clamps the pipeline with its clamping device and pushes it (in front of the pipe the micro tunneling machine is welded) forward through the borehole. Since the diameter of the microtunnelling machine is significantly larger than the diameter of the pipe a borehole is created. The borehole is filled with lubrication bentonite. The type of lubrication bentonite is determined by the soil conditions through which the borehole is made.

Figure 2. Adapted micro tunneling machine for the direct pipe method.

3. The calculation of the thrust force

3.1 General

The thrust force necessary to install the pipeline should be predicted/calculated in the design phase of the project. Since the capacity of the Pipe Thruster is limited, the success of the installation of long pipes is strongly related to the accuracy of the predicted thrust force. The prediction of the thrust force and the comparison of the force with the Pipe Thruster, should be carried out before starting the installation of the pipeline.

The thrust force is required to push the pipeline into the borehole was investigated by means of Finite element calculations using the ABAQUS software package [3]. In the analysis, the following mechanisms are incorporated, which contribute to the thrust force:

1. Friction of the pipeline behind the thruster on the rollers.
2. Friction between pipeline and lubricant fluid.
3. Front force at the cutting head of the microtunnelling machine.
4. Friction between pipeline and the borehole wall.
5. Friction due to buckling of the pipe.

Only the first mechanism is uncoupled, because the pipeline on the rollers is located behind the thruster. The other mechanisms have a strong interaction with each other, which are described by the nonlinear finite element simulations. For example, the overall thrust force creates the so-called "capstan" forces in the curved sections of the drilling line.

In the subsequent paragraphs the mentioned mechanisms are described and analytical expressions are given, which can be used for design purposes.

3.2 Friction of the pipeline behind the thruster on the rollers.

The theory developed for the horizontal directional drilling method [4] provides the following general friction formula for the section of the pipeline that is outside the borehole on the rollers:

$$F_r = L_{out} g_p f_1$$

Where:
F_r the roller friction force (N),
L_{out} the length of the pipeline outside the borehole (m)
g_p the weight of the pipeline per unit length (N/m)
f_1 the friction coefficient (-)

Since the pipeline can be welded during installation (different segments lengths can be applied), the length of the pipeline outside the borehole increases if a new segment is added and smoothly decrease then this segment is brought into the borehole. Often there is a sloped construction with slope length L_{slope} for guidance the pipeline, so that three cases can be distinguished in the calculation of the friction on the rollers:

1) $L_{out} \leq L_{slope}$,
The whole part of the pipeline outside the borehole is on the sloped construction at the entry point.

2) $L_{slope} > L_{out} \leq 2L_{slope}$,
The pipeline outside the borehole occupies the entire downward slope length L_{slope} and part or all of the pipeline occupies the upward slope.

3) $L_{out} > 2L_{slope}$,

In this case the sloped construction at the entry point with the upward/downward slope has no gravitational contribution to the friction force.

Note that in some cases with a relative high entry angle and relative short pipe segments, it is possible to achieve negative value for the friction force.

3.3   Friction between pipeline and lubricant fluid.

The theory developed for the horizontal directional drilling method [4] provides the following general friction formula for the friction between lubricant and pipeline:

$$F_{lb} = L_b \pi D_o f_2$$

Where:

F_{lb} the friction force due to the lubricant(N),
L_b the length of the pipeline inside the borehole (m)
D_0 the outer diameter of the pipeline (m)
f_2 the friction coefficient (N/m^2)

The friction coefficient depends on the type of lubricant used. A value of about 50 (N/m^2) is common for a standard lubricant.

3.4   Front force at the cutting head of the microtunnelling machine.

Drilling through the soil changes the stress conditions in the soil. The deviations from the original stress conditions are largely determined by the size of the overcut and the face support pressure of the applied shield. Small deviations form the original stress conditions are acceptable as the stability of soil in front of the micro tunneling machine is maintained. A relative low support pressure may lead to settlement in front of the tunneling machine which in turn may lead to settlement of the surface or to settlement of soil layers below a construction or pipeline. A relative high support pressure can lead to a blow out of drilling fluid or may lead to heave of the surface

Under normal circumstances, a relative low support pressure is usually sufficient for stable conditions of the soil adjacent to the micro tunneling machine. The minimal required support pressure is often a little higher than the water pressure [5]. The relative low required minimal support pressure to stabilize the soil in front of the micro tunneling machine (figure 3) is determined by the type of soil in front of the tunneling machine.
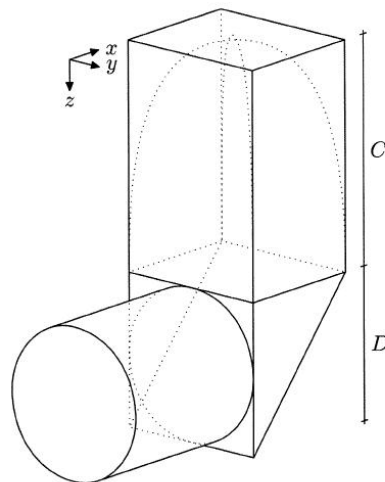

Figure 3. Soil wedge in front of the microtunnelling machine

$$\sigma_{\sup} = E_o + \sigma'_{h,\min} + u$$

Where:

$\sigma_{\sup}$ required support pressure (kN/m^2)
$\sigma'_{h,\min}$ minimal required horizontal soil stress (kN/m^2)
u waterpressure (kN/m2)
E_0 applied pressure above the minimal pressure (kN/m2)

Besides the face support pressure a relative small mechanical force is necessary to facilitate the penetration of the cutting wheel. The total front force can be calculated as follows:

$$F_f = \sigma_{\sup} \frac{\pi}{4} D_{o,m}^2 + F_{mec}$$

Where:

$\sigma_{\sup}$ required support pressure (kN/m^2)
$D_{o,m}$ outer shield diameter of the micro tunneling machine (m)
F_{mec} required mechanical force (kN)
F_f front force (kN)

This front force depends on the location of the micro tunneling machine on the drilling line and can be calculated for various locations along the drilling line.

3.5 Friction between pipeline and the borehole wall.

At the entry point, near the Pipe Thruster, the pipeline is pushed into the borehole. Assuming that the pipe is centered in the borehole, there is a distance over which the pipeline does not contact the borehole wall (figure 4).
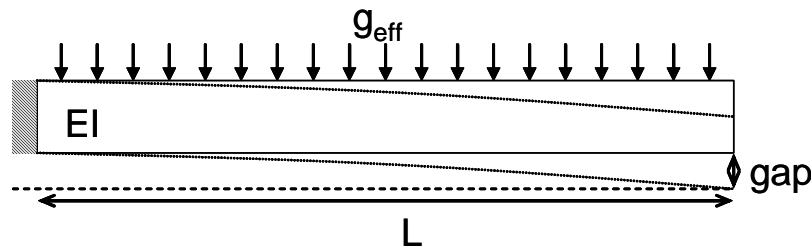

Figure 4. The no-contact zone at the entry point.

The length over which no contact between the bore hole wall and the pipe exists depends upon the stiffness and the effective weight of the pipeline (in the lubricant fluid) and can be calculated as follows:

$$L_t = \begin{cases} \sqrt[4]{\dfrac{8EIw_{gap}}{\left|g_{eff}\right|}}, & g_{eff} \neq 0 \\[2ex] 0 & , \quad g_{eff} = 0 \end{cases}$$

Where:

$$g_{eff} = g - g_{opw}$$

With:

$$g_{opw} = \pi \cdot r_e^2 \cdot \gamma_{fl}$$

Where:

r_e outer radius of the pipeline [m]
g_{opw} upward force of the pipeline [kN/m]
g weight of the ballasted pipeline [kN/m]
γ_{fl} unit weight of the lubricant fluid kN/m^3]
EI bending stiffness of the pipe [Nmm2]
w_{gap} difference between the radius of the borehole and the pipe radius [mm]

Friction between the pipeline and borehole wall is in general modeled by multiplying the force that the pipeline exerts on the soil (perpendicular to the drilling line) by a friction coefficient. This friction calculation is used for the horizontal directional drilling method for many years [3]. The friction can be expressed as:

$$\Delta F_w = f_3 \int_0^{L_b} |q(s)|\, ds$$

Where:

q the soil reaction perpendicular to the pipeline (kN)
s the distance along the drilling line (m)
f_3 the friction coefficient (-)
L_b total length of the borehole (m)

From horizontal directional drilling studies it appears that $f_3 = 0{,}2$ is a common value [3]. The soil reaction q, can be positive or negative depending on whether the pipeline touches the upper or lower borehole wall.

In the curved section of the drilling line the soil reaction due to bending of the pipeline can be calculated:

$$q_{max} = \frac{EI\lambda^2}{R} e^{-\pi/4} \sin(\frac{\pi}{4}) = 0.3224\frac{EI\lambda^2}{R}$$

Where:

$$\lambda = \sqrt[4]{\frac{k}{4EI}}$$

q_{max} maximum soil reaction near the end of the bend [N/mm^2]
k soil stiffness per length of pipeline. [N/mm^2]
EI bending stiffness of the pipe [Nmm^2]
R radius of the bend [mm]

The maximum soil reaction is used to determine the factor a:

$$a = \left| \frac{g_{eff}}{q_{max}} \right|, \text{ if } a > 1 \text{ then set } a = 1.$$

The factor a is used to calculate the contribution of the soil reaction force in the curved section to the friction. The subsequent formula yields the friction at the beginning or the end of the curve:

$$\Delta F_w^{bend} = \frac{f_3 EI\lambda}{R}(0.85a - 1.0903)(a - 1)$$

As explained before the previous described forces have a strong interaction with each other. The so-called "capstan" forces in the curved sections of the drilling line should be taken into

account. The total frictional force, built-up in a curved section F_p^{end} can be calculated based on the total fictional force at the beginning of the curved section F_p^0.

If $g_{eff}R > F_p^0$ then calculate the total friction force at the end of the bend using the following equations:

$$F_p^{end} = \frac{c_1}{f_3} + (F_p^0 - \frac{c_1}{f_3})e^{-f_3\alpha}$$
$$c_1 = \pi D_o f_2 R + f_3 R g_{eff}$$

Where:
α   angle at the beginning of the curve (radians)

If $g_{eff}R \leq F_p^0$ (which is always the case if g_{eff} is negative). Or after the result: $g_{eff}R < F_p^{end}$, then use the following equation to calculate the total friction force at the end of the curved section:

$$F_p^{end} = \frac{-c_1}{\mu} + (F_p^0 + \frac{c_1}{\mu})e^{f_3\alpha}$$
$$c_1 = \pi D_o f_2 R - \mu R g_{eff}$$

The basic idea underlying these equations is that if the pipeline is buoyant, a thrust force will have the effect that the soil reaction (and soil-pipeline friction) is reduced. In case of a negative or small effective weight, a thrust force will increase the soil-pipeline friction.

3.6 Friction due to buckling of the pipe.
The thrust force necessary to overcome the frictional forces may increase to a high level, so that buckling of the pipeline can occur. The buckling process is shown in figure 5 and is dependent on the stiffness of the pipe. The stiffness of the pipe is in turn dependent on the material of the pipeline and the combination of outer diameter and wall thickness [6].
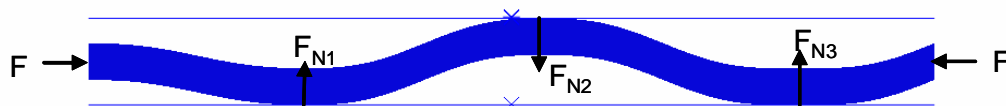

Figure 5. The buckling process.

In case the number of buckling modes in the pipeline and the thrust force F are known, the total contact force can be calculated. For the determination of the number of buckling modes it is necessary to apply a schematization of the pipeline in the borehole (figure 6).
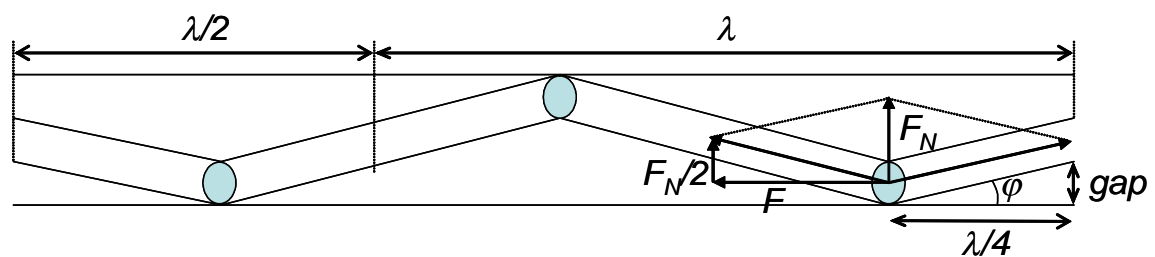

Figure 6. Schematization of the buckling modes.

For N buckling modes in the pipeline the so called buckling-wavelength is:

$$\lambda = \frac{2}{N} L$$

Where:
L   the length of the pipeline in the borehole (m)

The above described formula is used to derive the frictional force due to buckling of the pipe. This frictional force can be calculated as follows:

$$F_{buckle} = f_3 \frac{4}{3} \frac{LF^2}{\pi^2 EI} w_{gap}$$

Where:
F   the Thrust force without the occurrence of buckling (kN)
w_{gap} difference between the radius of the borehole and the pipe radius [m]
F_{buckle} the additional frictional force due to buckling (kN)

4.   Calculation results

The, in the previous paragraphs described, formulas have been used to calculate the total frictional force, which is equal to the Thrust force, for two Direct Pipe projects. The projects have been carried out in the Netherlands in the vicinity of Ommen.

A 48" steel pipeline was installed in Ommen. The drilling line of this Ommen DP-1 project had the following characteristics:
- Straight sections: L1 = 173.770 m, L2 = 33.540 m, and L3 = 40.480 m.
- Curve sections: LB1 = 97.738 m and LB2 = 171.042 m.
- Entry angle (αRi) = 4o.
- Exit angle (αRe) = 7o.
- Radius of the 1st curve (Ri) = 1400 m.
- Radius of the 2nd curve (Re) = 1400 m.
- Total length (including the machine) = 530.171 m.

In the subsequent figure 7, the measured and calculated thrust force of the Ommen DP-1 project, are plotted against the length of the drilling line.
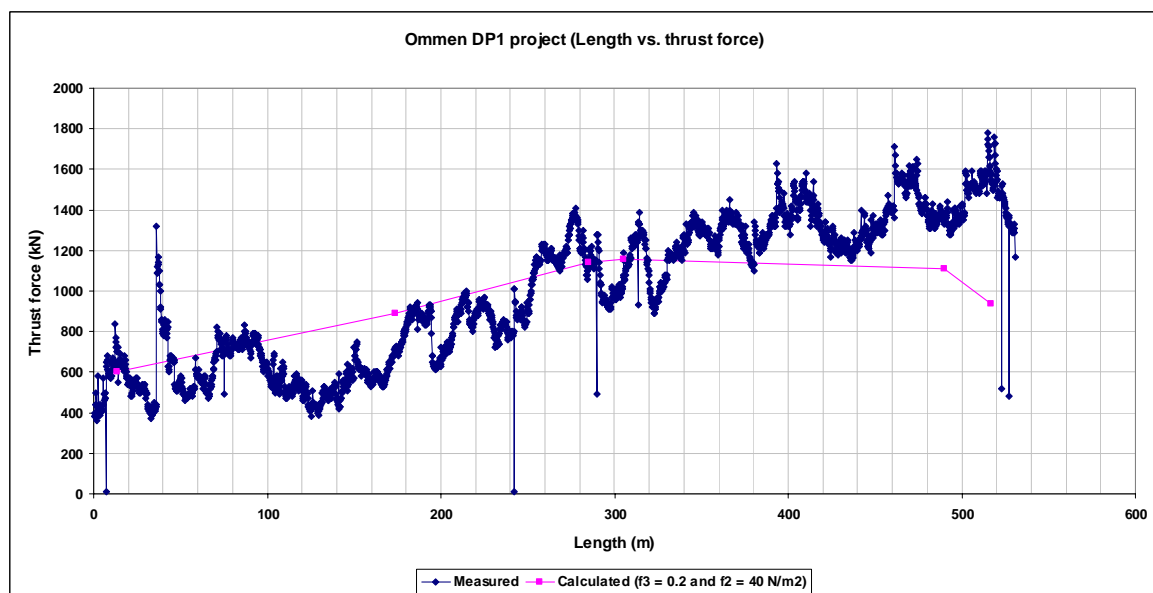

Figure 7. Measured and calculated thrust forces on Ommen DP-1 project.

At entry point, the thrust force increased from 640 kN to 830 kN after the machine had been idle for 16 hours. At L = 36 m, the thrust force increased from 430 kN to 1320 kN after the machine had not operated for approximately 2 days. The thrust forces measured between L = 250 m and exit point are mostly greater than the calculated ones.

At the second project near Ommen, again a 48" steel pipeline was installed. The drilling line of this Ommen DP-2 project had the following characteristics:
- Straight sections: L1 = 173.770 m, L2 = 33.540 m, and L3 = 40.480 m.
- Curve sections: LB1 = 97.738 m and LB2 = 171.042 m.
- Entry angle (αRi) = 4o.
- Exit angle (αRe) = 7o.
- Radius of the 1st curve (Ri) = 1400 m.
- Radius of the 2nd curve (Re) = 1400 m.
- Total length (including the machine) = 546.730 m.

The measured and calculated thrust forces are given in Figure 8.
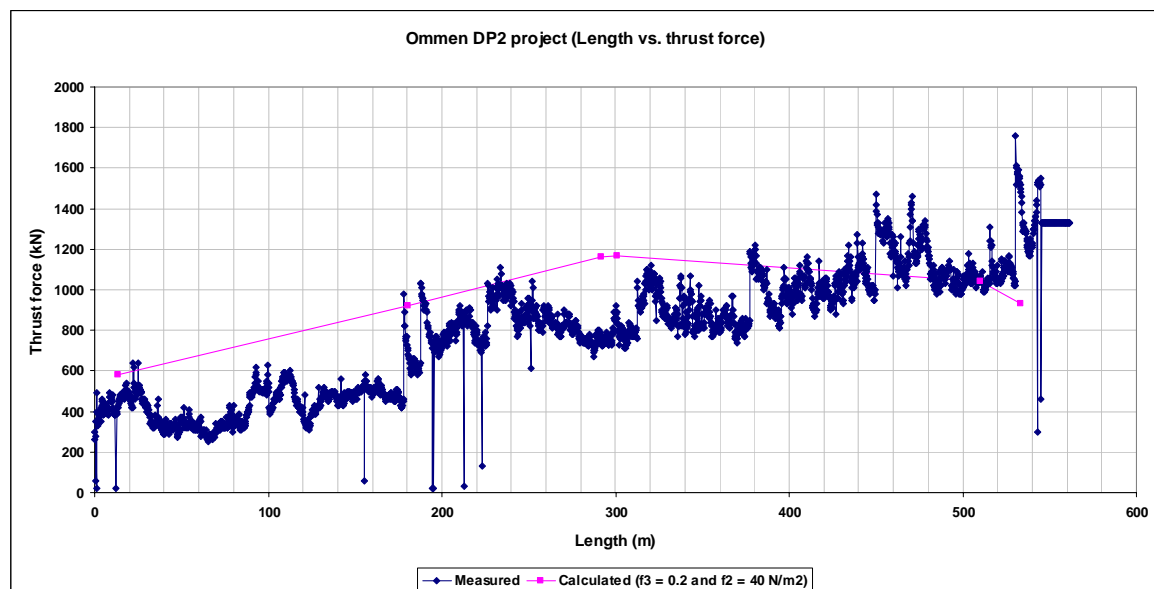

Figure 8   Measured and calculated thrust forces on Ommen DP-2 project.

Again, in this project the effect of stand still periods are visible. The measured thrust forces are a little greater than the calculated ones between L = 380 m and exit point, but the general fit is good.

5.   *Time dependent effects*

As mentioned in the previous paragraph, it has been observed that the required thrust forces were higher after a period of standstill. Once the pipeline was in motion again the thrust forces were lower. This effect is a common effect in microtunneling projects and is some times noticed in horizontal directional drilling projects as well.

In literature, no reliable explanations about the physics during a stand still period are found. It is thought that the increase in friction is related to the stability of the borehole, while the friction does not reduce entirely to the value before the standstill period.

At the moment the time dependent effects after a standstill period are investigated. The research results will have to indicate how the effects need to be considered. There are two options:

- The time dependent standstill effect can be calculated based on physical processes in the bore hole.
- A practical approach will be applied to estimate the time dependent standstill effects.

5. Conclusions

Since a few years a new trenchless technique developed by Herrenknecht exists. In October 2007 the world premiere for the new Direct Pipe technology took place. The Direct Pipe method enables to lay a prefabricated pipeline in one single, continuous working operation into the ground with the aid of the thrust unit "Pipe Thruster". As with Pipe Jacking, earth excavation is executed by means of a navigable microtunnelling machine, which is directly coupled with the pipeline (figure 2). The tunnel face is slurry supported and often uses a bentonite suspension for controlled excavation of the soil. Due to the success of the new method several other projects have been carried out. However the results of all the Direct Pipe projects were positive, design rules are not yet available. The magnitude of the thrust force generated by the Pipe Thruster is an important topic of the design of a Direct Pipe project. The predicted thrust force (by calculation) and the comparison of the force with the capacity of the Pipe Thruster, should be one of the engineering works carried out before the installation of the pipeline.

The thrust force is required to push the pipeline into the borehole and was investigated by means of Finite element calculations using the ABAQUS software package. The analysis of the Finite element calculation results shows the mechanisms, which contribute to the thrust force:

1. Friction of the pipeline behind the thruster on the rollers.
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5. Friction due to buckling of the pipe.

Only the first mechanism is uncoupled, because the pipeline on the rollers is located behind the thruster. The other mechanisms have a strong interaction with each other. The overall thrust force creates the so-called "capstan" forces in the curved sections of the drilling line. The interaction between the different mechanisms, which leads to capstan forces is a nonlinear relation which, is worked out to a comprehensive formula.

Besides the formula, which includes the capstan forces, other formulas were deduced per mechanism and per section of the drilling line. The centering effect of the Pipe Thruster at the start of the drilling line and the position of the microtunnelling machine at the end of the drilling line lead to unique boundary conditions, which have to be taken into account. In total, a set of 8 formulas was deduced for the calculation of the thrust force.

The measurement results of the thrust force from several projects, which have been carried out recently were compared with the calculated thrust forces using the new set of formulas. The results are quite promising. The effect of a higher friction after a standstill period is currently still a research topic. Soon a decision will be made whether the time dependent standstill effect can be calculated based on physical processes in the bore hole, or whether a practical approach should be applied to estimate the time dependent standstill effects.

6.   Literature

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