Theoretical problems of pipe inserting by making use of the method of horizontal directional drilling

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Teoretické problémy pri vkladaní potrubia pri pouzití horizontálneho riadeného vŕtania

The technology of pipe laying by making use of the method of horizontal directional drilling with a high-pressure liquid and with backward laying (hereinafter HDD technology – Horizontal Directional Drilling) has been considerably used in the Czech Republic in the course of the past few years. The article deals with the tractive forces applied to the PE pipes being laid and with functions of bentonite flushing in the HDD technology. The tractive forces have been measured in laboratories and assessed within a PhD thesis at STU in Bratislava. The measurement was performed on PE pipes of the company Pipe Life and with the bentonite of the company BDC Morava. At present there have been outlined the basic problems that may occur when pipes are laid by making use of the HDD technology.

Key words: *HDD, horizontal directional drilling, friction coefficient, tangential stress, forces*

Introduction

The importance of pipe laying by way of the method of horizontal directional drilling with high-pressure liquid and with backwards placing has risen in the course of the past few years. The HDD technology has been used for laying gas piping, water supply lines, cable ducts and sleeves. The technology is based on the principle that after a route is drilled with the drilling head, the head is removed and replaced with the laying equipment. In those cases that the laid piping is of a diameter smaller than the diameter of the pilot hole, it is laid immediately. When pipes of greater diameters are laid, the backreamer is installed. A flushing suspension (for instance a mixture of water, bentonite and other admixtures) prepared in mixing units is supplied to the backreamer by means of high-pressure pumps.

Before the work itself is performed it is of great importance to pay proper attention to preparations of the structure, especially as regards complex structures (water courses crossed by great profiles). The preparations for the drilling comprise the proposal of a route, geologic surveying, proposal and assessment of the flushing mixtures and materials to be laid. In case of complex structure it is necessary to calculate tractive forces that are transferred to the particular line or duct. The method of calculating forces applied to piping was proposed for instance by Huye (1996).

Forces applied to the laid pipes

The following forces occur in case of the HDD method:

a, when the pilot hole is drilled – the pressure force and the torque moment are transferred from the drilling machine via the drilling string to the drilling head;

b, when extending the hole – the tractive force from the drilling machine is transferred via the drilling string to the backreamer and the connected dragged drilling string;

c, when laying the pipes – the tractive force from the drilling machine is transferred via the drilling string to the backreamer and the laid piping.

Forces applied to the piping when it is being laid are decisive for pipe dimensioning and for the pipe attachment to the drilling string. On the basis of the theorem of “action and reaction“ the tractive force in any point of the section to be laid must be the sum of particular tractive resistance.

The total necessary tractive force on the drilling machine when laying the pipes is the sum of resistance of the drilling string, the backreamer, the laying equipment and piping.

$$F_c > F_{vk} + F_{rh} + F_{tz} + F_p + F_o \ , \tag{1}$$

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where:

F_c – total tractive force on the drilling machine [N],
F_{vk}– resistance on the drilling string [N],
F_{rh} – resistance on the backreamer [N],
F_{tz} – resistance on the laying equipment [N],
F_p – resistance on the piping [N],
F_o – resistance occurring when pulling the piping on the ground, before the piping enters the hole [N].

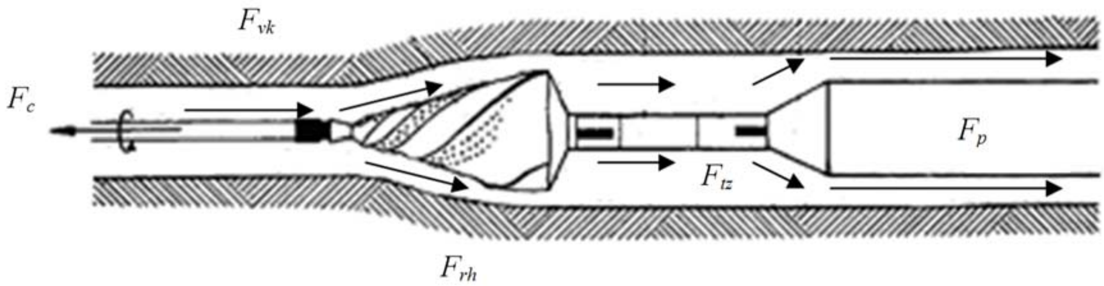

Fig. 1. Resistance on the drilling string, backreamer, laying equipment and the piping.

When PE piping is laid the tractive force occurs on the transition piece and the backreamer, it is the sum of resistance occurring as a result of:

- friction between the piping and the soil,
- tangential stress τ_{vs} occurring between the PE piping and the flushing suspension,
- resistance of the laying equipment (in a number of cases the resistance of the laying equipment is reduced by making use of the protecting coat of the transition piece),
- resistance of piping pulled on a surface,
- resistance of the laying equipment F_{tz} [N]

$$F_{tz} = \frac{D_a^2}{4} \cdot B \,, \qquad (2)$$

where:

D_a - outside diameter of the laying equipment [m],
B - specific resistance of the laying equipment [Pa].

The specific resistance on the laying equipment differs depending on the mixture of the flushing suspension with the soil and the kind of the design of the laying equipment.

Resistance on the piping coat F_p [N] is:

$$F_p = D \cdot \pi \cdot L \cdot M \,, \qquad (3)$$

where:

D – outside diameter of the piping [m],
L – length of the piping [m],
M – specific friction of the piping / soil / flushing suspension [Pa].

The total specific resistance on the piping coat F_p is the function of 6 quantities:

$$f\,(D, D_{vrt}, \tau_{vs}, \mu_z, v, E_p), \qquad (4)$$

where:

D – outside diameter of the piping [m],
D_{vrt} – hole diameter [m],
τ_{vs} – tangential stress between the piping coat and the flushing suspension [Pa],
μ_z – friction coefficient between the piping and the soil [-],
v – relative velocity of the movement of the piping and the flushing suspension in the hole [m.s^{-1}],
E_p – modulus of elasticity of the piping [Pa].

At the department of geotechnics of STU Bratislava, Klepsatel et al. (1978) carried out laboratory tests to find out the friction coefficient between the piping and the soil when pushing the steel and concrete tubes. The values of the friction coefficient μ_z between the PE piping / soil and the tangential stress τ_{vs} between the PE piping / flushing suspension have not been evaluate so far and therefore the author focused in his PhD thesis on the measurement of these values.

Friction coefficient μz between the PE tube/ soil and the tangential stress τvs between the PE tube/ bentonite flushing suspension

The laboratory tests with 5 different representative soil samples (Tab. 1)) – sandy loam, gravel, sand 0/4mm and 0/8mm and fine sand were performed to determine the friction coefficient μ_z (between the PE tube and the soil) and the tangential stress τ_{vs} (between the PE tube and the bentonite flushing suspension).

The bentonite flushing suspension was prepared from the natural bentonite of the sodium type (trade name "SWELL GEL" supplied by BDC Morava) of the concentration of 40 kg of bentonite.m^{-3} of water. This type of bentonite is among the bentonite of the montmorillonite type of high concentration (type Wyoming). A great advantage of the SWELL GEL of the bentonite when the measurement was being performed was its swelling in the course of a few minutes – approx. 8-12 minutes. Mixing was carried out by means of a propeller in a barrel of the volume 40 l. The PE tube 100 DN 225 x 13.4 SDR 17 (manufactured by Pipe Life) was used as the testing tube. The friction coefficient μ_z and the tangential stress τ_{vs} were measured on two models.

Tab. 1. Characteristic values of soil samples.

Sample no.	**1**	**2**	**3**	**4**	**5**
Quantity/identification	**loam**	**gravel**	**sand 0/4mm**	**sand 0/8mm**	**fine sand**
2 mm	92.85 %	15.27 %	80.2 %	68 %	98.4 %
0.063 mm	42.5 %	4.27 %	0.50 %	0.34 %	4.91 %
Different fineness modulus C_u	-	28.6	2.58	3.57	2.33
Curve number C_c	-	5.16	0.96	0.78	1.19
Classification by the Czech standard ČSN 73 1001	F3, MS sandy loam	G2, GP gravel of poor granulation	S2, SP Sand of poor granulation		
Soil moisture	25.63 %	1.52 %	1.04 %	1.92 %	9.65 %

The measurement of the friction coefficient μ_z was performed on the model that was designed just for this purpose. The movement was allowed owing to an electric motor with the possibility of setting the velocity determined in advance. During this test the PE plate, which was pushed under a particular pressure, was dragged about the surface treated equally as the tested soil at a constant velocity and at the same time the required tractive force F was measured.

The velocity of the PE tube movement about the soil within the model was kept as the average velocity v = 0.03 m/s (the average velocity measured in situ while laying the pipes)

With respect to every sample there were made altogether 3 different states and 10 measurements for every sample:

- PE tube – naturally moist soil sample;
- PE tube – soil sample under water;
- PE tube – soil sample + bentonite flushing suspension (for lubricating purposes).

The magnitude of the friction coefficient was evaluated graphically and according to the following relation

$$\mu_z = tg\ \Psi + a, \qquad (5)$$

where:

μ_z - friction coefficient [-],
Ψ - friction angle between the soil and the sample of material [-],
a - adhesion of the soil to the sample of material [-].

The results of the measurement of the friction coefficient μ_z are contained in Tab. 2.

When the bentonite flushing suspension (the concentration Tab. 3) was used, the following friction reduction was achieved:

Sandy loam (sample 1): the friction coefficient dropped from μ_z = 0.7 (dry sample), or μ_z = 0.51 (sample under water), when the bentonite flushing suspension was used, to μ_z = 0.2. The bentonite flushing suspension shows high lubricating effects and reduces tractive forces.

Gravel (sample 2): the friction coefficient was the same both for the dry soil sample and for the use of the bentonite flushing suspension, that is μ_z = 0.37. In this case the bentonite flushing suspension meets especially the supporting function.

Sand 0/4mm (sample 3): the friction coefficient dropped from μ_z = 0.38 (dry sample), or μ_z = 0.32 (sample under water), when the bentonite flushing suspension was used, to μ_z = 0.29.

Sand 0/8mm (sample 4): the friction coefficient dropped from μ_z = 0.47 (dry sample), or μ_z = 0.41 (sample under water), when the bentonite flushing suspension was used, to μ_z = 0.37.

Fine sand (sample 5): the friction coefficient dropped from μ_z = 0.47 (dry sample), when the bentonite flushing suspension was used, to μ_z = 0.34.

Tab. 2. Measured friction coefficients μ_z between PE piping and the soil.

Sample	State	Dry/PE		Under water/PE		Bentonite flushing suspension/ PE	
-	-	Ψ	μ_z	Ψ	μ_z	Ψ	μ_z
		[°]	[-]	[°]	[-]	[°]	[-]
1	Sandy loam	35.0	0.7	27.0	0.51	11.3	0.2
2	Gravel	20.3	0.37	-	-	20.3	0.37
3	Sand 0/4mm	20.8	0.38	17.7	0.32	16.2	0.29
4	Sand 0/8mm	25.2	0.47	22.3	0.41	20.3	0.37
5	Fine sand	25.2	0.47	-	-	18.8	0.34

For the measurement of the tangential stress τ_{vs} between the PE tube and the bentonite flushing suspension the author designed a model device through which he measured the tangential stress τ_{vs}. The device for the measurement of the tangential stress τ_{vs} consisted of a vessel filled with the bentonite suspension and a tube of PE 100 DN 225 and 50 cm long attached in the spindle head. The torque moments were measured on the model in a pure bentonite suspension and in a suspension of the bentonite and the mixed sample no. 3 - sand 0/4 mm (Fig. 1):

- in the pure bentonite flushing suspension (40 kg of bentonite.m^{-3} of water) the author measured the tangential stress τ_{vs} = 2.5 Pa;
- in the bentonite flushing suspension mixed with soil (sample 3 – sand 0/4 mm, 500 – 1500 kg. m^{-3} of the suspension) the author measured the tangential stress τ_{vs}= 3.5 – 5 Pa.

Tab. 3. Parameters of the bentonite flushing suspension 40 kg of bentonite/m^3 of water.

Measurement	**Hydro-meter**	**Viscosimeter model Marsh**	**Rotary (dynamic) viscosimeter**								
Benton. flushing	**Specific weight**	**Time t**	**FAN 600**	**FAN 300**	**Apparent viscosity η_{AV}**	**Plastic viscosity η_{PV}**	**Yield point**	**Gel 10 s**	**Gel 10 min**	**pH**	**Filtration by IPA**
(kgm^{-3})	(kgm^{-3})	(s)	(-)	(-)	mPas	mPas	Nm^{-2} (lb/100ft^2)	Nm^{-2} (lb/100ft^2)	Nm^{-2} lb/100ft^2	(-)	ml/30min
40 (old)	1030	53	49	40	24,5	9	14,83 (31)	6,70 (14)	4,78 (10)	7	22,5
40	1030	50-51	46	37	23	9	13,40 (28)	7,66 (16)	5,26 (11)	7	24

For the purposes of calculating the tractive force concerning the PE piping the author recommends that there should be used τ_{vs} = 20 Pa (for the flushing with the concentration of 40 kg of the bentonite.m^{-3} of water, soil sample 3), that takes into account the mixing of the bentonite flushing suspension with the excavated soil and a 12-hour interruption of the laying (Fig. 2).

The final measured values support their importance for the optimisation of the proposal of the dimensions of the piping. The PhD thesis proved a great influence of the proposal and the use of flushing suspensions when laying the piping.

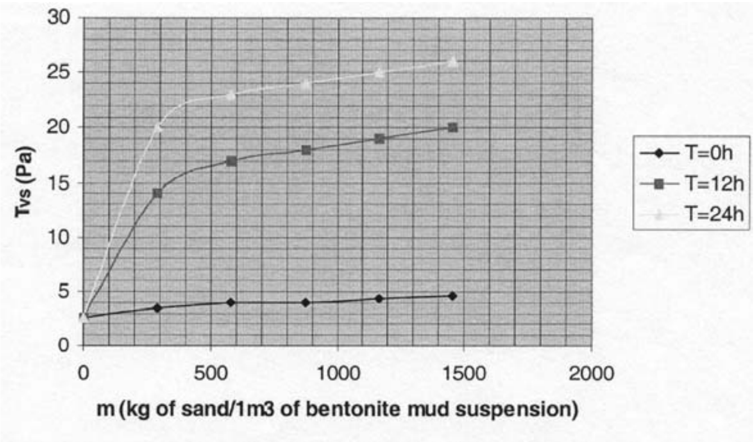

Fig. 2. The magnitude of the tangential stress τ_{vs} as a result of the friction of the PE tube / bentonite flushing suspension + sand depending on the time of the interruption of laying T (velocity of the mutual movement v = 0.03 – 0.05m/s, the profile of the hole is greater by 30 % in comparison with DN of the laid piping).

Through a mathematical calculation (program e-HDD v. 1.01.) and a measurement on the model the author proved the influence of the technology of laying a line or a duct, namely:

- laying with water flushing (without using the flushing suspension);
- laying with the use of the bentonite flushing suspension, the so-called:
  - a, "dry process" – a line or a duct floating in the bentonite flushing suspension;
  - b, "wet process" – a line or a duct hanging suspended in the bentonite flushing suspension (by balancing the lifting force with water).

The most optimum way of laying the piping is the so-called "wet" process with the use of the bentonite flushing. The thesis proved the reduction of the tractive force when using the so-called "wet" process while:

a, 50 % water filling of the profile – the drop of tractive forces in comparison with the empty PE piping being laid by 40 - 50 % (according to DN);

b, 100 % water filling of the profile – the drop of tractive forces in comparison with the empty PE piping being laid by 80 - 90 % (according to DN).

At the same time the laying of the PE piping hanging suspended eliminates the residual stress in the piping once the laying is finished.

When measuring the tangential stress τ_{vs} between the PE piping and the flushing it was proved through a long-time measurement that the time of the interruption of the laying is of great importance for the magnitude of the resistance and thus also the tractive forces (Fig. 2).

Results of the PhD thesis can be used by building companies when planning and drilling optimum controlled horizontal holes with a high-pressure liquid and backwards laying of lines, ducts or piping.

Flushing suspension

The flushing suspension as it is described by Dowler (1998) and Hradil (2000) is a mixture of bentonite or another suitable material and water or chemical admixtures, it meets the following functions during the laying through the HDD technology:

a, transfer of the hydraulic energy to the drilling head and the backreamer for cutting and disconnecting in water;

b, soil transport and hole cleaning;

c, circulation of the flushing suspension;

d, lubrication and cooling of the drilling tool;

e, supporting and protecting the hole against collapsing.

A high-quality flushing suspension must, when used within HDD, meet the following properties:

a, ability to form a gel that can keep the free particles of a rock and soil hanging suspended for the time of work breaks and standstill in the hole;

b, ability to prevent from partial or complete losses of the working liquid into permeable intervals;

c, good inhibition properties with respect to clay and clay shale, that is the ability to eliminate swelling and caverning of these positions and the ability to keep the "dimension" of the holes;

d, good stabilising and consolidating properties in non-cohesive soils;

e, biological degradability and ecological acceptability.

According to FENGLER (1998) all the above-mentioned properties can be provided only by means of high-quality bentonites, special polymers and PHPA additives (Partially Hydrolyzed Polyacrylamid) of various concentrations.

The bentonite or clay minerals create a basic structure of a liquid in the flushing suspension. In case of more difficult geological conditions the properties of flushing suspensions are improved by means of polymers (there is influenced viscosity, filtration, shear stress and thixotropic properties of the suspension).

Conclusion

The measurement of friction coefficients μ_z and tangential stress τ_{vs} was based on a laboratory model of a small part of the PE piping, the results are in accordance with values measured in situ while laying PE-HD DN 400x36 394.6 m long – the subway Dahme/Zeuthen and the water supply line in V. Bílovice.

When proposing the maximum tractive force, verifying the piping wall thickness and a machine performance the least favourable value is used and the coefficient of safety corresponds to the size of the profile, the length of the work and the probability of work interruption. This is based on the fact that we can hardly find out in advance the exact geological profile of a drilled route. The geological survey in the route is checked only by carrying out local wells. That is why owing to the results of this paper it will be possible to propose the corresponding thickness of the wall of the piping laid and the type of equipment.

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