Calculation of forces in cable during installation in pipes for different methods

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ABSTRACT

A complete theory is given of force build-up in cables pulled in pipes, beyond "classic" Rifenburg equations, including large radius bends and/or pushing the cable, following the outside facing wall of the bend. Also 3D-bends are treated. This is used in software, where besides gravity friction and capstan effect also "waving" the cable during pushing and the effect of cable stiffness in bends and undulations in the pipe are taken into account. Not only pulling and pushing, also other installation techniques are evaluated, like those making use of fluid propelling (blowing and floating).

KEYWORDS

Cable; Pipe; Pulling; Pushing; Blowing; Floating; WaterPushPulling; FreeFloating; Undulations; Horizontal-; Vertical-; 3D-; Bends; Capstan effect, Cable stiffness.

INTRODUCTION

A complete theory is given of the force build-up in cables pulled in pipes. The well-known "classical" equations of Rifenburg et al. for pipes with horizontal and vertical bends, taking into account gravity friction and capstan effect, are reviewed. An extension of the theory has been derived for bends with large radius (like in HDD drills) and/or for the cables being pushed. In both cases the cable might be pressed against the outside facing pipe wall. Furthermore, bends are treated which are neither in a horizontal, nor in a vertical plane. Analytic equations have been derived for the total bend angle related to the entry and exit slope and to the angle in the horizontal plane. Analytical calculation of force build-up is no longer possible in this case and must be performed numerically. Therefore, a software program was developed to treat those 3-dimensional bends.

The software program takes more effects into account than just 1) gravity friction and 2) capstan effect, namely: 3) additional friction in bends and undulations in the pipe due to cable stiffness and 4) additional friction during pushing due to "waving" of the cable (also related to cable stiffness). Furthermore, the software can evaluate installation techniques other than winch pulling. Not only pushing, also pushing/pulling, and new techniques as described below.

The action of (high-speed) fluid distributed propelling forces can also be calculated. With air as fluid the cable blowing technique is included, a method widely used for smaller cables, like optical cables. Water as fluid is also suitable for energy cables, where the floating technique can be used for pipes with internal diameter up to the order of 100 mm. Here there is benefit from the reduced effective weight of the cable in water due to buoyancy. For larger pipes (and cables) a pig is used at the front end of the cable. The technique is then called waterpushpulling and can be used for any cable and pipe size. Advantages are that no winch line needs to be installed, all material and operation is at one side of the track and forces (axial and sidewall) are lower than with traditional winch pulling. The software can calculate it all. Last but not least also freefloating can be evaluated, a technique where the cable, once installed by waterpushpulling, can be transported further to any location, loose from the machine, like "tube post". Some examples of real installations will be given, with evaluation.

CALCULATION PULLING (PUSHING)

Calculations will be done for straights and different bends.

Straight section

The coefficient of friction (COF) is defined as the force to move a body over a surface divided by the normal force between that body and surface. When pulling a cable into a straight and sloped pipe section (inclination angle α with horizontal, negative when downhill) the axial force dF to pull an infinitesimal length ds of that cable is given by [1,2]:

$$dF = \left[fW\cos\alpha + W\sin\alpha\right]ds$$

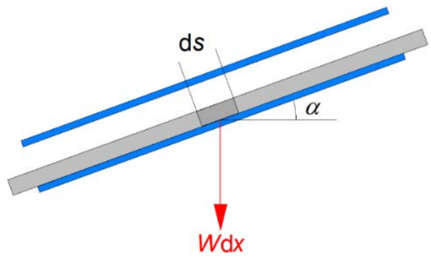

Fig. 1: Straight pipe (sloped) section with inclination (slope) with the horizontal α

Here f is the COF between cable and pipe and W the weight per unit of length of the cable. The term at the right side is the force needed to pull the cable to another elevation. Carrying out the integration it is found that the axial (pulling) force in the cable increases linearly along the pipe as a result of gravity friction (which is constant over the length). The axial force F_2 after pulling a cable over a length L with an axial force F_1 when entering the section is given by [1,2]:

$$F_2 = F_1 + \left(f\cos\alpha + \sin\alpha\right)WL \quad [1]$$

The above friction is called gravity friction. If this was the only contribution to the axial force build-up in the cable very long pulling lengths could be achieved. However, already built-up axial forces in the cable in bends (and undulations) in the pipe are usually dominant and cause exponential force build-up, limiting cable pulling lengths.

Horizontal bend

When the cable is pulled through a bend in the pipe the friction is proportional to the already built-up pulling force. The harder you pull, the harder the cable is pulled against the inside facing wall of the pipe, with linear normal (radial) force density F_n (often erroneously called sidewall pressure or radial force), and the more friction is generated. The axial force will then increase exponentially, called the capstan effect. When gravity friction works together with this capstan effect, the formulas become a bit different.

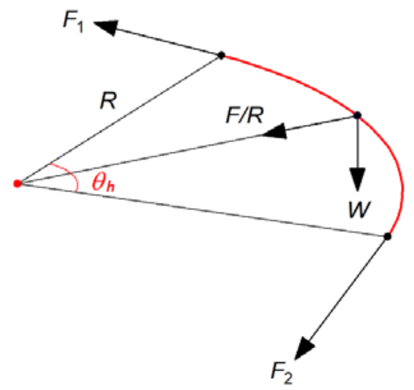

Fig. 2: Horizontal bend with angle θ_h of 90°

For a horizontal bend the sidewall force makes a right angle with the gravity force and the axial pulling force increase d*F* over infinitesimal length d*s* is given by [1,2]:

$$dF = fF_n = f\sqrt{W^2 + \left(\frac{F}{R}\right)^2}ds = f\sqrt{(WR)^2 + F^2}d\varphi$$

Here *R* is the bending radius of the bend. Integrating over the angle dφ the force F_2 after the bend with (horizontal) angle θ_h follows from the force F_1 before the bend by [1,2]:

$$F_2 = WR\sinh\left[f\theta_h + \sinh^{-1}\left(\frac{F_1}{WR}\right)\right] \qquad [2]$$

For F_1<<*WR* Eq. (2) becomes Eq. (1) (α = 0), for F_1>>*WR* Eq. (2) becomes the well-known exponential formula:

$$F_2 = F_1 e^{f\theta_h}$$

In literature, e.g. in [1], also another equation is given, which turns out to be exactly the same equation as Eq. (2):

$$F_2 = F_1\cosh(f\theta_h) + \sqrt{F_1^2 + (WR)^2}\sinh(f\theta_h)$$

Vertical bend

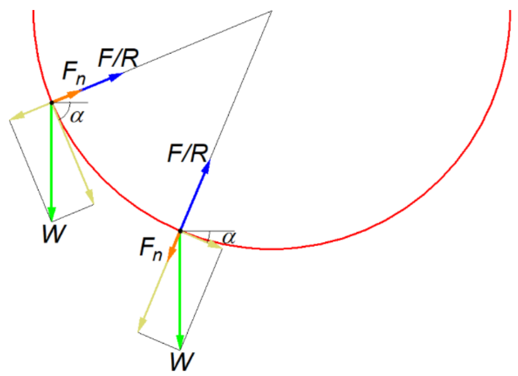

Fig. 3: Example with concave vertical bend with slope α from -90° until 90°

For vertical bends the angle between the sidewall and gravity force varies with the local angle of the pipe with the horizontal. The vertical bend can be concave (curving up) or convex (curving down) and different equations are found in literature for different situations. Also the cable is not always pulled along the inside facing pipe wall, sometimes it follows the outside facing wall, e.g. for relatively large bend radius (like in HDD drills) when axial force is still low.

In the Fig. 3 at left the standard situation in a concave (downward) vertical bend is shown. The radial linear force density *F*/*R* is indicated by a blue arrow. The linear weight density *W* is indicated by a green arrow. It can be split into two components, axial and radial, with magnitude *W*cosα and *W*sinα, respectively, indicated by the light green arrows. The radial component is opposing the radial linear force density and is therefore subtracted from it, resulting in the total linear normal force density F_n=*F*/*R*-*W*cosα, indicated by the orange arrow. When multiplying this total radial linear force density by the coefficient of friction *f* the change d*F* in axial force by friction is found. When also adding the sec gravity component *W*sinα (which is negative here, because of negative slope α) the following differential equation is obtained (with the transition from d*s* to dα similar to that from d*s* to dφ for horizontal bends):

$$dF = \left[f(F - WR\cos\alpha) + WR\sin\alpha\right]d\alpha$$

The solution of this differential equation for a bend from α_1 to α_2 is given by:

$$F_2 = F_1 e^{f(\alpha_2-\alpha_1)} - \frac{WR}{1+f^2}\left[\psi(\alpha_2) - \psi(\alpha_1)e^{f(\alpha_2-\alpha_1)}\right]$$

With:

$$\psi(\alpha) = 2f\sin\alpha + (1-f^2)\cos\alpha$$

The same can be done for the situation right of the first one in Fig. 3. Now the radial component of the linear weight density *W* has grown so much that it has become larger than the radial linear force density *F*/*R* resulting from the axial force *F*. The sum of the radial force densities, given by the orange arrow, now points in the other direction, the outside facing wall of the pipe. As for the friction the absolute value of the radial forces needs to be taken the negative term *F*/*R*-*W*cosα must now be inversed:

$$dF = \left[-f(F - WR\cos\alpha) + WR\sin\alpha\right]d\alpha$$

The solution of this differential equation is now given by:

$$F_2 = F_1 e^{-f(\alpha_2-\alpha_1)} + \frac{WR}{1+f^2}\left[\psi(\alpha_2) - \psi(\alpha_1)e^{-f(\alpha_2-\alpha_1)}\right]$$

With:

$$\psi(\alpha) = 2f\sin\alpha - (1-f^2)\cos\alpha$$

In [3] the full set of equations was derived, for all situations:

$$F_2 = F_1 e^{\pm f|\alpha_2-\alpha_1|} \mp \frac{WR}{1+f^2}\left[\psi(\alpha_2) - e^{\pm f|\alpha_2-\alpha_1|}\psi(\alpha_1)\right] \qquad [3]$$

with:

$$\psi(\alpha) = 2f\sin\alpha \pm (1-f^2)\cos\alpha \qquad \text{(concave)} \qquad [3a]$$

Or with:

$$\psi(\alpha) = 2f\sin\alpha \mp (1-f^2)\cos\alpha \qquad \text{(convex)} \qquad [3b]$$

where Eq. (3) with Eq. (3a) and (3b) describe all concave and convex situations, respectively. The top and bottom parts of the $\pm$ and $\mp$ signs refer to following the inside and outside facing pipe wall, respectively. The inside facing wall of the pipe is followed for $F_1 > WR\cos\alpha_1$ and $F_1 > -WR\cos\alpha_1$ in case of a concave and convex bend, respectively, else the outside facing wall is followed. It follows directly from the entry angle α_1 and exit angle α_2 what kind of bend it is: concave for $\alpha_2 > \alpha_1$ and convex for $\alpha_2 < \alpha_1$.

For α_1, α_2 equal to 0, φ for concave up, 90°, 90°-φ for convex up, 0, -φ for convex down and -90°, -90°+φ for concave down the equations take a simpler form, which for the case that the inside facing wall is followed become the well-known Rifenburg equations for the subsequent sections [1-3], given by Eqs. (4a)–(4d), respectively:

$$F_2 = F_1 e^{\pm f\varphi} \mp \frac{WR}{1+f^2}\left[2f\sin\varphi \pm \left(1-f^2\right)\left(\cos\varphi - e^{\pm f\varphi}\right)\right] \quad [4a]$$

$$F_2 = F_1 e^{\pm f\varphi} \mp \frac{WR}{1+f^2}\left[2f\left(\cos\varphi - e^{\pm f\varphi}\right) \mp \left(1-f^2\right)\sin\varphi\right] \quad [4b]$$

$$F_2 = F_1 e^{\pm f\varphi} \pm \frac{WR}{1+f^2}\left[2f\sin\varphi \pm \left(1-f^2\right)\left(\cos\varphi - e^{\pm f\varphi}\right)\right] \quad [4c]$$

$$F_2 = F_1 e^{\pm f\varphi} \pm \frac{WR}{1+f^2}\left[2f\left(\cos\varphi - e^{\pm f\varphi}\right) \mp \left(1-f^2\right)\sin\varphi\right] \quad [4d]$$

In the above Eqs. (4b) and (4d) the sections start vertically. It is also practical to consider these sections ending horizontally, like occurs in combined uphill or downhill pulls [1]. In this case Eqs. (4b) and (4d) become:

$$F_2 = F_1 e^{\pm f\varphi} \pm \frac{WR}{1+f^2}\left[2f e^{\pm f\varphi}\sin\varphi \pm \left(1-f^2\right)\left(1 - e^{\pm f\varphi}\cos\varphi\right)\right] \quad [4b']$$

$$F_2 = F_1 e^{\pm f\varphi} \mp \frac{WR}{1+f^2}\left[2f e^{\pm f\varphi}\sin\varphi \pm \left(1-f^2\right)\left(1 - e^{\pm f\varphi}\cos\varphi\right)\right] \quad [4d']$$

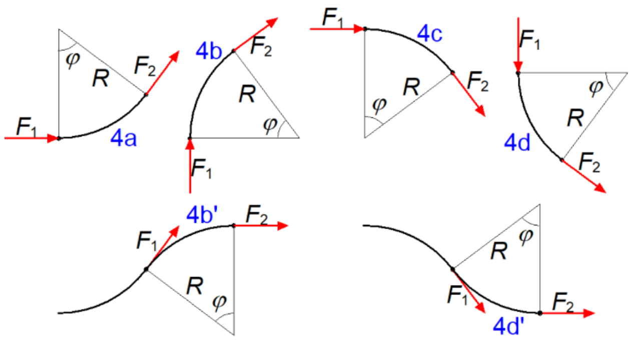

Fig. 4: Summary of vertical bends

In Fig. 4 the treated different special situations given by Eqs. 4a-d' are shown. When there is a vertical bend it shall be defined what kind of bend it is. Even then not all situations are covered. When instead using Eqs. 3-3b only slopes α_1 and α_2 are required and the bend is concave or convex when α_2 is larger or smaller than α_1, respectively. In case the cable follows the inside facing pipe wall the top parts of the ± and ∓ signs are taken. For pulling ($F > 0$) the cable can only follow the outside facing wall when the bend is concave. This occurs when the pulling force is not large enough to pull the cable away from the bottom of the pipe.

It is also possible that the cable crosses from the inside facing wall of the bend to the outside facing wall of the bend or vice versa. In Fig. 5 an example is shown where the cable crosses twice in one bend. Here the pull starts concave down with a relatively low force F_1 of 10 kN and the bend has a relatively large bend radius R of 100 m (can be much larger for a HDD drill). The cable starts following the inside facing wall of the bend (when vertical gravity does not yet pull the cable away from the inside facing wall). Then the cable crosses over to the outside facing wall (gravity wins and the cable follows the bottom of the pipe). During going up the cable crosses over again to the inside facing wall. The crossing (X) line is given by $F = WR\cos\alpha$. Below this line the cable follows the outside facing pipe wall for concave bends. For convex bends the X line is given by $F = -WR\cos\alpha$ and the X-line will be "negative" (mirrored in the x-axis), so penetrating into the pushing regime. The negative sign in the exponent in the formulas when the outside facing pipe wall is followed can e.g. be understood by a loss of pushing force instead of a gain in pulling force.

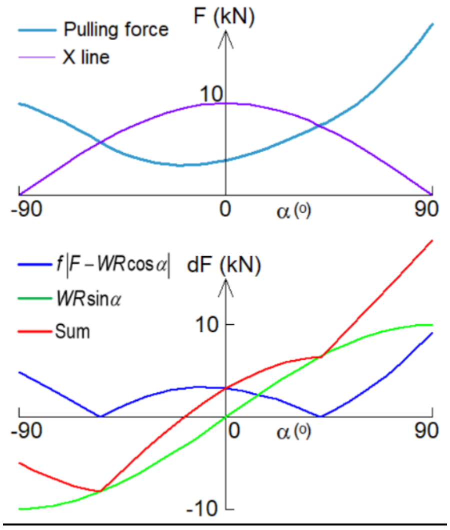

Fig. 5: Top: Force *F* to pull cable (*W*=100 N/m) through vertical concave bend (*R*=100 m, COF=0.5), starting with α_1=-90°, F_1=10 kN and ending with α_2=90°. Below the X line the cable follows the outside facing pipe wall. Bottom: friction (blue), axial gravity component (green) and total force change d*F* (red).

3D bend

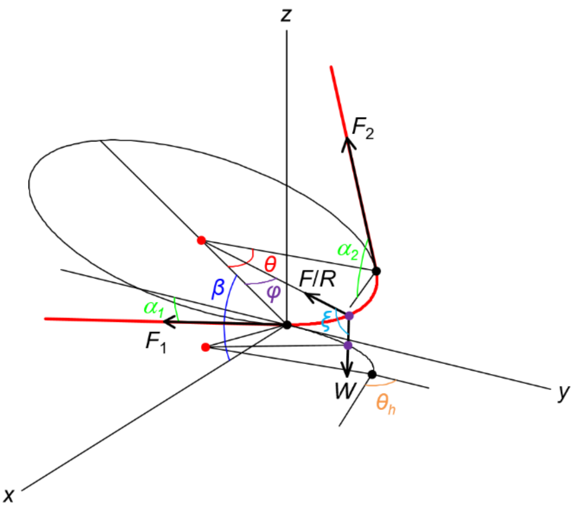

Fig. 6: Bend in 3D plane with horizontal bend angle θ_h of 75° and inclination angles α_1 of 15° and α_2 of 60° at entry and exit, respectively. Other parameters in text

Bends are not always horizontal or vertical, they can also be 3-dimensional (3D), i.e. circle sections in an arbitrary plane. This is already the case when an "almost horizontal bend" is part of an inclined trajectory, with equal entry and exit inclination (slope) α_1 and α_2. Also more complex situations exist, with different slopes α_1 and α_2. In general a 3D bend is determined by a horizontal angle θ_h and slopes α_1 at the entry and α_2 at the exit of the bend, see Fig. 6. Note that the bends are not helical, which would not be in a single plane and is also not how e.g. PVC pre-shaped pipe bends and bends in piping isometrics in offshore platforms look like. The 3D bends treated in this paper cover all cases, from pure horizontal to pure vertical.

The total angle θ of a 3D bend is found from its horizontal angle θ_h and its entry and exit slopes α_1 and α_2 [3]:

$$\cos\theta = \cos\alpha_1 \cos\alpha_2 \cos\theta_h + \sin\alpha_1 \sin\alpha_2 \qquad [5]$$

The local inclination (slope) along the bend as a function of angle φ is given by [3]:

$$\sin\alpha = \cos\alpha_1 \sin\beta \cos\varphi + \sin\alpha_1 \cos\varphi \qquad [6]$$

With the angle β (help-variable only) given by:

$$\tan\beta = \frac{\sin\alpha_2 \cos\alpha_1 - \sin\alpha_1 \cos\alpha_2 \cos\theta_h}{\cos\alpha_2 \sin\theta_h} \qquad [7]$$

To calculate the axial force build-up of the cable in the bent pipe the following differential equation has to be solved:

$$\frac{dF}{d\varphi} = fRF_n + WR\sin\alpha \qquad [8]$$

Here F_n is the linear normal force density between cable and pipe, found by adding the gravitational force per unit of length $W\cos\alpha$ and the capstan force per unit of length F/R:

$$F_n = \sqrt{(W\cos\alpha)^2 + \left(\frac{F}{R}\right)^2 + 2\frac{F}{R}W\cos\xi} \qquad [9]$$

With ξ the angle between the gravitational force and the capstan force, see Fig. 6, given by [3]:

$$\cos\xi = \sin\alpha_1 \sin\varphi - \cos\alpha_1 \sin\beta \cos\varphi \qquad [10]$$

Solving the differential equation for the force build-up of the cable in the bent pipe cannot be done analytically anymore. For pulling the cable through a 3D bend in the pipe the force is now calculated numerically using Eqs. (5)-(10), with as input parameters the horizontal angle θ_h, bend radius R and slopes α_1 and α_2 of the straight sections before and after the bend, respectively. This is how calculation is done in the software. For the horizontal and vertical "extremes" the results match with the analytical results from Eqs. (2)-(4d').

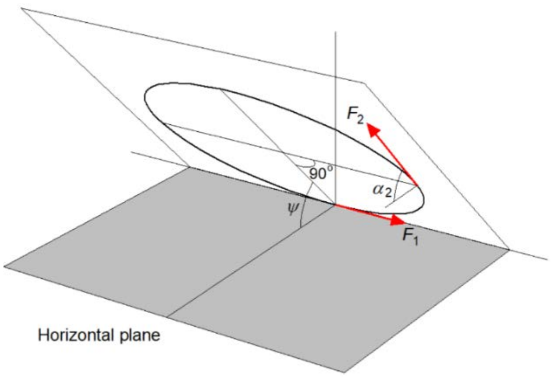

Fig. 7: Bend in inclined plane, angle ψ with horizontal

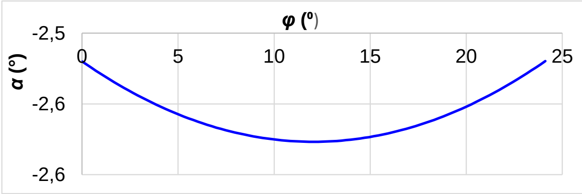

Fig. 8: Slope α along a bend in an inclined plane with entry and exit slope α_1 and α_2 equal to -2.52° and horizontal angle θ_h of 24.11°. The inclination angle ψ of the plane is the minimum in the curve

Another case worth mentioning is a bend in an inclined plane with equal α_1 and α_2. Although for small inclination angle ψ of the plane and small total angle θ of the bend the slope along the bend is not varying much, it is not constant. This is clearly illustrated in the extreme case of Fig. 7 where α_1=0 and α_2=ψ. In Fig. 8 the variation of the slope is shown along the bend for an inclined plane with slopes α_1 and α_2 equal to -2.52° and horizontal angle θ_h of 24.11°. The inclination angle ψ of the plane is the curve minimum.

OTHER FRICTION EFFECTS

Until now two effects causing force buil-up in the cable being pulled (pushed) were treated, gravity friction and the capstan effect. Two more effects, usually not taken into account, must be added.

Waving friction (during pushing)

In the preceding section waving (snaking, buckling) of the cable during pushing (compressive force) was not considered. This causes additional friction on top of gravity and capstan forces (remaining the same), see Fig. 9. For these effects Eqs. (1)–(3b) remain valid, but on top of that a waving friction term has to be added to Eq. (9) (including waving also requires numerical calculation) for a cable under axial compression [3]:

$$F_n = \sqrt{(W\cos\alpha)^2 + \left(\frac{F}{R}\right)^2 + 2\frac{F}{R}W\cos\xi + \left(\frac{D_d - D_c}{\pi^2 EI}F^2\right)} \qquad [9a]$$

Here D_d is the internal diameter of the pipe, D_c the diameter of the cable and EI the bending stiffness of the cable. The less stiff the cable, the more waving friction occurs. Note that the stiffer the cable, the less waving friction!

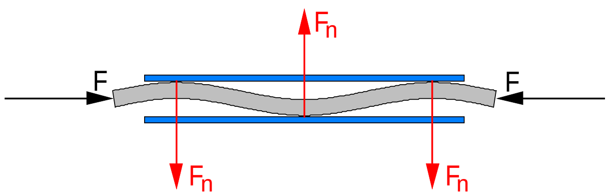

Fig. 9: Cable under compressive axial force

Cable stiffnes friction

Friction during pushing from waving of the cable is smaller for stiffer cables. But, to negotiate cables through bends and undulations in the pipe stiffer cables give more friction.

Cable stiffness friction in pipe undulations

The software also takes into account undulations in the pipe. Here the cable undergoes direction changes, just like in bends, also causing a capstan effect. For sine shaped undulations with amplitude A and period P, see Fig. 10, the change in direction per unit of length T is given by [2,4]:

$$\mathrm{T} = \frac{8\pi\left[A - \frac{1}{2}\left(D_d - D_c\right)\right]}{P^2} \qquad [11]$$

To include the capstan effect from undulations $(\mathrm{T}F)^2$ is added to the term under the square root in Eq. (9a) [2,4].

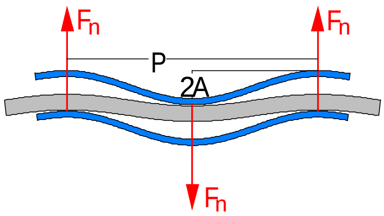

Fig. 10: Undulations in pipe

Besides the capstan effect the undulations in the pipe also cause a friction effect due to bending the stiff cable. While for pushing the waving friction is larger for smaller cable stiffness, the friction for bending the stiff cable through the undulations is larger for larger cable stiffness. This stiffness is characterized by the term W_B which is a force per unit of length, just as the cable linear weight density [2,4]:

$$W_B = \frac{3\left[A - \frac{1}{2}\left(D_d - D_c\right)EI\right]}{2\left(P/4\right)^4} \qquad [12]$$

As this effect is in the same direction as the capstan effect from undulations both effects are included by adding $(W_B+\mathrm{T}F)^2$ under the square root in Eq. (9a) [2,4].

Cable stiffness friction in bends in pipe

When the cable enters a bend from a straight section and leaves it again into another straight section the stiff cable also experiences friction. This friction depends among others on the radius of the bend and on its angle (and of course on the cable stiffness). This friction is also higher when the cable is with its end still in the bend than when the cable has passed the bend. For the different situations the formulas are given in [4]:

	non-full bend	full bend [13]
Friction passed bend	$F_b = \dfrac{\frac{1}{9} fEI\theta^3}{\left(D_d - D_c + \frac{1}{8}\theta^2 R\right)^2}$	$F_b = \dfrac{2fEI}{\sqrt{6\left(D_d - D_c\right)R^3}}$
Friction in bend	$F_{bh} = \dfrac{\frac{1}{6} fEI\theta^3}{\left(D_d - D_c + \frac{1}{8}\theta^2 R\right)^2}$	$F_{bh} = \dfrac{3fEI}{\sqrt{6\left(D_d - D_c\right)R^3}}$
Repulsion in bend	$F_{ch} = \dfrac{\frac{1}{72} EI\theta^4}{\left(D_d - D_c + \frac{1}{8}\theta^2 R\right)^2}$	$F_{ch} = \dfrac{EI}{2R^2}$

Here F_b is the friction when the cable head has passed the bend, F_{bh} when in the bend and F_{ch} the repulsion force when the cable head is in the bend. A full bend is reached for an angle θ_{fb}, where the cable starts following the pipe bend curvature:

$$\theta_{fb} = 2\sqrt{\frac{6\left(D_d - D_c\right)}{R}} \qquad [14]$$

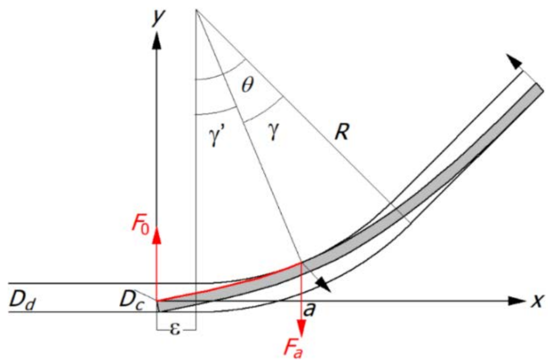

Fig. 11: Example of cable just passed a non-full bend

More cables in one pipe

JetPlanner 4.0 can also handle installation of more cables in one cable, where the friction correction factors of [1] are used. When already occupied with a cable (overriding) the wedge correction factors of [5] are used.

FLUID PROPELLING FORCES

Another technique to install cables in pipes is using fluid propelling forces. Here fluid under pressure is injected into the pipe at the entry side, flowing through the pipe under a pressure gradient. Even though these forces are relatively low they are very effective because they are distributed over the cable length. With the right parameters gravity friction can be compensated locally, so the capstan effect is suppressed. Long installation lengths can be reached with relatively low axial (and radial) forces on the cable.

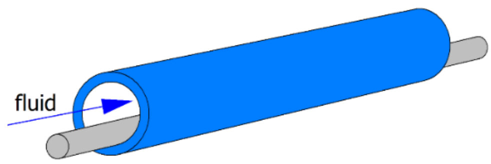

Fig. 12: Installation with help of fluid

The fluid propelling force of the flowing medium dF_{flow}/dx exerted on the cable is proportional to the pressure gradient dp/dx along the cable and is given by [2,4,5]:

$$\frac{dF_{flow}}{dx} = \frac{1}{4}\pi D_c D_d \left|\frac{dp}{dx}\right| \qquad [15]$$

The propelling forces can be subtracted from the friction forces by rewriting Eq. (8) with dx instead of $d\varphi$:

$$\frac{dF}{dx} = fF_n + W\sin\alpha - \frac{dF_{flow}}{dx} \qquad [8a]$$

Note that the backpressure force to push the cable into the pressure zone is subtracted from the applied pushing force [2]. For cable bundles propelling forces are corrected [4].

When the propelling fluid is a gas (air) the technique is called Blowing, used a lot in optical cable installation. The propelling fluid can also be a liquid (water). In that case there is an additional buoyancy benefit. This technique is called Floating and is also used for energy cables. For large cables and pipes (>100 mm ID) a pig can be mounted at the cable's front end. Then it is called WaterPushPulling [6], see Fig. 13. Even though now the capstan effect is back lengths up to 3.3 km in one shote were reached.

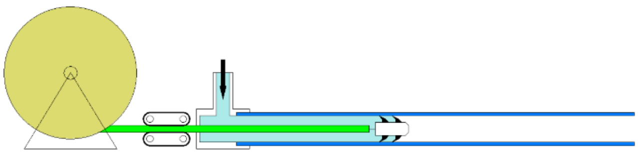

Fig. 13: Principle of WaterPushPulling

Fig. 14: Project with WaterPushPulling [7]

Examples of WaterPushPulling are presented at this conference [7,8]. It can be combined with FreeFloating [6], where the cable is transported (like "tube post") from a suitable launch location to any desired remote destination.

SOFTWARE TO CALCULATE FORCES

Software has been developed to calculate the forces to install the cable in the pipe, taking into in account all effects treated in this paper for all installation methods. In Table 1 an example trajectory with different kind of bends is shown of a 1000 m long track (pipe length). The blue numbers are calculated. In Fig. 15 the elevation profile and top view are shown. With a 145 kV 2000 mm^2 AL cable with D_c=111 mm and W=125 N/m in a 180/158 mm pipe and a COF of 0.16 this cable can be pulled in with 30 kN, see Fig. 16 (top).

Table 1: Example trajectory. Blue = calculated

Section	L (m)	α (°)	θ_h (°)	R (m)	θ (°)	h (m)
straight	50	-30				-25
3D	112.3		60	100	64.34	-56.45
straight	500	0				-56.45
hor	104.72		-60	100	60	-56.45
straight	10	0				-56.45
vert	122.91		0	234.75	30	-25
straight	50	30				0
3D	9.42		90	6	90	3
straight	40.64	0				3

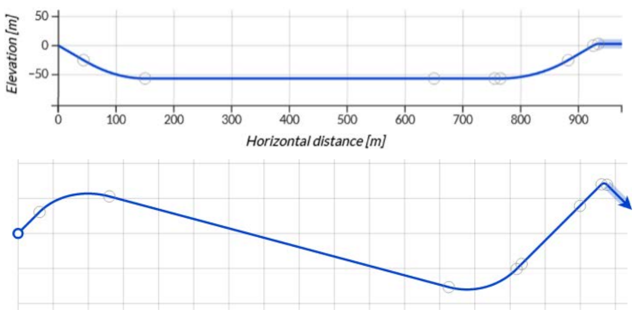

Fig. 15: Example trajectory. Elevation profile (top) and top view (bottom, grid 50x50 m)

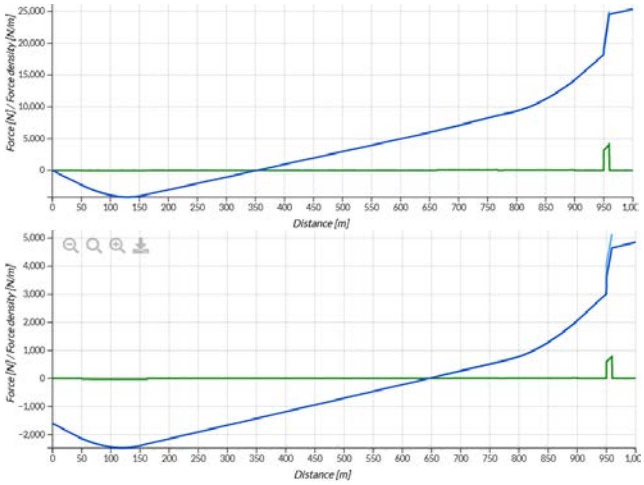

Fig. 16: Cable Pull (top) and WaterPushPull (bottom), - axial force, - radial force density, more details in text

The same is done with WaterPushPulling in Fig. 16 (bottom), 3 bar water, 4500 N push (note the low forces!). More examples with calculations are presented in [8].

Conclusions

The "classis" Rifenburg cable pulling theory was extended for pushing and large bend radius. 3D-bends are calculated too and new software based on that matches all and also incudes other installation techniques, e.g. those using fluid.

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REFERENCES

[1] R.C. Rifenburg, 1953, "Pipe-line design for pipe-type feeders", Transactions AIEE Power Apparatus and Systems, vol. 72, part III, 1275-1284

[2] W. Griffioen, 1993, "Installation of optical cables in ducts", Plumettaz SA, Bex, CH (ISBN: 90 72125 37 1)

[3] W. Griffioen, D. Plumettaz, 2021, "Cable pulling force in pipes with 3-dimensional bends for different installation methods", ASCE's Journal of Pipeline Systems - Engineering and Practice, Vol. 12, Issue 4: 04021060, November 2021

[4] W. Griffioen, H.G. Nobach, G. Plumettaz, 2006, "Theory, software, testing and practice of cable in duct installation", Proceedings 55th IWCS, 357-365

[5] W. Griffioen, W. Greven, T. Pothof, "A new fiber optic life for old ducts", Proc. 51th IWCS (2002) 244-250

[6] W. Griffioen, C. Gutberlet, A. Uhl, G. Laurent, S. Grobety, 2019, "Projects with Remote Installation ("Tube Post") of Energy Cables in Ducts", Proceedings Jicable, Versailles, 23-27 June 2019, paper A3.2

[7] J. Smit, 2023, "A pilot using water pressure to install 2 150 kV cable circuits in a horizontal directional drilling", Proceedings Jicable, Lyon, 18-22 June 2023

[8] J. Parciak, V. Gonçalves, E. Gulski, M. Czarnecka, 2023, "Water propulsion cable laying and non-destructive commissioning of power cables", Proceedings Jicable, Lyon, 18-22 June 2023