Installing a Cable in a Duct Solely by the Flow of Water, Faster than the Flow Itself!

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Abstract

Installation of cables by floating (water) combines benefits of blowing (distributed propelling forces avoiding capstan effect) and buoyancy (reduction effective cable weight). 12.4 km in one shot was already reached. In this paper tests were done in a 2.54 km dummy track to evaluate feasibility of a 30 km project. Multiple loops were placed to eliminate all other effects than water flow. With 1.5 bar the cable would still move, extrapolated 30 km with 18 bar. A remarkable phenomenon was found: the cable moved faster than the water! This was already forecasted and is further explained in this paper.

Keywords: Cable; duct; installation; blowing; floating.

1. Introduction

Installation of cables in ducts assisted by fluid drag is a well-known practice. When the fluid is air the method is called blowing or jetting and is the most common technique to install optical cables. When the fluid is water it is called floating, besides for optical cables also used for metallic cables. With blowing the common advantage is that the distributed fluid propelling forces can locally compensate gravity friction, minimizing built-up axial forces, hence strongly reducing the capstan effect, and enabling long lengths per single shot. Floating has an additional benefit of reducing the effective cable weight because of buoyancy. This makes it possible to even install longer distances per single shot, the world record now being 12.4 km. That's not yet the theoretical limit. In the present study tests were done in a 2.54 km dummy track (same construction as in the targeted project) in Norway to evaluate a project where the length will be 30 km (rather straight and smooth) and where the cable density is tuned to (sea) water density.

To make sure that extrapolation from the 2.54 km test to the 30 km target is based on pure floating, care had been taken to eliminate all side effects that could influence the test. The flow of water, and nothing else, shall propel the cable.

In the tests the cable was floating with a speed close to that of the water flow propelling it (as only source), even faster. The "old" blowing formulas already forecasted that this is possible. In this paper it is explained how.

2. Blowing and Floating Theory

In order to understand installation of cables into ducts by floating it is needed to dive a bit into the existing theory. A formula for the fluid propelling forces was first introduced in 1982 by British Telecom for Blowing flexible and lightweight fiber members (blown fiber) [1]. Here two kinds of forces propelling the cable were defined, hydrostatic and hydrodynamic propelling force.

2.1 Hydrostatic Propelling Force

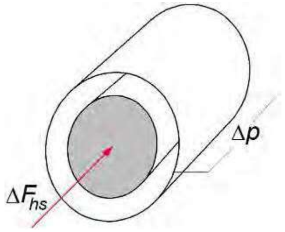

Figure 1. Schematic view hydrostatic propelling force

The hydrostatic force dF_{hs}/dx finds its origin in the pressure drop $|dp/dx|$ of the fluid over the cable volume and is simply given by the cross-sectional area of the cable times this pressure drop [1]:

$$\frac{dF_{hs}}{dx} = \tfrac{1}{4}\pi D_c^2 \left|\frac{dp}{dx}\right| \tag{1}$$

Here D_c is the cable diameter. It seems a bit strange that forces perpendicular to the cable surface contribute to propelling the cable. But, they virtually distribute along the cable the force already given by the machine when pushing the cable into the zone with pressure p, the so-called backpressure force F_{back} [1,2]:

$$F_{back} = \tfrac{1}{4}\pi D_c^2 \cdot p \tag{2}$$

This phenomenon was called the "spaghetti paradox" in [2] and was independently found for pipes under internal or external pressure, called the "Bridgman's paradox" [3].

2.2 Hydrodynamic Propelling Force

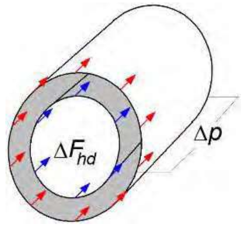

Figure 2. Schematic view hydrodynamic propelling force, on cable (blue) and on duct wall (red)

The hydrodynamic force dF_{hd}/dx is the drag force exerted by the fluid on the cable. A formula for this force is obtained by considering the total force dF_{an}/dx as a result from the pressure drop over the cross-sectional area of the annulus between cable and duct [1,2]:

$$\frac{dF_{an}}{dx} = \tfrac{1}{4}\pi\left(D_d^2 - D_c^2\right)\left|\frac{dp}{dx}\right| \tag{3}$$

Here D_d is the internal duct diameter. In most installations the flow is turbulent. For a non-moving cable (or cable speed much lower than fluid speed, which is the case when cables are blown in) it is assumed that the forces are equally distributed over the surfaces of the cable and of the inner wall of the duct. In that case the cable takes the fraction $D_c/(D_d+D_c)$ of the force over the annulus, resulting in [1,2]:

$$\frac{dF_{hd}}{dx} = \tfrac{1}{4}\pi D_c\left(D_d - D_c\right)\left|\frac{dp}{dx}\right| \tag{4}$$

2.3 Total Propelling Force

The total fluid propelling force dF_{prop}/dx on the cable is equal to the sum of the hydrostatic and hydrodynamic propelling force [1,2]:

$$\frac{dF_{prop}}{dx} = \tfrac{1}{4}\pi D_c D_d\left|\frac{dp}{dx}\right| \tag{5}$$

The trick of blowing is that the distribution of this force along the cable is limiting the capstan effect when compensating gravity friction locally. It was found in 1987 by PTT Netherlands that also cables with quite some stiffness could be blown in and that the pressure gradient was non-linear (air is a compressible fluid), even resulting in doubling of the installation length by synergy of blowing and pushing those stiff cables [2].

2.4 Common Misunderstandings

There are quite a few misunderstandings around cable blowing (and floating). It is good to understand them before treating the remarkable floating phenomena presented in this paper.

1. *Flow is the primary factor and shall be measured*. Yes, the flow plays a role, but is only a secondary factor, directly related to the pressure gradient and geometry. That's why you do not see the flow in the formulas. As long as the pressure is measured there is all information you need. For constant inlet pressure the flow decreases during cable installation, because of the increased pneumatic resistance of the cable filled part of the duct. The effect on the pressure gradient along the cable can be calculated.
2. *During blowing the cable is flying*. This is not true. The flow-lines along a cable in a duct (constant diameters) are parallel, so unlike with airplane wings no Bernouilli lift force is present. The cable just drags over the bottom of the duct (you can hear this when blowing a cable in an above ground duct). Also, if the cables were flying the blowing lengths reached would be far away from the calculated lengths.
3. *The fluid propelling force decreases for large cable filling factor because of limited airflow*. Not true, see Fig. 3, where the static, dynamic and total propelling force are given dimensionless as a function of filling factor D_c/D_d, following directly from the formulas. Only the hydrodynamic force decreases for $D_c/D_d>½$. If for very high filling factor the speed of the fluid is no longer much higher than that of the cable the hydrodynamic force is smaller than shown in Fig. 3. But, still then the static propelling force and the total force increase to the max for 100% filling! In practice, the blowing length in the same duct decreases for larger cable diameter, simply because the weight of the cable grows with the square of it (while the total propelling force only increases linearly). Increased (stiffness) friction due to micro-undulations of cable and/or duct even cause more abrupt decrease in blowing distance for a filling factor above 80%.

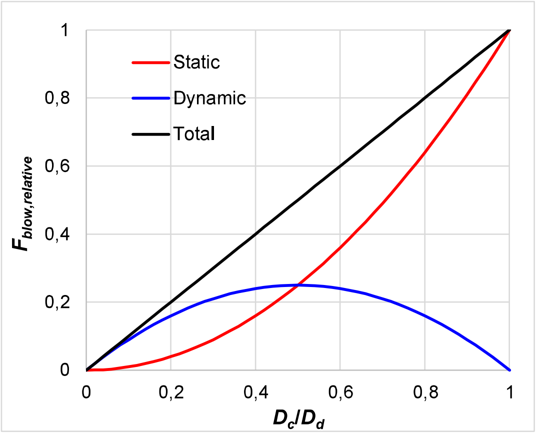

Figure 3. Cable propelling forces dimensionless

2.5 Cable Speed Comparable to Fluid Speed

As already mentioned, the formulas for the propelling forces of blowing can also be used for floating. Here not only the effective weight of the cable is reduced, also now the pressure gradient is linear (water is a non-compressible fluid) so linear extrapolations in floating length can be made (for pure floating). Furthermore, the fluid speed is not always much higher than that of the cable, so the cable speed has to be taken into account too. According to theory, it is possible to float cables with a water speed equal to that of the cable, already forecasted in [6]. Indeed, in floating installations of 5.5 km [4] and 12.4 km [5] it was observed that the cable came almost immediately when the first water poured out of the duct. The cable could not come earlier because the installations started with an empty duct, where the cable would run dry when moving faster than the water flow.

In the tests described in this paper (duct pre-filled with water) the cable speed was even higher than that of the water flow propelling it, the only remaining propelling force (all other possible forces were eliminated). This is indeed possible according to the formulas. The hydrodynamic propelling force equation (4) was derived for a cable speed zero. This cable's fraction of the force over the annulus gets lower when the cable speed becomes close to that of the water. The hydrodynamic propelling force even becomes negative (counter-acting) when the cable moves with a higher speed than that of the water. But, even then the flow can still move the cable forward when the hydrostatic propelling force dF_{hs} compensates the sum of the counter-acting hydrodynamic propelling dF_{hd} and friction force dF_f:

$$\frac{dF_{hs}}{dx} \geq \frac{dF_{hd}}{dx} + \frac{dF_f}{dx} \tag{6}$$

3. Setup and Tests

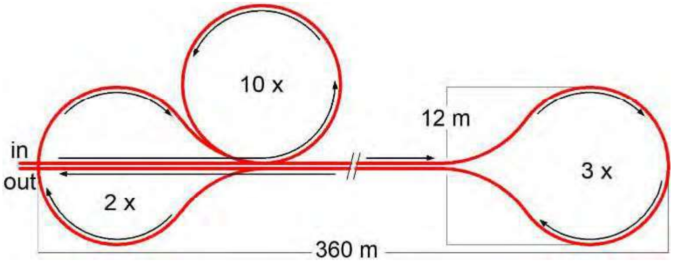

Figure 4. Schematic view of looped duct track (minimum bend radius 6 m)

Floating test were done in a 2.54 km dummy track (same construction as in the targeted project) in Norway to evaluate a project where the length will be 30 km (rather straight and smooth) and where the cable density is tuned to (sea) water density. An 18 mm, 2.47 N/m "buoyancy tuned" (for the local seawater, some margin for compression of the cable under water pressure) cable was installed into 6 parallel 40/30 mm PP ducts in a special configuration, connected by 6 m radius loops and with 10 of those loops immediately at the start of the track, see Fig. 4 and 5.

For pure floating the installation length increases proportionally with the water pressure. In order to extrapolate to a 30 km project from a relatively short test track of 2.54 km it is important to eliminate all edge effects disturbing the test and leading to false information. That is why 10 loops of duct were placed immediately at the entrance of the track. The capstan effect will then kill excess pushing forces, pushing forces which are needed where the cable is injected into the pressure zone, to overcome the so-called backpressure force. If this is not done sufficiently, floating is not effective.

The floating equipment used was a SuperJet (with flow meter) and a 120 l/min water pump, pushing the cable and supplying the water pressure. Lubricant (Jetting Lube) was added to the duct (under pressure) using a lubricant dosing pump. The pressure was measured with a class 0.2 (0.2%) digital manometer.

3.1 Tests

Figure 5. Installation of 18 mm cable in 40/30 mm PP duct, in total 2.54 km long, by floating

First the duct was filled with water (only wall lubricated by first blowing a foam pig with lubricant through). After the duct was filled with water the flow was measured as a function of applied water pressure. This showed that Blasius' law [2] is followed, see Fig. 6.

Then lubricant was added to the water. This was done by continuously feeding lubricant with the lubricant dosing pump. The whole process (until lubricant "reached the end") took about 70 min. Then the flow as a function of applied water pressure was measured again. The expected effect of the lubricant on the flow (increased flow, the "fireman effect") could not be seen during filling with lubricant. No difference was found with the situation before lubrication, see Fig. 6.

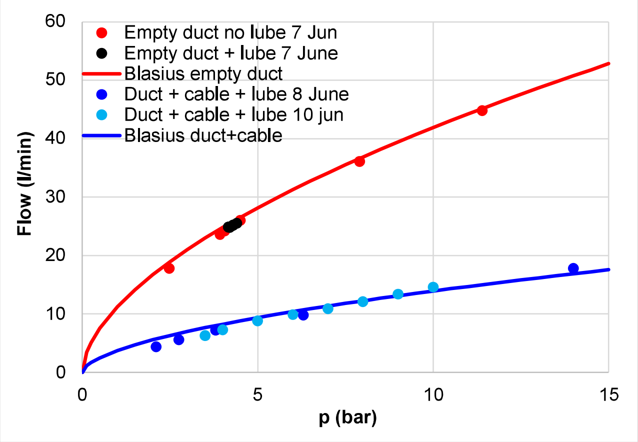

Figure 6. Measured water flow as a function of applied pressure over 2.54 km of 40/30 mm PP duct, with and without 18 mm cable, compared with Blasius' law. Further details in text.

The first cable installation (6 June 2022) was done most of the time with a water pressure of 5 bar, with the speed adjusted to 30 m/min. It was found at the end that the speed (then about 23 m/min) was limited by the settings of the SuperJet, because at the end the water pressure could be reduced to 2.33 bar before the speed started to drop. When reducing the water pressure further to 1.95 bar (could not set lower, pump motor running idle and bypass fully open) the cable speed dropped to 18 m/min.

Also when the duct was filled with cable Blasius' law was followed, when for the annulus between cable and duct the standard hydraulic diameter D_h is taken, defined as "4 times cross-sectional area divided by wetted surface", resulting in $D_h = D_d - D_c$.

After Floating the cable back a second Floating installation (7 June 2022) was done, most of the time with a water pressure of 6.4 bar and with the speed adjusted to 55 m/min most of the time. At the end again measurements were done of pressure, speed and flow, both for moving and non-moving cable. Again Blasius' law was followed for the non-moving cable. For the moving cable the measured water speed took a value between that of Blasius' law for an empty and for a cable-filled duct, see Fig. 8 (note: here speed given instead of flow).

In 2023 two more tests were done, now even 73 m/min reached (most of the time) with a water pressure of 10.2 bar.

The cable speeds for different water pressures with data taken at the end (cable out) from 2022 and 2023 are summarized in Fig. 7.

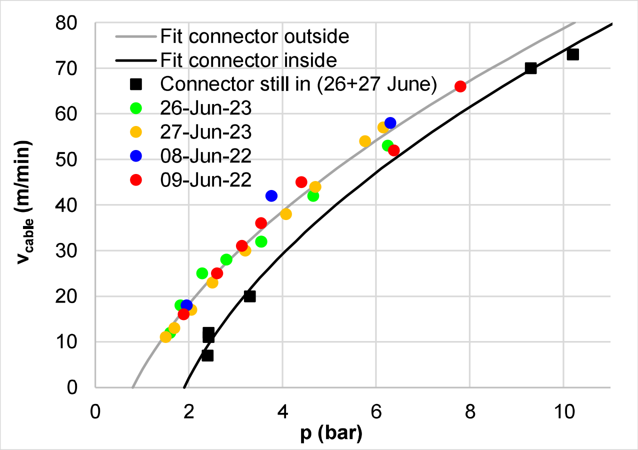

Figure 7. Measured cable speed from tests and data fit

Besides measurements of pressure, speed and flow after the cable came out also a few measurements were done with the cable just did not come out (there was not much time for such measurements because the cable is only for a short time in that region, certainly at the higher speeds). It was found that the cable speed is a bit lower then, see Fig. 7, indicating that the cable end (stiff, with connector) adds a bit to the friction and needs extra fluid drag to overcome this.

According to Fig. 7, installation would even be possible with a cable speed of 10 m/min and a water pressure as low as 1.5 bar (we could not yet get sufficiently low water flow with the equipment we used to reach lower pressures). With the cable end still inside we would need about 2.4 bar for this speed of 10 m/min (if we do not do something to reduce this friction).

A very interesting phenomenon is the fact that the cable speed was higher than that of the water around the cable in all measurements, see Fig. 8. They become about equal in the lowest pressure and speed settings.

Another interesting observation is that the cable can reach higher speeds (for the same pressure) than water flow in the empty duct. In other words: "the cable slides more easily through the duct than water".

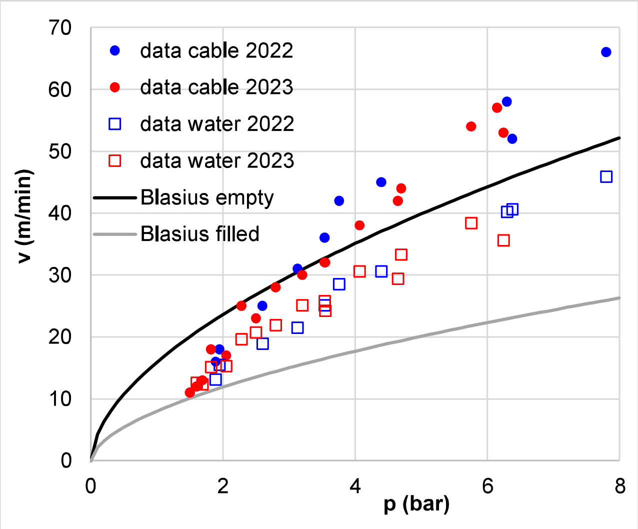

Figure 8. Measured cable and water speeds from tests

3.2 Analysis (for zero cable speed)

The test was done such that the flow of water, and nothing else, propels the cable. For that reason 10 loops of duct were placed immediately at the start of the test track in order to kill by the capstan effect all excessive pushing forces remaining after compensation of the backpressure force. The importance of this is shown in Fig. 9 where a calculation (JetPlanner 4.0 software [7]) was done for the minimum pressure needed to install the cable (diameter 18 mm, linear weight density 2.47 N/m, cable stiffness 8 Nm^2) into a 2.54 km straight duct (coefficient of friction with cable 0.19, "standard" undulations with 4 cm amplitude and 8 m period), no loops programmed yet. The same was done with 10 loops of duct with 6 m radius placed at the entry of the duct (same total length). Here the result is about the same with and without undulations. Note that the calculation still assumed a cable speed much lower than that of the propelling water.

Without the loops the pushing force still has such a large effect that with 400 N almost no water pressure is needed, while with the lowest force 0.65 bar is required, see Fig. 9. With the loops the pushing force hardly influences the minimum pressure needed to install the cable, which is remarkably higher (1.95 bar) than without the loops. But, even a large bend radius of the loops of 6 m still has an effect (due to cable stiffness friction in bends) as can be seen in Fig. 9 with larger bend radii. At 12 m bend radius the cable stiffness effect is close to saturation (not much changes anymore with 40 m loops, about the limit for loops-only on a 2.54 km track). So, the test with 6 m bend radius is worst case and could be closer to reality when selecting larger bend radii. However, this is true for the undulations assumed (which also give cable stiffness friction). And the latter is what we investigate. So, the 6 m loops give a worst case estimate, but we do not exactly know "how worse" it is.

The almost horizontal straight lines in Fig. 9 suggest the situation of pure floating, with the effect of cable stiffness in undulations of the duct and in the loops the only relevant friction contributors. The effect of the loops is clearly shown. Furthermore, to the left of the round points no installation is possible (pushing force not enough to compensate backpressure force).

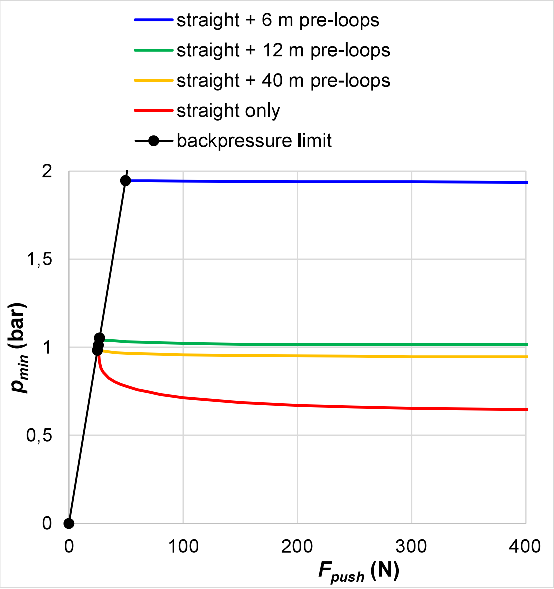

Figure 9. Calculated minimum pressure to install cable in full length of 2.54 km duct when straight and when straight with pre-loops

More loops were placed (programmed) in the track to make the looped 2.54 km length with 6 parallel ducts. All loops have a minimum bend radius of 6 m to limit friction in those loops arising from cable stiffness (last friction contributor). The extra loops have no effect, in fact they "restore" faster from the bending stiffness friction than the initial 10 loops. This can be seen in the JetPlanner 4.0 software [7] simulation, again for a water pressure of 1.95 bar, see Fig. 10.

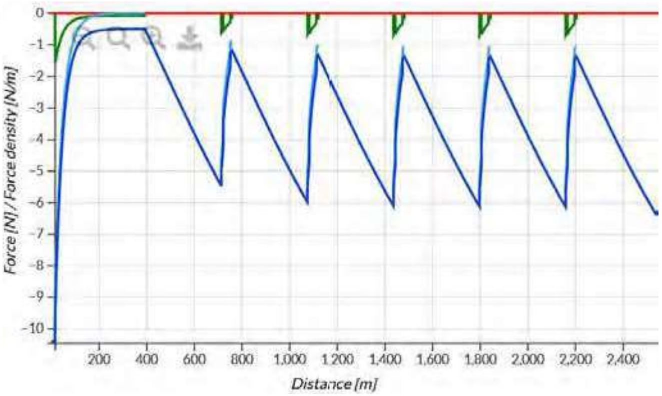

Figure 10. Software simulation of axial force (blue) and radial force density (green) in the cable during floating

3.3 Extrapolation to longer length

It was found that the cable could be floated through the test track with a water pressure of only 1.5 bar and a speed of 10 m/min. Extrapolation (this can be done linear proportionally) to 30 km says that this could be done with a pressure of 18 bar, no problem for an installation time of a few days for a 40/30 mm PP duct. In case the loops in the test track were indeed the dominant factor for the required water pressure, even longer installation length would be possible.

4. Conclusions

It was found that the cable could be floated through the test track of 2.54 km of 40/30 mm PP duct with a water pressure of only 1.5 bar and a cable speed of 10 m/min. Extrapolation, to 30 km, says that this could be done with a pressure of 18 bar, no problem for an installation time of a few days for this PP duct. A higher pressure resulted in a higher speed. This is because of the relatively low water speed. So low that the cable was running faster than the water flow, the only source propelling the cable! This can be explained by the fact that the "hydrostatic" propelling forces from the pressure gradient over the volume of the cable compensate the sum of gravity and cable stiffness friction and even the then counter-acting "hydrodynamic" drag forces. Also it was found that the cable could move faster through the duct than water in the empty duct under the same pressure! The measured water flow in an empty and cable (non-moving) filled duct match with Blasius' law. When the cable moves the water gets a speed between the empty and filled Blasius' speed.

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