



Calculation Force to Pull Cables into Pipes

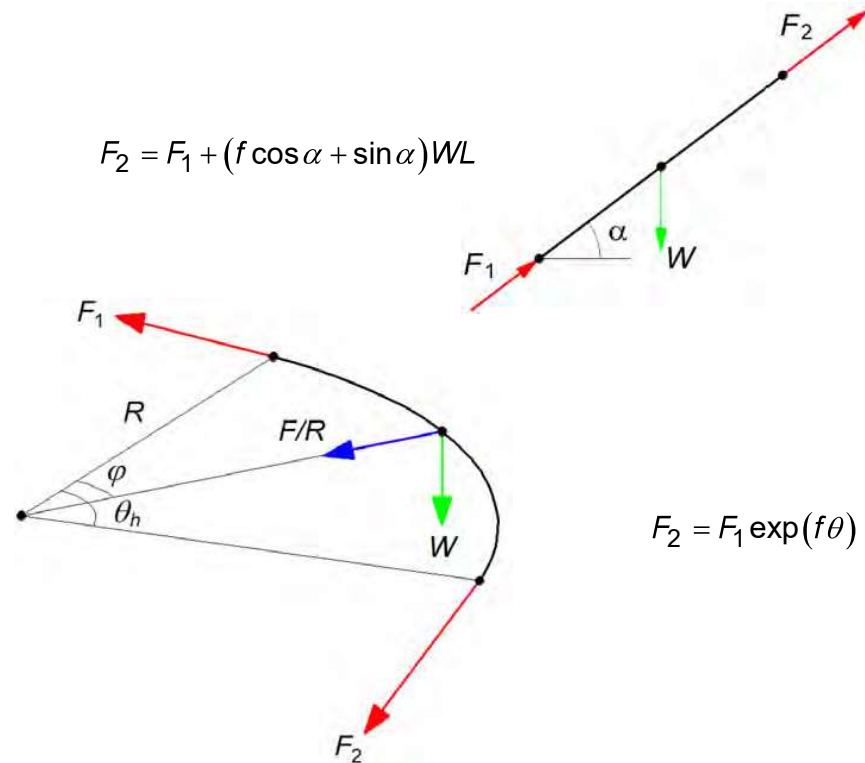
UPDATE THEORY FROM 1953

Willem GRIFFIOEN

CALCULATION FORCE TO PULL CABLES INTO PIPES Theory

Gravity friction

- Coefficient of friction (COF) f
- Straight section
- Bends
 - Cable tension
 - Sidewall force
 - Capstan effect
 - Exponential formula
 - Together with gravity more complex
 - See next slide



CALCULATION FORCE TO PULL CABLES INTO PIPES Theory

Rifenburg formulas (1953)

- Horizontal bend
- Vertical bend

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

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

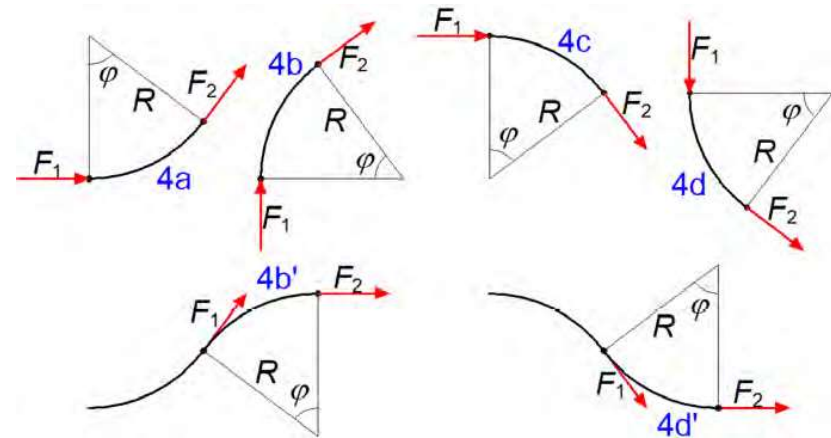
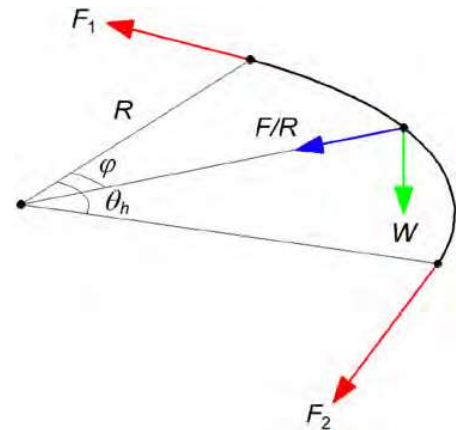
$$F_2 = F_1 e^{f\varphi} - \frac{WR}{1+f^2} \left[2f(\cos \varphi - e^{f\varphi}) - (1-f^2) \sin \varphi \right] \quad 4b$$

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

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

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

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



CALCULATION FORCE TO PULL CABLES INTO PIPES Theory

Rifenburg drawbacks for vertical bends (still):

- Formulas given only cover special cases (else formulas get more complex)
- User must define what kind of bend it is
- Does not cover large radius bends, like in horizontal directional drills (HDD)
 - When mass dominant cable follows outside facing pipe wall
- Does not cover pushing at all

Drawbacks taken away with new theory:

- Covers all situations, only α_1 and α_2 needed (vertical bends)
- Also full down to up (or vice versa) bends, covers 2 quadrants

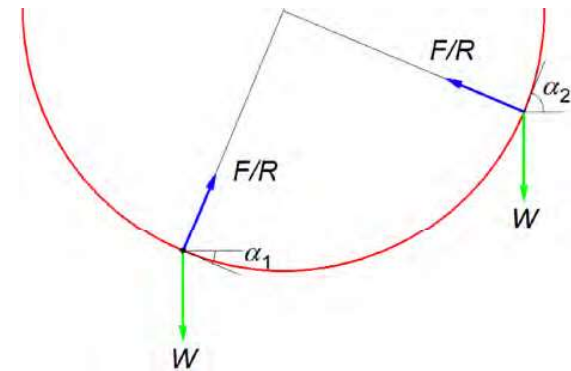
$$F_2 = F_1 e^{\pm f|\alpha_2 - \alpha_1|} \mp \frac{WR}{1 + f^2} [\psi(\alpha_2) - e^{\pm f|\alpha_2 - \alpha_1|} \psi(\alpha_1)] \quad \text{with:}$$

$$\psi(\alpha) = 2f \sin \alpha \pm (1 - f^2) \cos \alpha \quad \alpha_2 > \alpha_1 \quad (\text{concave})$$

$$\psi(\alpha) = 2f \sin \alpha \mp (1 - f^2) \cos \alpha \quad \alpha_2 < \alpha_1 \quad (\text{convex})$$

$$F \gtrless \pm WR \cos \alpha$$

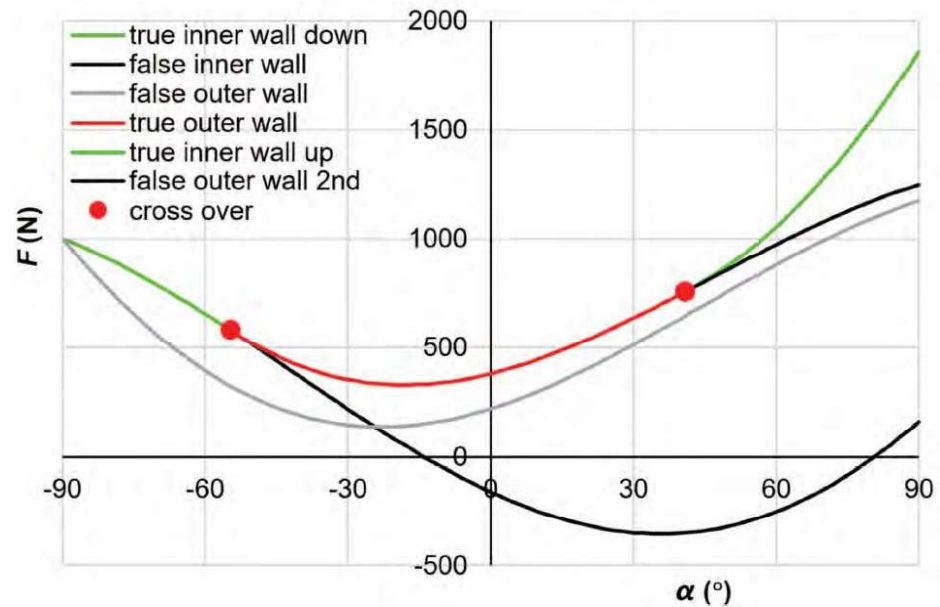
± ∓ Inside facing wall
Outside facing wall



CALCULATION FORCE TO PULL CABLES INTO PIPES Theory

Example showing difference with old theory (extreme case)

- Vertical bend starting 90° down, ending 90° up, bend radius 10 m
- Cable with linear weight density 100 N/m
- Coefficient of friction 0.5
- Pulling force before bend 1000 N
- Starts following inside facing pipe wall
 - Like in old theory
- Then crosses over to outside facing wall
 - New theory takes this into account
- Finally crosses back to inside facing wall
 - Like in old theory again
 - But, totally different answer



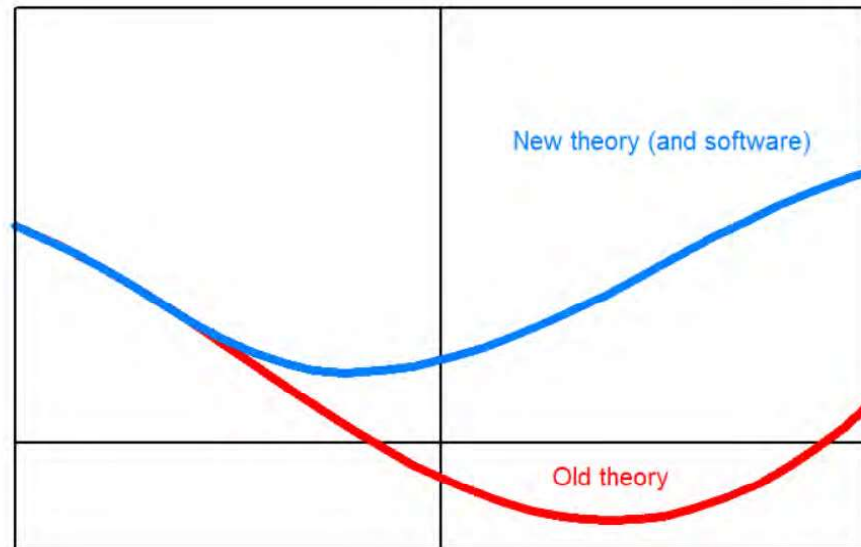


CALCULATION FORCE TO PULL CABLES INTO PIPES

Theory

Example showing difference with old theory (extreme case)

- Vertical bend starting 90° down, ending 90° up, bend radius 10 m
- Cable with linear weight density 100 N/m
- Coefficient of friction 0.5
- Pulling force before bend 1000 N
- Starts following inside facing pipe wall
 - Like in old theory
- Then crosses over to outside facing wall
 - New theory takes this into account
- Finally crosses back to inside facing wall
 - Like in old theory again
 - But, totally different answer



CALCULATION FORCE TO PULL CABLES INTO PIPES Theory

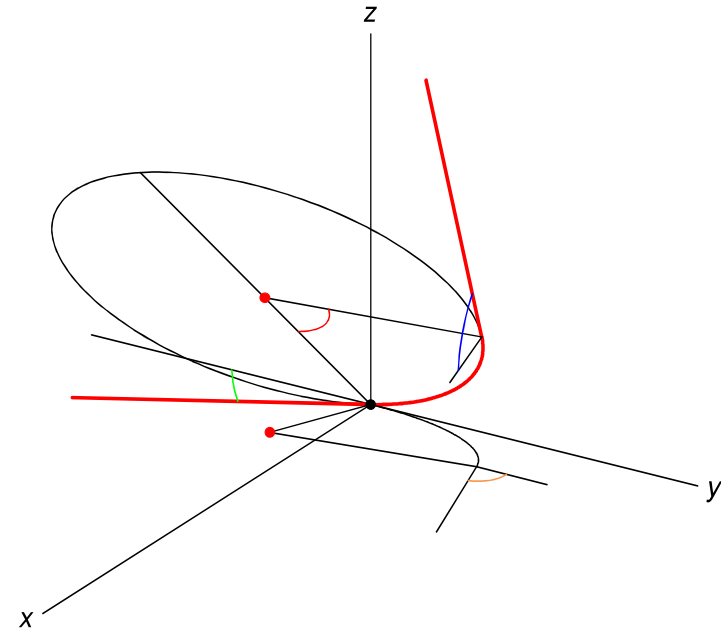
3-Dimensional bends

- Input parameters
 - Slope at entry bend α_1
 - Slope at exit bend α_2
 - Angle of horizontal bend θ_h
- Calculated parameters
 - Help parameter β
 - Total angle 3D bend θ (function of local real angle φ)
 - Local slope along bend α
 - Angle between gravity and capstan force ξ (needed to calculate pulling force)

$$\cos \theta = \cos \alpha_1 \cos \alpha_2 \cos \theta_h + \sin \alpha_1 \sin \alpha_2$$

$$\sin \alpha = \cos \alpha_1 \sin \beta \cos \varphi + \sin \alpha_1 \cos \varphi$$

$$\cos \xi = \sin \alpha_1 \sin \varphi - \cos \alpha_1 \sin \beta \cos \varphi$$



$$\tan \beta = \frac{\sin \alpha_2 \cos \alpha_1 - \sin \alpha_1 \cos \alpha_2 \cos \theta_h}{\cos \alpha_2 \sin \theta_h}$$

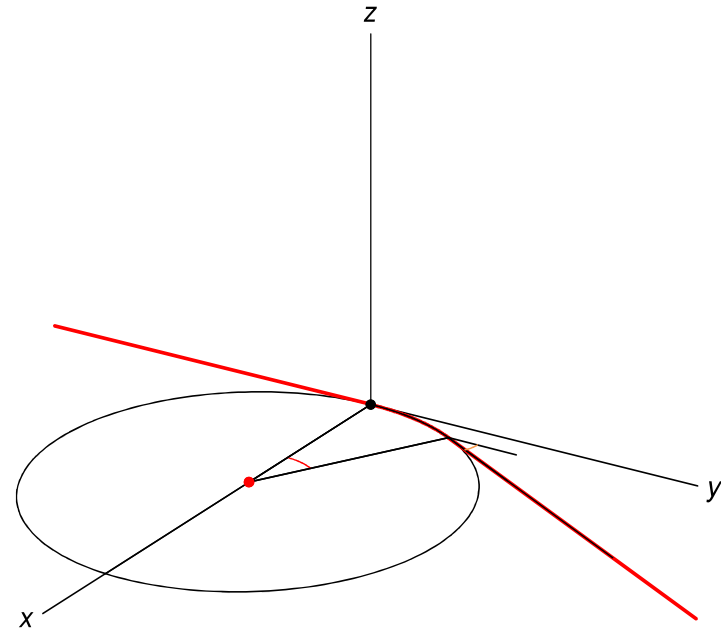


CALCULATION FORCE TO PULL CABLES INTO PIPES

Theory

3-Dimensional bends

- A few configurations α_1 α_2 θ_h θ
- Horizontal



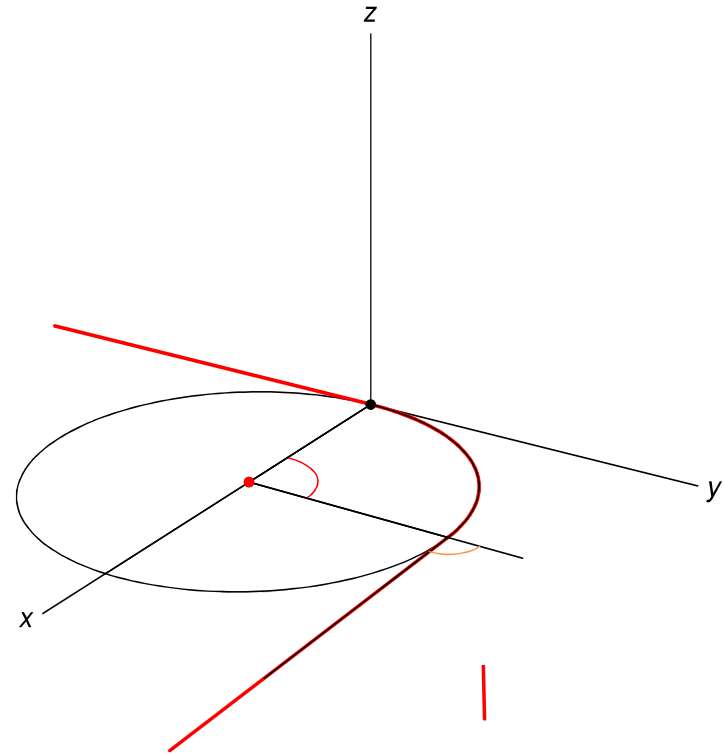


CALCULATION FORCE TO PULL CABLES INTO PIPES

Theory

3-Dimensional bends

- A few configurations α_1 α_2 θ_h θ
- Horizontal

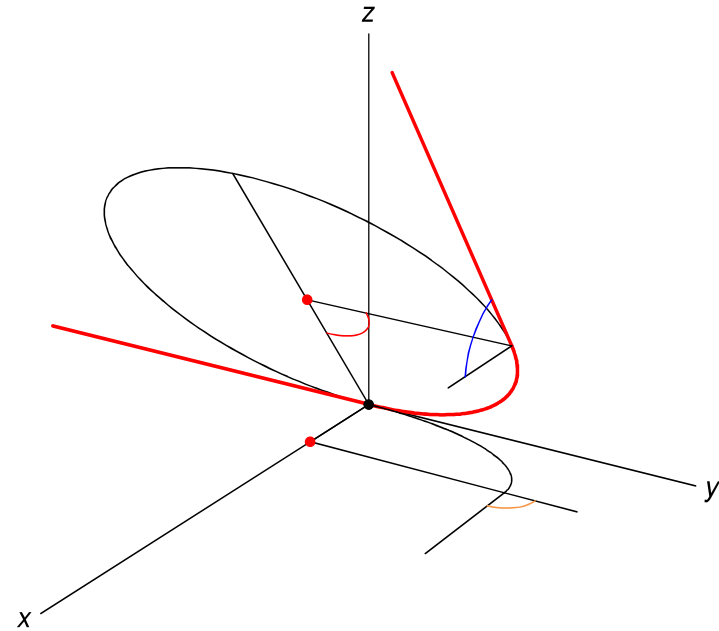




CALCULATION FORCE TO PULL CABLES INTO PIPES Theory

3-Dimensional bends

- A few configurations α_1 α_2 θ_h θ
- Horizontal
- Inclined

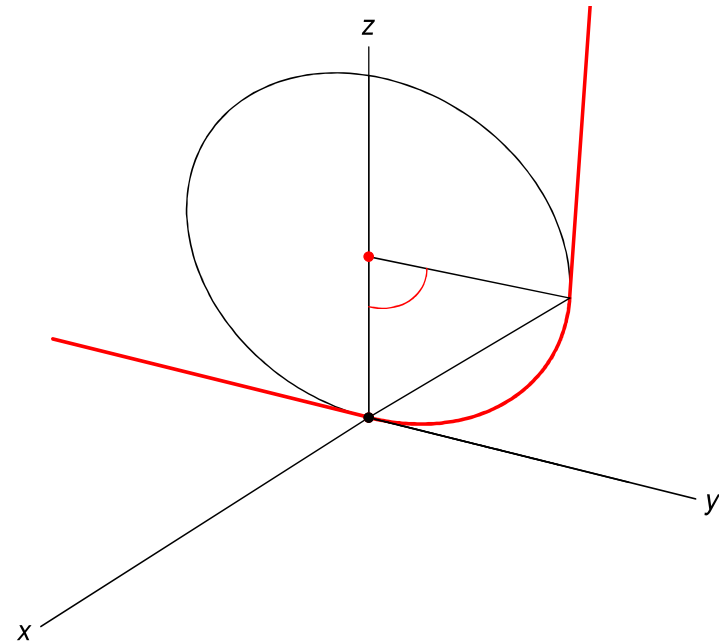




CALCULATION FORCE TO PULL CABLES INTO PIPES Theory

3-Dimensional bends

- A few configurations α_1 α_2 θ_h θ
- Horizontal
- Inclined
- Vertical

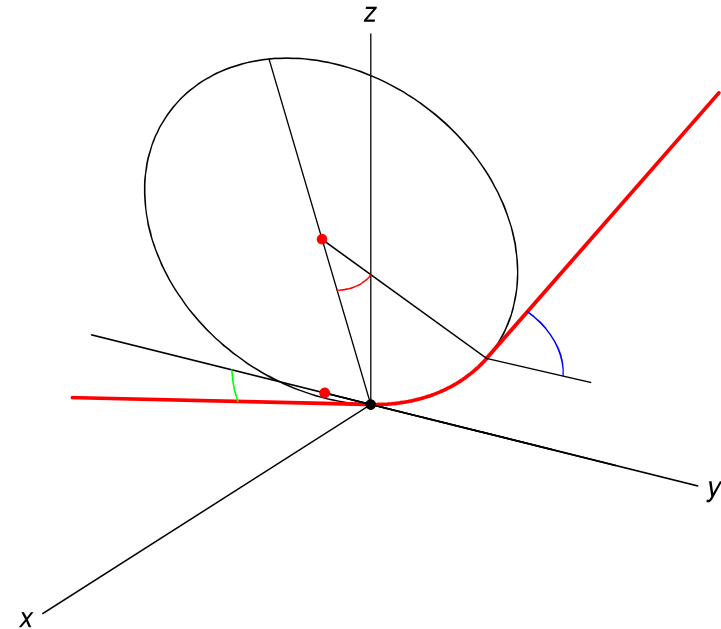




CALCULATION FORCE TO PULL CABLES INTO PIPES Theory

3-Dimensional bends

- A few configurations α_1 α_2 θ_h θ
- Horizontal
- Inclined
- Vertical

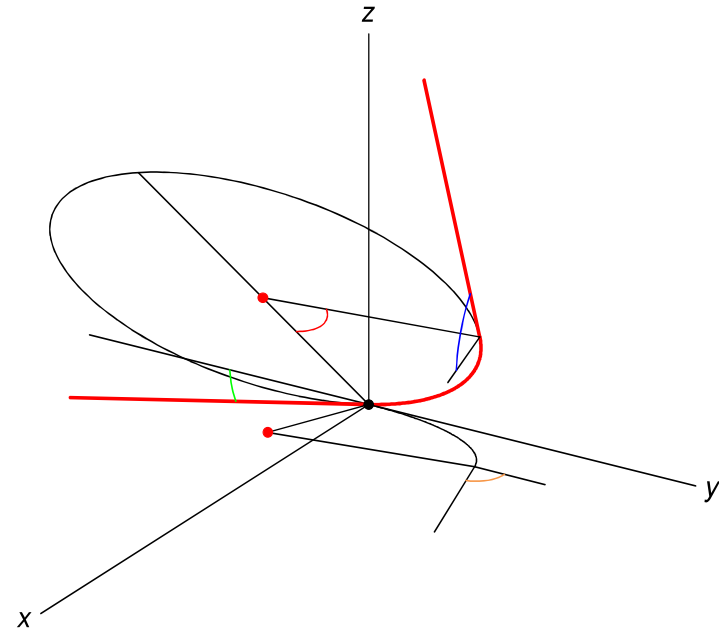




CALCULATION FORCE TO PULL CABLES INTO PIPES Theory

3-Dimensional bends

- A few configurations α_1 α_2 θ_h θ
- Horizontal
- Inclined
- Vertical
- Arbitrary

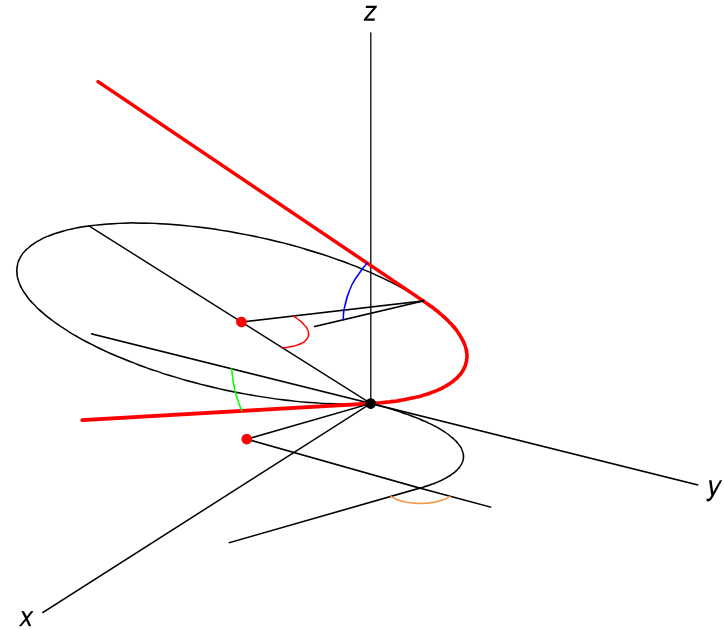




CALCULATION FORCE TO PULL CABLES INTO PIPES Theory

3-Dimensional bends

- A few configurations α_1 α_2 θ_h θ
- Horizontal
- Inclined
- Vertical
- Arbitrary





PULLING FORCE CALCULATION SOFTWARE TRAJECTORY INPUT

Sequence of alternating straights and bends which each only 2 parameters

- Straights
 - Length and slope
- Bends
 - Horizontal angle and bend radius

No need to identify type of bends:

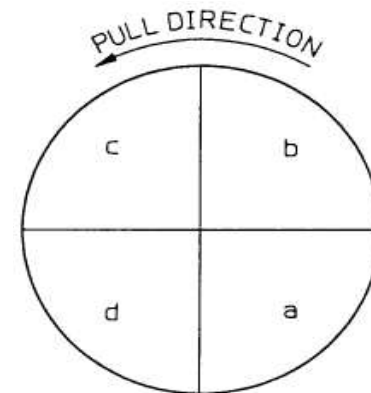
- Whether horizontal or vertical
- Which quadrant for vertical bend

Any entry and exit slope possible

- No need to start or end horizontally or vertically

Possibility to have bends over 2 quadrants

- a) Concave up
- b) Convex up
- c) Convex down
- d) Concave down

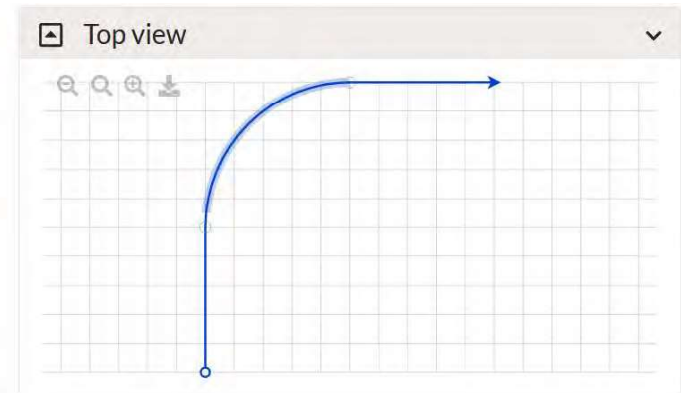
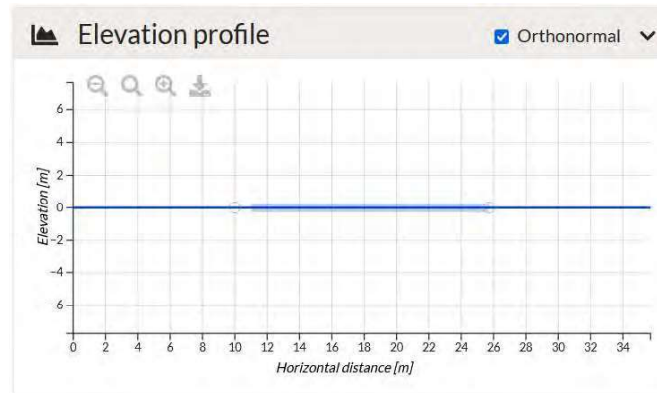


PULLING FORCE CALCULATION SOFTWARE TRAJECTORY INPUT

Example

1. Horizontal bend

1		Straight	Length Slope	10.00 m 0.00°	Cumulative length	10.00 m	Altitude at end	0.00 m
2		Curve	Length Horizontal angle	15.71 m 90.00°	Cumulative length Total angle	25.71 m 90.00°	Altitude at end Bending radius	-0.00 m 10.00 m
3		Straight	Length Slope	10.00 m 0.00°	Cumulative length	35.71 m	Altitude at end	-0.00 m

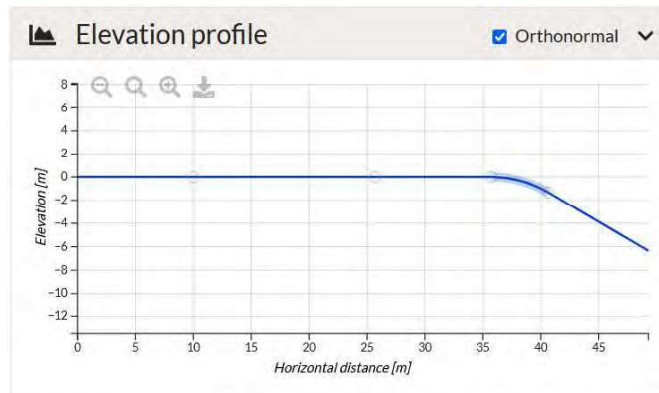


PULLING FORCE CALCULATION SOFTWARE TRAJECTORY INPUT

Example

1. Horizontal bend
2. Next vertical bend

3		Straight	Length 10.00 m	Cumulative length 35.71 m	Altitude at end -0.00 m	
4		Curve	Length 5.24 m Horizontal angle 0.00°	Cumulative length 40.94 m Total angle 30.00°	Altitude at end -1.34 m Bending radius 10.00 m	 
5		Straight	Length 10.00 m Slope -30.00°	Cumulative length 50.94 m	Altitude at end -6.34 m	

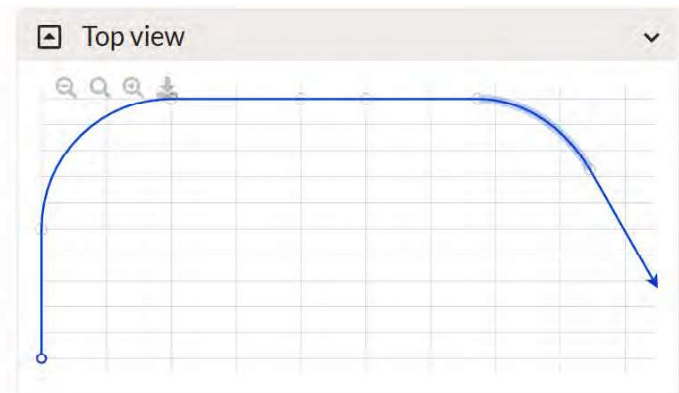
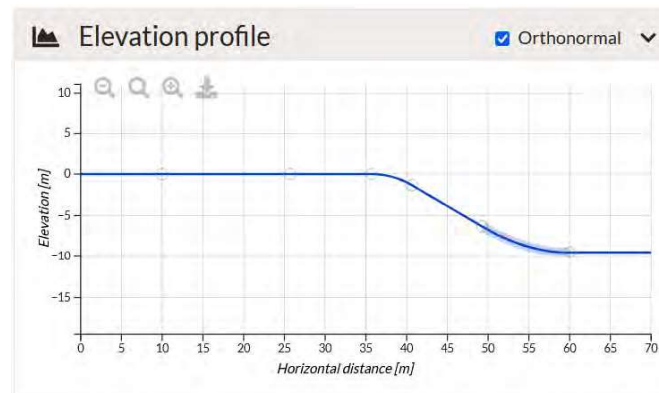


PULLING FORCE CALCULATION SOFTWARE TRAJECTORY INPUT

Example

1. Horizontal bend
2. Next vertical bend
3. Next 3D bend

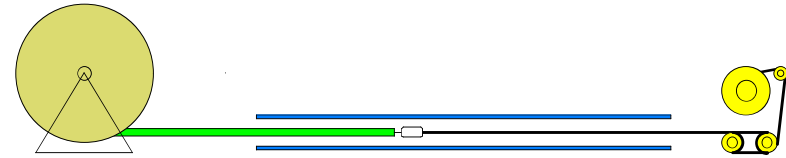
5		Straight	Length: 10.00 m Slope: -30.00°	Cumulative length: 50.94 m	Altitude at end: -6.34 m	
6		Curve	Length: 11.23 m Horizontal angle: 60.00°	Cumulative length: 62.17 m Total angle: 64.34°	Altitude at end: -9.48 m Bending radius: 10.00 m	 
7		Straight	Length: 10.00 m Slope: 0.00°	Cumulative length: 72.17 m	Altitude at end: -9.48 m	



PULLING FORCE CALCULATION SOFTWARE SIMULATIONS

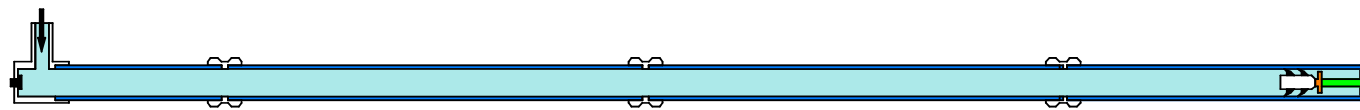
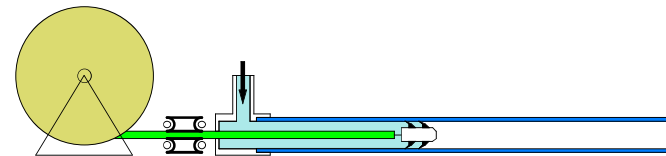
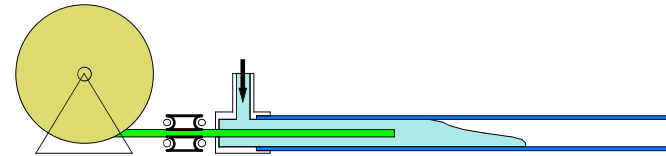
Techniques to install cables into pipes

- Traditional: winch pulling



Alternative installation methods

- Floating (pipes ID up to 100 mm)
- WaterPushPulling (unlimited pipe ID)
- FreeFloating (unlimited length!)





PULLING FORCE CALCULATION SOFTWARE SIMULATIONS

Cable parameters

- Mass, diameter, stiffness, max force (pulling, pushing, radial), min bend radius

Pipe parameters

- Outside and inside diameter, max pressure, undulations

Trajectory

- See previous

Installation method

- Pulling, Pushing, Pushpulling, Floating, WaterPushPulling, FreeFloating, Blowing (optical cables)
- This presentation focuses on Pulling (optional with pushing assistance)
- Cable stiffness (not taken into account in other software) important because:
 - High cable stiffness reduces buckling friction loss (on top of capstan effect) during pushing
 - If pushing can be calculated in other software, then buckling friction not taken into account
 - High cable stiffness also increases friction in bends (especially when sharp) and undulations in trajectory

Coefficient of friction

PULLING FORCE CALCULATION SOFTWARE SIMULATIONS

Cable pulling example

- Start new project
 - Method
 - Equipment
 - Stretches
 - Cable parameters
 - Trajectory
 - Add segment
 - Add more segments
- Curve between straights
And straight between curves
- Note bend 2 (3D)

The screenshot displays the software interface for cable simulation. On the left, two diagrams illustrate different adjustment modes: 'preserve geometry' and 'preserve segment length'. The 'preserve segment length' mode is selected. Below the diagrams is a navigation menu with options: Cable (checked), Trajectory (checked), Settings, Simulation, and Reprc. To the right, the 'Edit segment #2' panel is open, showing settings for a 'Curve' segment: Horizontal angle is 60.0, Adjustment mode is 'Preserve segments length', and Bending radius is 100.0 m. At the bottom, a table lists the segment data:

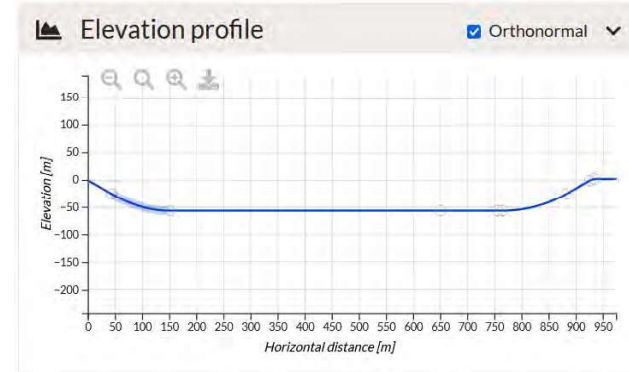
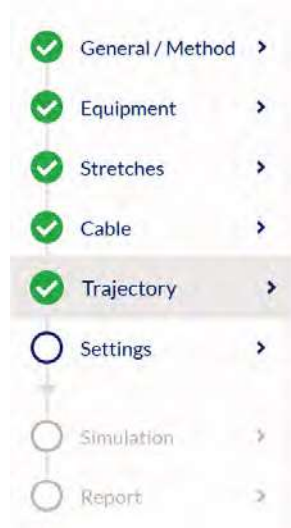
Segment	Type	Length	Cumulative length	Altitude at end
1	Straight	50.00 m	50.00 m	25.00 m
2	Curve	112.30 m	162.30 m	56.45 m
3	Straight	500.00 m	662.30 m	56.45 m

Additional details for Segment 2 (Curve):
 Slope: -30.00°
 Horizontal angle: 60.00°
 Total angle: 64.34°
 Bending radius: 100.00 m

PULLING FORCE CALCULATION SOFTWARE SIMULATIONS

Cable pulling example

- Start new project
- Method
- Equipment
- Stretches
- Cable parameters
- Trajectory
 - Overview



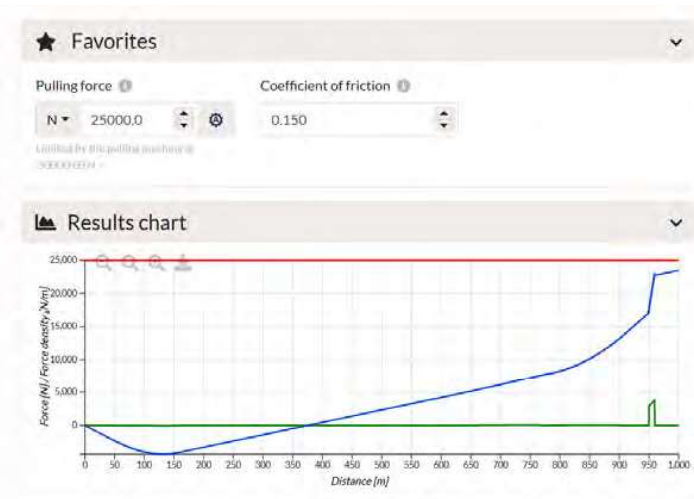
PULLING FORCE CALCULATION SOFTWARE SIMULATIONS

Cable pulling example

- Start new project
- Method
- Equipment
- Stretches
- Cable parameters
- Trajectory
- Settings
- Simulation
 - Vary favorite
 - Pulling force
 - Or another favorite (coefficient of friction)

The screenshot shows a software interface with a sidebar on the left containing a list of settings: General / Method, Equipment, Stretches, Cable, Trajectory, Settings, Simulation (highlighted), and Report. The main area is divided into two panels: 'Messages' and 'Results'. The 'Messages' panel contains an information icon and a message: 'Based on the laying method and parameters, the installation will require approximately 15.80 l of lubricant.' The 'Results' panel contains an information icon and the following data: 'The cable can be laid along the entire trajectory.', 'Simulated distance: 1000 m', 'Force at end of the trajectory: 23477 N', and 'Installation duration: 67 min'.

- Blue line = axial force built up in cable
- Red line = potential available axial force
- Green line = radial force density





CALCULATION FORCE TO PULL CABLES INTO PIPES

Conclusions

Theory for calculating force to pull cables into pipes (1953)

- Still used today
- Not accurate for large bend radii in pipe (like HDD drills) when force still low
- Also not accurate when pushing cable

Upgrade of theory presented

- Corrected for above inaccuracies
- Recognizes crossing over cable from inside to outside facing pipe wall
- Also includes 3D bends
 - Calculates 3D bend parameters from
 - Straights with lengths and slope
 - Bends with horizontal angle and bend radius
 - Easy programming
 - Takes into account pulling force build-up for 3D bends
- Software presented that does it all, plus more:
 - Other installation techniques, effect of cable stiffness, etcetera



THANK YOU
FOR YOUR ATTENTION





PERMISSION TO PUBLISH

In consideration of my participation in the **Insulated Conductor Committee Meeting** (the "ICC Meeting"), I grant to The Institute of Electrical and Electronics Engineers, Incorporated, acting through the Power & Energy Society (the "PES"):

1. The unlimited, worldwide, irrevocable right to use, distribute, publish, exhibit, digitize, broadcast, reproduce and archive, in any format or medium, whether now known or hereafter developed: (a) my presentation and comments at the ICC Meeting; (b) any videotaped interviews of me; and (c) any materials, including written, audio and visual works that I submit for use in connection with the ICC Meeting (collectively, the "Materials").
2. The rights granted include the transcription and reproduction of the Materials for inclusion in products sold or distributed by IEEE and live broadcast of my presentations at the ICC Meeting.
3. In connection with the rights granted in Section 1, I further grant IEEE the unlimited, worldwide, irrevocable right to use my name, picture, likeness, voice, and biographical information in connection with the advertisement, distribution, and sale of products by IEEE, and release IEEE from any claim based on right of privacy or publicity.
4. Where necessary, I have obtained all third party permissions and consents to grant the rights above and have provided copies of such permissions and consents to IEEE.
5. Except for the rights expressly granted to IEEE above, **I retain ownership and copyright of the intellectual property rights in the Materials.**

Presentation Title: Calculation Force to Pull Cables into Pipes, update theory from 1953 _____

Author(s): Willem Griffioen _____

Subcommittee, Working Group, Discussion Group Identification: Sub C _____

Meeting Date: 12-15 May 2024 _____

Meeting Location: Palm Springs (CA) _____

Presenter (s) Signature: _____ Date: 3 May 2024 _____



<http://www.pesicc.org/>



IEEE ICC PES & Design is a registered trademark of The Institute of Electrical and Electronics Engineers, Inc.