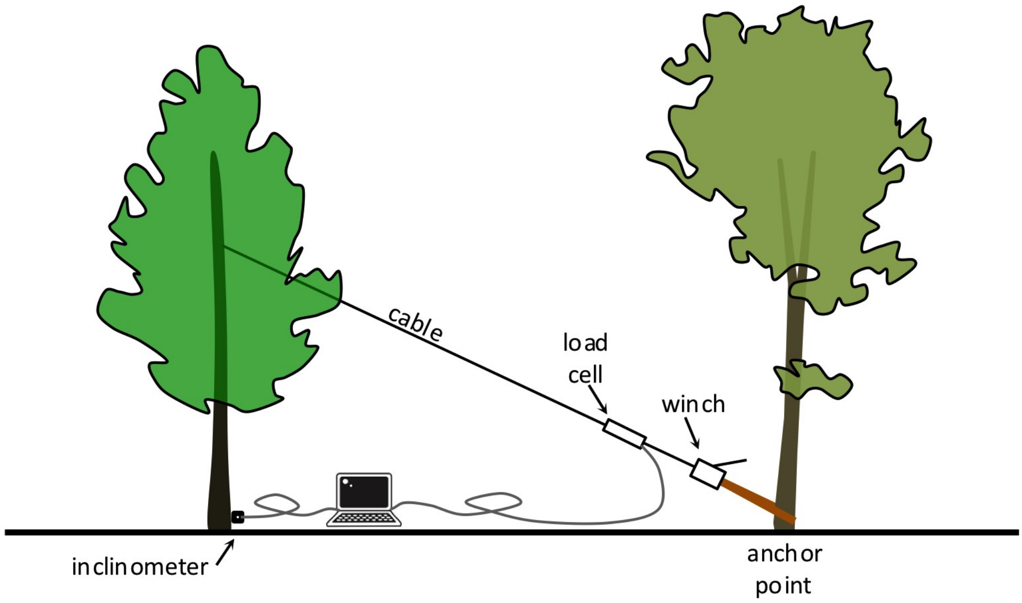
The FAKOPP pulling test

1. Introduction

The stability of urban trees is a key question that affects everyone. Diseased and unstable urban trees pose much risk for everyone, and are a serious liability for municipalities in case of an accident. Tree stability and safety assessment is therefore of the utmost importance. In the meantime it tends to be much neglected in many areas.

At present, the most accepted method for evaluating the safety and stability of trees is the pulling test. It involves applying a bending load on the trunk via a cable attached to the tree. The method can be used either to assess the uprooting stability of the tree (by measuring the inclination at the bottom of the trunk), or to establish the risk of trunk breakage (through measuring the bending stresses using extensiometers attached to the trunk). Both of these methods are introduced here briefly.

2. Pulling test for uprooting safety evaluation



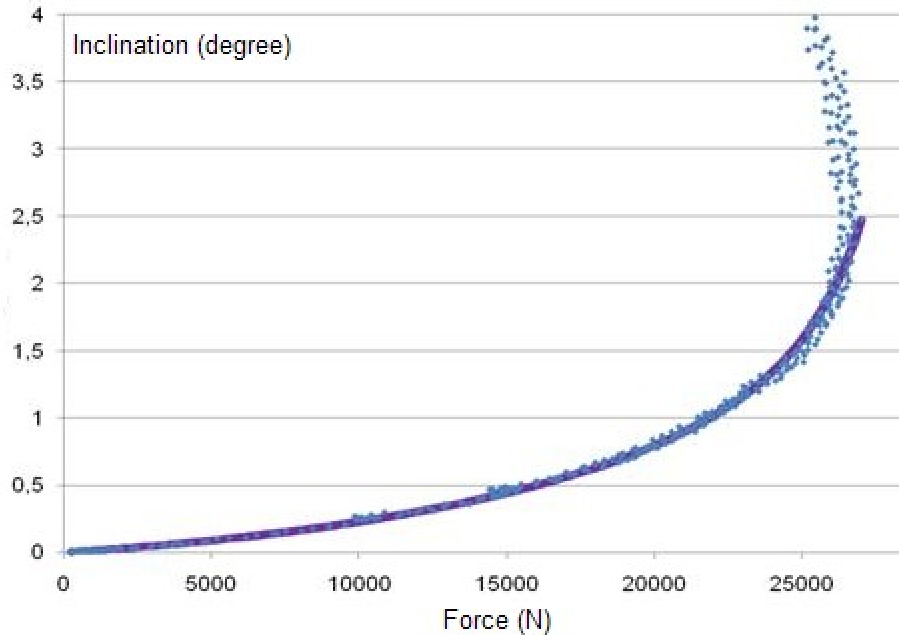
The pulling test is based on affixing a cable at approximately mid-height to the tree to be evaluated, and applying a moderate load, while measuring the inclination at the base of the trunk. The induced inclination is slight (less than .25 degrees), to make sure that the test itself does not damage or start uprooting the tree.

The cable is attached to the tree at approximately mid-height in the crown. This typically requires a ladder, or climbing the tree to the appropriate height. A metal cable of appropriate loading capacity is attached to the trunk. A soft belt is typically used for this to avoid damaging the tree. The other end of the cable enters a winch, which is affixed to an anchor point. The anchor point can be any object that is safely secured to the ground, most often a stump or the bottom of another tree. If another tree is used, care should be taken that the bark is not damaged (typically using a soft rope or belt).

The winch applies tension to the cable. A load cell attached to the cable measures the tensile load. Since the cable is at an angle, the horizontal component of the load is calculated and used for the evaluation. A relatively moderate load is applied in order to avoid causing damage to the trunk or uprooting the tree. Load is continually measured and sent to a computer for recording and evaluation.

Uprooting safety evaluation requires inclination, as well as load data. Inclination is measured at the tree collar. The inclinometer provides data of sufficient precision and frequency. This data is also sent to the same computer where it is recorded and evaluated simultaneously with the load measurements.

The recorded load and inclination data provides the inclination curve:



The general function below approximates the curve:

$$\varphi = \frac{1}{3}\tan\left(\frac{100}{73.85}\frac{F}{F_{max}}\right) + \frac{1}{3}\left(\frac{F}{F_{max}}\right)^2 - \frac{1}{10}\left(\frac{F}{F_{max}}\right),$$

where: φ - inclination at the root collar,
F - the horizontal load,
F_{max} - the maximum horizontal load.

Fitting the above equation to the measured load and inclination data, it is possible to estimate F_{max}, the horizontal load required to uproot the tree, and from F_{max}, we can calculate M_{max}, the maximum torque that the tree can withstand without uprooting:

$$M_{max} = F_{max} h,$$

where h is the height at which the rope is attached to the tree.

Based on M_{max}, it is possible to calculate the risk of uprooting at a given wind velocity. The torque acting on the tree at a certain wind velocity is calculated using the following equation:

$$M_{wind} = A\frac{\rho}{2}v^2 c_w h_{cr},$$

where: A - crown surface area,
ρ - air density,
v - wind velocity
c_w - aerodynamic drag factor
h_{cr} - the height of the crown centerpoint

The drag factor is a constant that is different for each wood species. The drag factor values are provided in the table at the bottom of this page (based on Wessoly and Erb 1998).

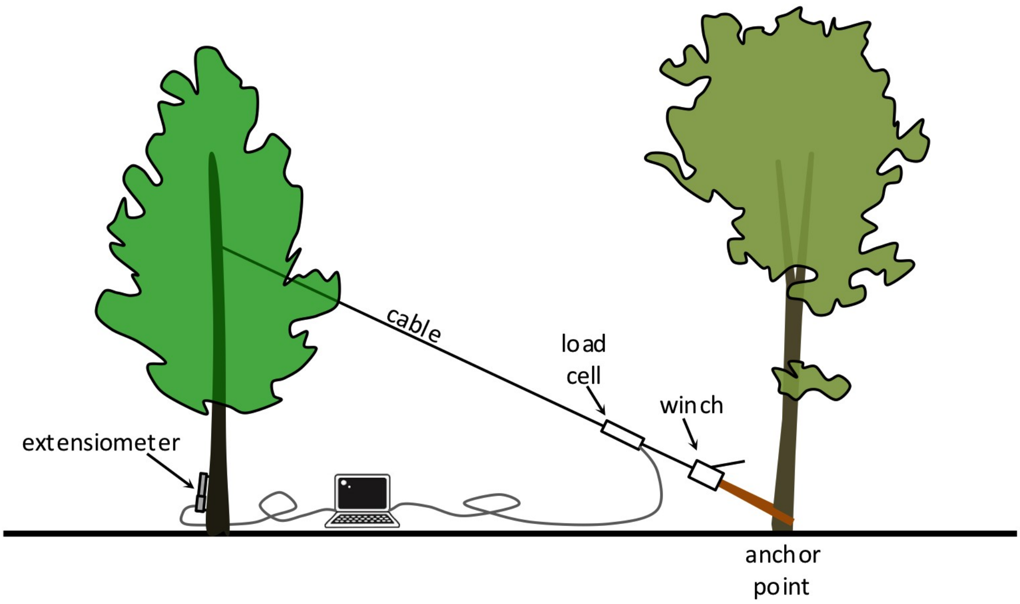
Comparing M_{wind} to M_{max}, we can calculate the so-called Safety Factor (SF) that indicates the probability that the tree will be uprooted at the given wind velocity:

$$SF = \frac{M_{max}}{M_{wind}}$$

If this value is above 1.5, the tree is safe, while a SF below 1 signals high risk. In-between these two values, there is a moderate risk of uprooting.

3. Pulling test for trunk safety evaluation

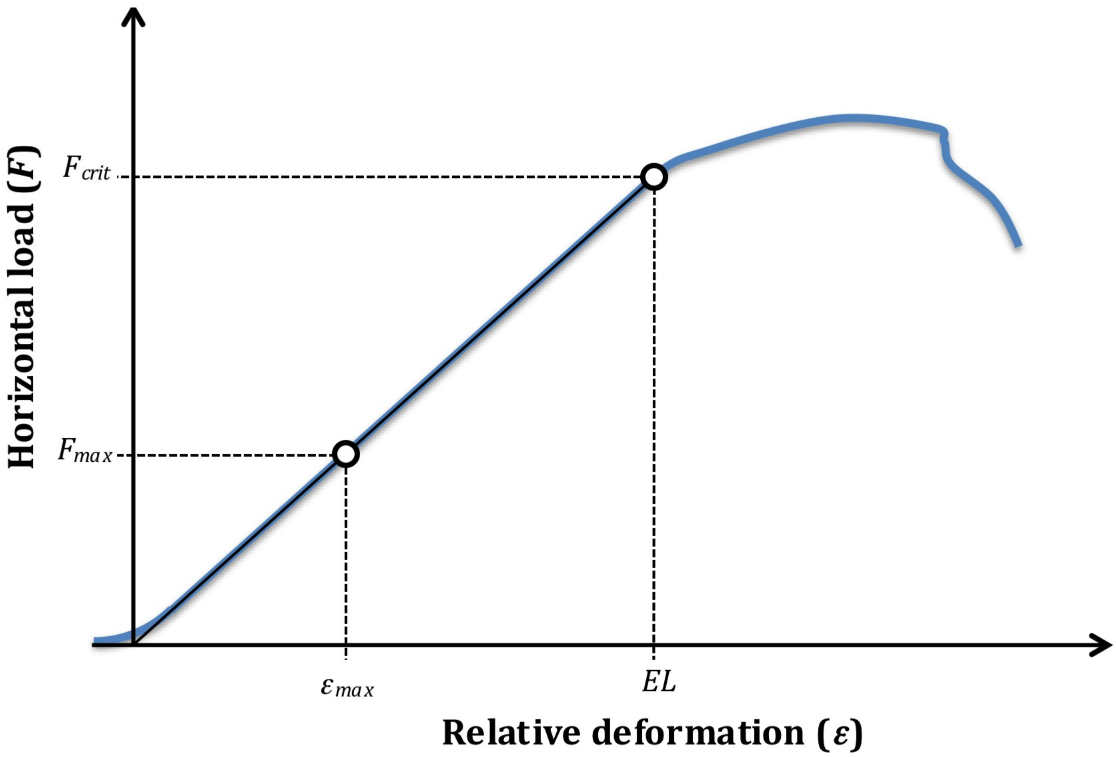
When trees sway in the wind, the trunk of the tree bends. If the wind load is severe, excessive bending may lead to permanent damage, or even the breakage of the tree trunk, even if the roots are strong enough to hold. This is especially true if the trunk is diseased, hollow or otherwise damaged. The trunk safety test is designed to assess the safety of the tree in this respect.



Trunk safety evaluation is a technique very similar to uprooting safety evaluation, except, in this case, instead of inclination, we measure the deformation of the tree trunk. During the pulling test, the trunk bends. Bending causes both compaction and elongation in the trunk, on the side nearest to and farthest from the cable, respectively. By measuring the extent of this deformation on either or both sides, it is possible to predict the safety of the tree against trunk damage.

The testing procedure is much the same as in the case of uprooting safety determination, but in this case an extensiometer is used on the compression or the tension side (or possibly both sides) of the trunk, instead of an inclinometer. The load and deformation data are collected analyzed by a computer software.

Trunk safety is determined based on the so-called linear elastic limit. When trees bend, up to a point, their deformation is linear. More importantly, this deformation is not permanent, and, up to this point, there is no permanent damage to the trunk. This safe limit of relative deformation is called the linear elastic limit (*EL*).



The linear elastic limit is a constant that depends on tree species (see the table at the end of the page). Like in the case of the uprooting test, the deformation induced by the pulling test (ε_{max}) stays well below the *EL*. Based on the measured horizontal load and deformation data, it is possible to extrapolate to the critical load (F_{crit}) that would be required to reach the *EL*.

Once we have the critical load, the Safety Factor calculation is very similar to the one used for uprooting safety:

$$M_{crit} = F_{crit} h,$$

and

$$SF = \frac{M_{crit}}{M_{wind}},$$

where M_{wind} is calculated the same way as described at the uprooting safety calculations, and the meaning of SF is the same as well, i.e. if it is above 1.5, the tree is safe, a value below 1 signals high risk, and in-between there is a moderate risk of uprooting.

4. The FAKOPP pulling test apparatus

The FAKOPP pulling test apparatus is capable of both tests described above. The components, test procedure and some important safety advice are described below:

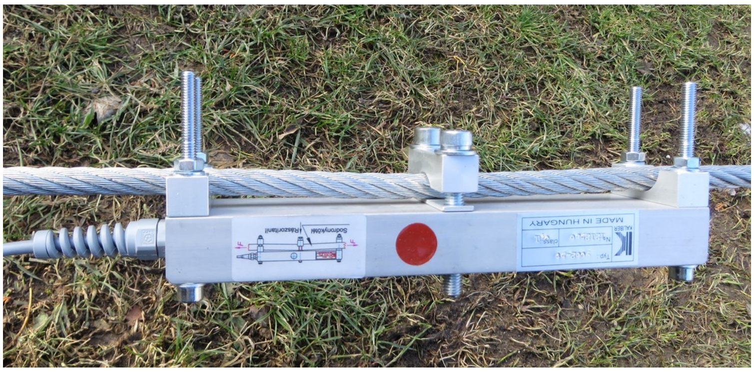
4.1. Components

Cable and winch

The system contains a 20-meter (65 feet) length of high capacity metal cable with a 1.6 metric ton (optionally 3.2 ton) manually operated winch. The winch has a ratchet mechanism that multiplies the force of the operator to exert sufficient tension on the cable. The cable and the winch are equipped with safety hooks and two soft belts for fitting it around the tree trunk and the anchor point.

Load cell

- calibrated cable-mounted load cell, 5T capacity
- external display unit by Rinstrum
- serial connection to central unit
- sampling rate: 1 Hz
- hex key, 6 mm
- 4 AA size rechargeable batteries + charger

Inclinometer

- Inclinometer sensor, ST-015
- Ratchet lashing
- Sensor mounting plate
- External battery unit with bluetooth signal source
- biaxial leveling device
- 9V rechargeable battery + charger
- Measurement range ± 2 degrees
- Resolution: 0.001 degree
- Temperature compensated
- Sampling rate: 10 Hz
- Mounted by a single screw
- Operating voltage and current: 12V, 20 mA
- Weather proof, IP65

Extensiometers

The system includes two LVDT extensiometers that are mountable on the tree trunk. Signal is sent to the central unit via a common interface box. Extensiometer parameters:

- LVDT extensiometers
- Dimensions: 30x30x270 mm (closed)
- Span: 250 mm

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- Sampling rate:
- Power source

Note: calibration constants are indicated in the supplied calibration sheet and are to be entered in the software upon the first time the device is used.

The FAKOPP Pulling test software

- PC software, runs under Windows7 or higher,
- Simultaneous load, inclination and extension measurements,
- Load-inclination and load-deformation curves generated
- Automatic Safety Factor calculation for uprooting and trunk safety
- Can handle one inclinometer and two extensiometers simultaneously
- Drag Factor and Elastic Limit entered manually
- Continuous software development
- Latest version is available to download from fakopp.com

4.2. Operation guide

Setting up the test

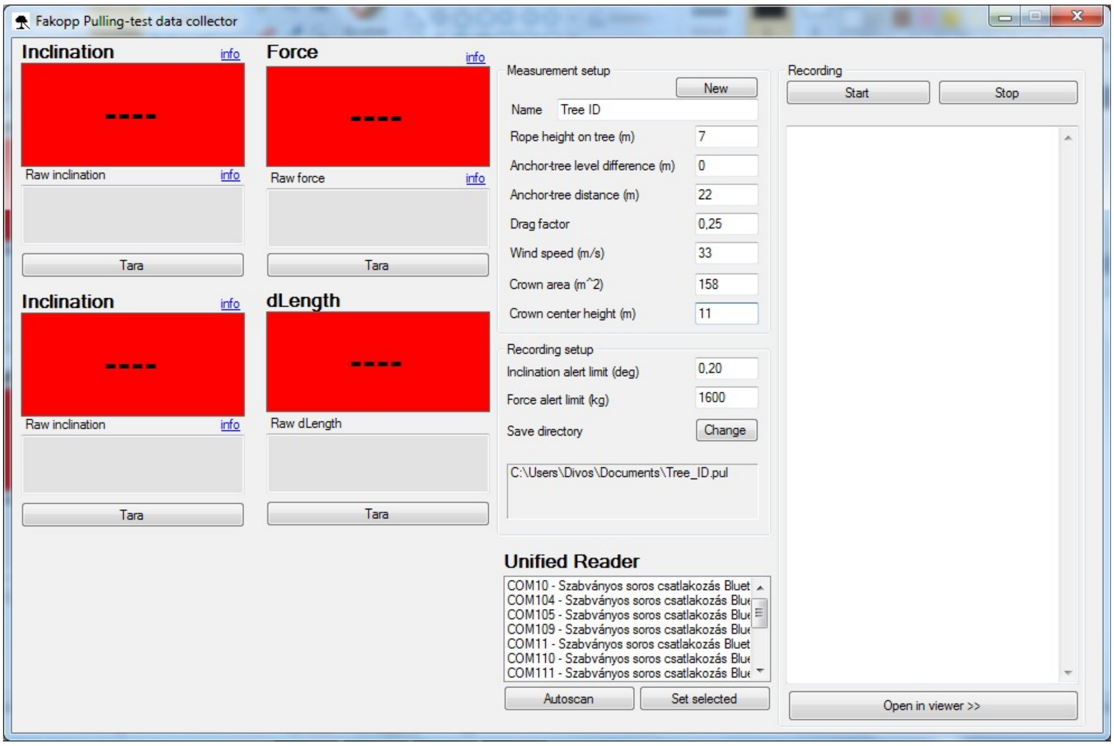
- Attach the cable to the trunk in the crown of the tree, as high as possible. In case you are above the top end of the trunk, attach it to a strong, centrally located branch. Use a soft belt, in order to avoid damaging the bark.
- Chose an anchor point in the appropriate direction, about 10 to 15 m from the tree.
- Set up the winch and ropes according to the guide. <u>Follow the safety instructions!</u>
- Install the load cell using the hex key. <u>Avoid over-tightening the bolts</u>! Select the optimal position, relatively low to the ground, but not too close to the winch.

Connect the load cell to the external display unit and the display unit to the central unit.

- Install the first inclinometer sensor mounting plate on the tree trunk, as close to the ground as possible, using the ratchet lashing. In case of decay in the tree trunk, the position of the inclinometer may affect the test result. We recommend that you avoid decayed areas when mounting the device.
- Attach the inclinometer sensor and level it using the biaxial leveling device.
- Attach the battery back and turn the inclinometer on. Connect the battery pack to the central unit.
- Optionally, repeat the process for the other inclinometer.
- Mount the first extensiometer on the tree trunk. Try to select the weakest region (based on visual inspection.) Screw in the top (2) and bottom (6) screws without releasing the securing jaws. Then loosen the thumb screw (4) and slide up the collar (3) to release the jaws (5) and thus allow the extensiometer to move freely.
- Optionally, repeat the process for the other extensiometer.
- Note: you may mount the extensiometers either on the tension or on the compression side of the trunk (i.e. the side closest to or farthest from the anchor point, respecticely), or even on alternate sides, but not in any other position around the trunk!
- Connect the extensiometer cables to the dual elastometer unit, and connect the unit to the central unit.
- Switch on the units, and press “Tara” on the load cell.
- Start the Fakopp Pulling Test software.

Test procedure

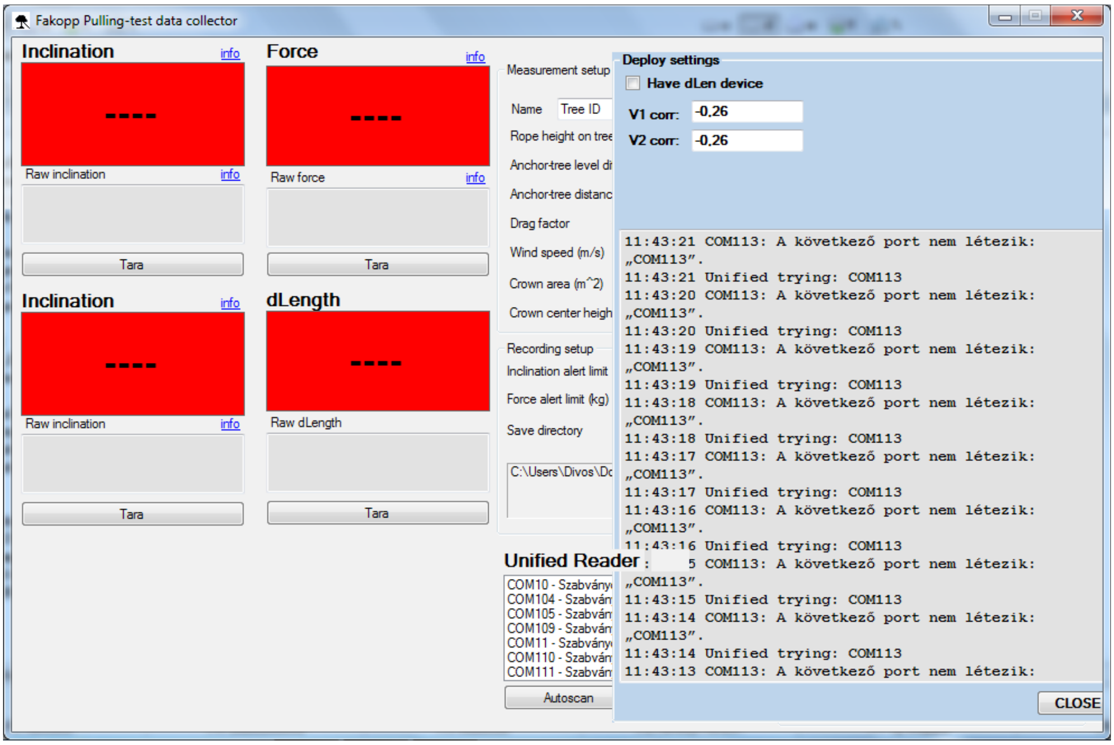
1. **Setting the COM port:** LED-ek villognak – program zöld! A kapcsoló pöcök pedig a külső tápláláshoz használatos, de az USB táp elegendő. Once connected, your computer assigns a communication (COM) port to the Pulling test central unit. There is a way for the software to automatically identify this COM port, but it may take a long time if you had connected many different devices to your computer in the past. If this is the case, you might want to identify the COM port manually before starting the program. This can be done either in Device Manager (where you need to choose 'Ports').
2. **Setting up the software:** start the program PullingCollect.exe. This will pull up the setup window:



First, you need to find the communication port for the central unit. This can be done automatically by clicking the Autoscan button. The central unit needs to be connected to the computer for this to work. The Autoscan process may take a long time if it has to scan through many ports, i.e. if there had been many devices connected to it in the past. In this case, it may be a good idea to locate the ports manually from Device Manager then choose the appropriate port form the list, and click 'Set selected'. Once the central unit has been found and readings are being received, the red LEDs near the communication ports starts blinking (rapidly), the red readout areas in the software turn green, and you can see the values. You can tare each value by hitting the Tara button.

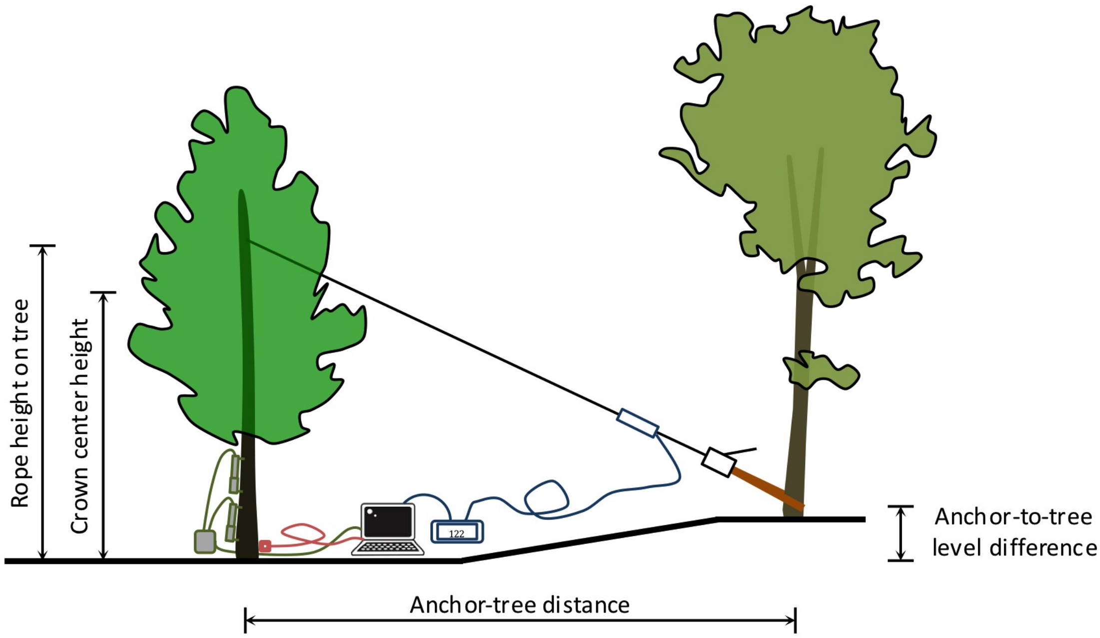
If you are connecting the extensiometer for the first time, or after repairs or recalibration, you need to enter the calibration constant for both extensiometers. There is a hidden button in your setup window, right below the 'Open in viewer »' button. Click this area to access the settings:

Enter the calibration constant for extensiometer #1 and #2 (V1 corr and V2 corr, respectively.) The constants are indicated in the calibration sheet. Make sure that you do not mix up the two extensiometers, and to use the correct sign (positive for compression and negative for tension)! If you don't use the appropriate sign,



one or both dLen graphs may result in negative deformation readings. Should that happen, return to the settings window and correct the sign of the constant(s), and restart your measurement. The program remembers the calibration constant, so you don't need to re-enter it for each measurement, except when using a new extensiometer or after repairs and recalibration.

Finally, you need to enter the test parameters. This includes the following geometric parameters:



(The geometric parameters are needed for the program to calculate the angle of the pulling cable, in order to calculate the horizontal component of the pulling force and the torque. The crown center height is needed for the wind load calculation.)

Test parameters also include the aerodynamic drag factor and the elastic limit. These are characteristic to the given tree species. Drag factor and Elastic limit values are listed in the table at the end of this page for many species. (NOTE: the elastic limit is given in %, but is to be entered as ‰, i.e. you need to multiply the elastic limit value in the table by 10.) The wind speed for which the SF is to be calculated, and the estimated crown area (m^2) should also be entered here. Finally, you can choose the name of your file, and change the folder where files are saved. Test parameters may also be entered or changed in the viewer window later.

Please note: when entering values, use decimal point. The decimal comma does not work in the program.

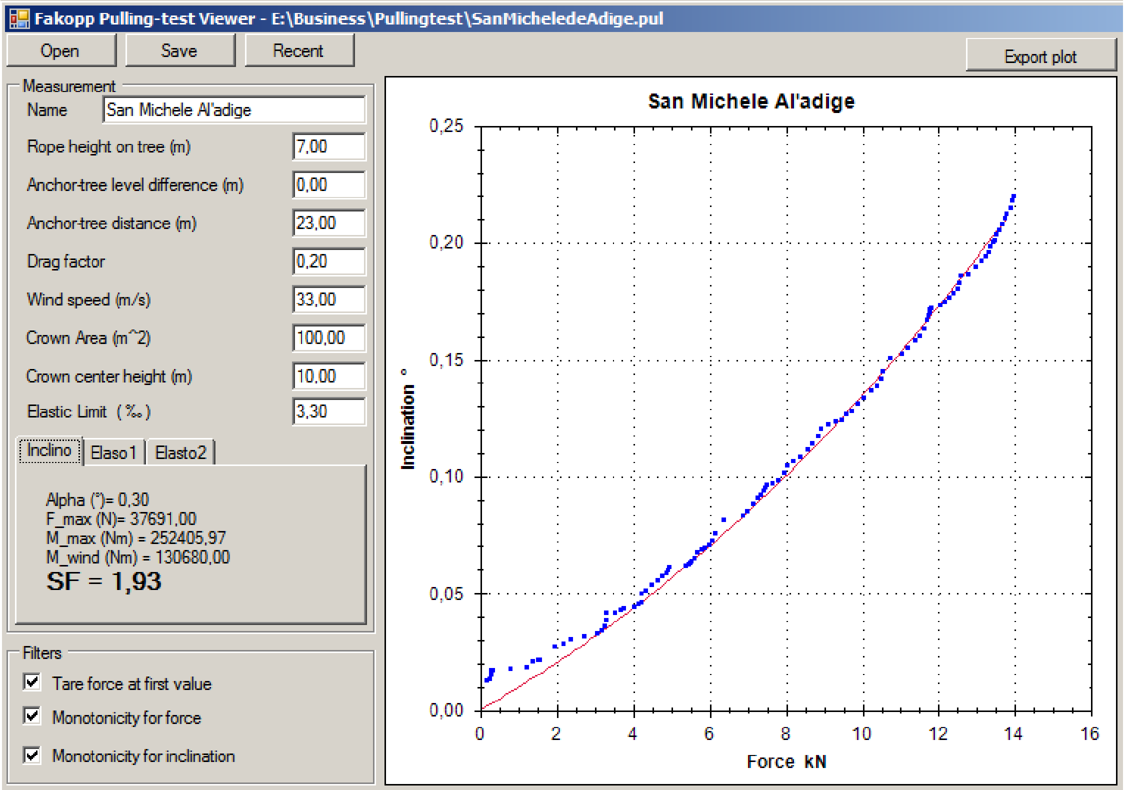
3. Testing

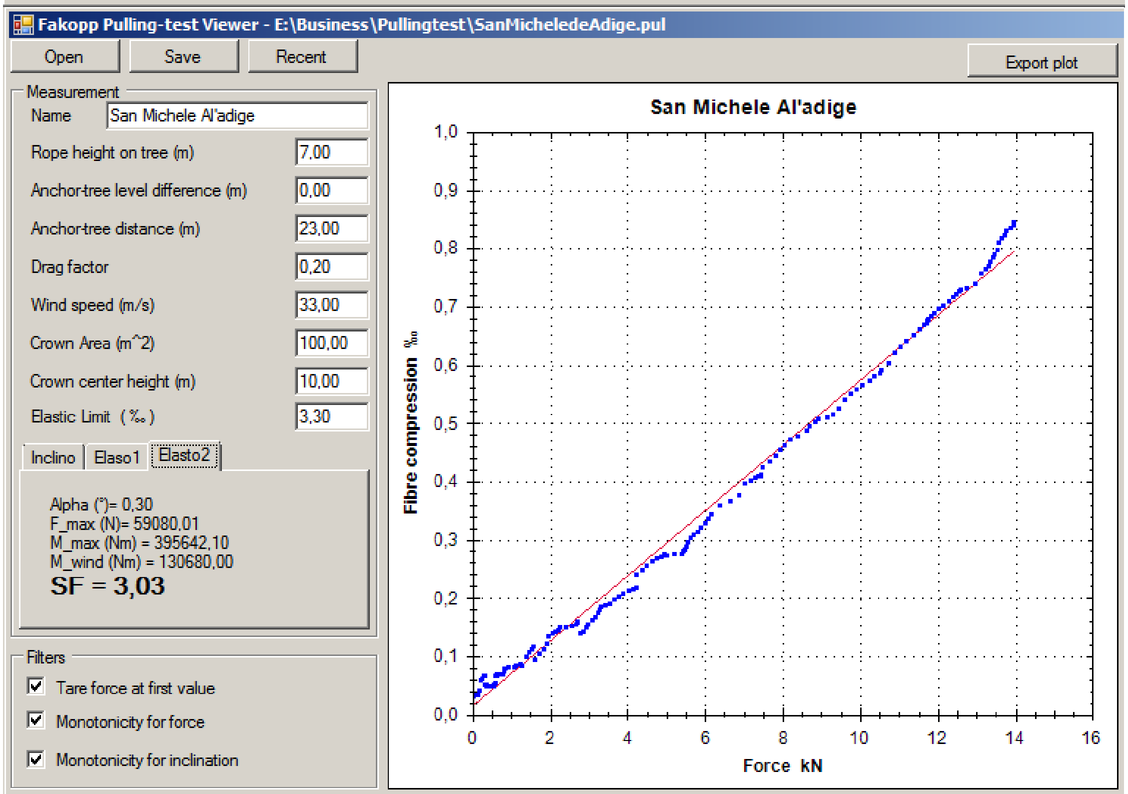
Once everything is set up, you may start your test. First, switch the software to viewer by clicking the 'Open in viewer »' button. Now you may start the measurement. It is a good idea to first apply a moderate load and check the deformation ('Elasto1', 'Elasto2') graphs in case the calibration constant was entered incorrectly. In case of negative fibre compression values, stop the measurement, and go back to the settings window, and change the sign of the calibration constant.

Load the cable slowly and evenly using the winch. Load continuously until reaching 0.2 degrees of inclination or winch capacity, whichever comes first. You can set up the maximum inclination and load capacity in the setup window. Once you reach either of these values, the program will warn you by beeping. Observing these limits will almost certainly ensure that there is no danger of trunk damage either. In case of a severely decayed trunk, you should also monitor the fibre compression so that it does not approach the elastic limit. (Note: the software does not warn you for excessive deformation, you should monitor this yourself!)

Make sure that you observe the safety guidelines throughout the test!

The viewer allows you to watch the load-inclination and load-deformation curves in real time as the test proceeds:





You can toggle between the inclinometer and the two extensiometer curves using the tabs underneath the test parameters. The program automatically fits the appropriate tangential function and straight trendlines on the inclination and deformation data, respectively. It also calculates the statistical parameters and the Safety Factor based on each measurement.

Upon completion of the test, click safe to terminate data collection. Your data will be saved in a format that allows viewing in the viewer window later.

4. **After the test is complete**, turn off the sensors, release the winch, and remove the sensors and ropes. Make sure that you observe the safety guidelines!

4.3. Data evaluation

After the test is complete, you can immediately establish whether the tree is safe, based on the calculated Safety Factor. If SF is above 1.5, the tree is safe, while a SF below 1 signals high risk. In-between these two values, there is a moderate risk. Separate SF values are calculated for uprooting (inclination) and for each of the extensiometers. (Extension-based SF-values signal the safety of the section of the trunk where each extensiometer was mounted.) Remember that the SF is specific to the wind velocity entered; a tree declared safe at a certain wind velocity may be unsafe at higher winds!

Note: pulling test data points typically fit the curve / trendline very well. In case of a poor fit, the results and the calculated SF should not be trusted. This may typically occur if there are high winds at the time of testing. Reject your results and repeat the test when winds are lower.

A saved measurement may be opened in the viewer window for later reference or further evaluation. Use the Open or Recent buttons to open and view earlier test results. After opening a measurement file (or after the conclusion of the test), you can also export the results in comma-delimited (CVS) format, for opening it in a spreadsheet program (e.g. MS Excel).

4.4. Safety guidelines

Significant loads of up to 3.2t may be applied during the pulling test. Pulling test may be dangerous if proper protocol is not observed. Rope failure can cause serious injury, so follow the safety instructions:

1. The leader of the pulling test team is responsible for the safe execution of the test.
2. Only trained personnel is allowed to perform the pulling test
3. The pulling device, including belts, cable and winch must be intact. Inspect the equipment before the test for any damages.
4. All devices must be protected from high moisture, frost and extended periods of sunlight exposure.
5. The work area should be closed off from the public. Unauthorized persons must not be allowed to pass under or climb over the cable.
6. Pulling test team members need to stay at least 2m from the cable, except for the winch operator.
7. Above 1 kN of load, the winch operator should use the long arm, and stand as far as possible from the cable.
8. Check your escape route from the test site to a safe place. In case of any unexpected event like tree breakage or cable failure, immediately run for cover.
9. Stop the pulling test after reaching 0.2 degree of inclination.
10. Follow all of the safety instructions listed in the winch's operation manual.
11. Pulling test must not be performed in rain, or in freezing temperatures.

IMPORTANT NOTICE: the pulling apparatus, including the ropes, cable and winch are furnished by a third party vendor. **Fakopp Enterprise Bt. is not responsible for any**

damage or injury related to the pulling test procedure!

Table 1. Stuttgart table of wood strength (Wessolly and Erb 1998).

Species	Modulus of elasticity (N/mm²)	Comparable strength in longitude (N/mm²)	Elastic limit (%)	Proposed Aerodynamic drag factor (c_w)
Abies alba	9500	15	0.16	0.20
Acer pseudoplatanus	8500	25	0.29	0.25
Acer negundo	5600	20	0.36	0.25
Acer campestre	6000	25.5	0.43	0.25
Acer saccharinum	6000	20	0.33	0.25
Acer saccharum	5450	20	0.37	0.25
Aesculus hippocastanum	5250	14	0.26	0.35
Ailanthus altissima	6400	16	0.25	0.15
Betula pendula	7050	22	0.31	0.12
Chamaecyparis lawsonia	7350	20	0.27	0.20
Cedrus deodora	7650	15	0.20	0.20
Fagus sylvatica	8500	22.5	0.26	0.25–0.30
Alnus glutinosa	8000	20	0.25	0.25
Fraxinus excelsior	6250	26	0.42	0.20
Picea abies	9000	21	0.23	0.20
Picea omorika	9000	16	0.18	0.20
Carpinus betulus	8800	16	0.18	0.25
Castanea sativa	6000	25	0.42	0.25
Cercis siliquastrum	0	15	—	0.20
Larix decidua	5035	17	0.32	0.15
Liriodendron tulipifera	5000	17	0.34	0.25
Pinus pinaster	8500	18	0.21	0.20
Pinus sylvestris	5800	17	0.29	0.15
Platanus × hybrid	6250	27	0.43	0.25
Populus × canescens	6050	20	0.33	0.2–0.25
Populus nigra 'Italica'	6800	16	0.24	0.30
Populus nigra	6520	20	0.31	0.2
Populus alba	6400	20	0.31	0.2
Pseudotsuga menziesii	1000	20	0.20	0.20
Pyrus communis	5800	17	0.29	0.30
Quercus robur	6900	28	0.41	0.25
Quercus rubra	7200	20	0.28	0.25
Robinia pseudoacacia	7050	20	0.28	0.15
Robinia monophyla	5200	20	0.38	0.15–0.20
Salix alba	7750	16	0.21	0.20
Salix alba 'Tristis'	7000	16	0.23	0.20
Sequoiadendron gigantum	4550	18	0.40	0.20
Sophora japonica	6450	20	0.31	0.15
Sorbus aria	6000	16	0.27	0.25
Tilia x *hollandica*	4500	17	0.38	0.25
Tilia euchlora	7000	17.5	0.25	0.25
Tilia tomentosa	8350	20	0.24	0.25–0.30
Tilia platyphyllos	8000	20	0.25	0.25
Tilia cordata	8300	20	0.24	0.25
Ulmus glabra	5700	20	0.35	0.25

(Source: Wessolly, L., and M. Erb 1998. Handbuch der Baumstatik und Baumkontrolle. Patzer Verlag, Berlin, Germany.)