

Project: Partnership for the development of training standards for tree assessors in Central and Eastern Europe
PROJECT NUMBER – 2019-1-PL01-KA202-065670



TREE ASSESSOR

Instrumental tree assessment

Advanced tree assessment –
manual for professionals

TREE ASSESSOR

Advanced tree assessment
– manual for professionals
Instrumental tree assessment

INFORMATION ABOUT THE PROJECT:

Project name and number:

Partnership for the development of training standards for tree assessors in
Central and Eastern Europe. 2019-1-PL01-KA202-065670

Project implementation time:

1.09.2019 – 31.12.2021

Leader of the Project:

Dobre Kadry Centrum badawczo-szkoleniowe Sp. z o.o. (Wrocław, Polska)

Partners of the Project:

Instytut Drzewa sp. z o.o. (PL, replaced Firma Ekorozwoju sp. z o.o.),
Latvian Arboriculture Society (LV),
FAKOPP Enterprise Bt. (HU).

The publication was created as a result of a project implemented with the financial support of the European Commission under the Erasmus + programme. This publication reflects the views only of the authors. The European Commission's support for the production of this publication does not constitute an endorsement of the contents, which reflect the views only of the authors, and the Commission cannot be held responsible for any use which may be made of the information contained therein.

Editor: Ágnes Kinga Buza

Principal authors: Ferenc Divós, Ágnes Kinga Buza, László Bejő, Jaroslav Kolařík

Contributing authors and consultations: Beata Pachnowska, Jerzy Stolarczyk, Piotr Tyszko-Chmielowiec, Kamil Witkoś-Gnach, Anna Pszkit, Andris Spaile, Vilmos Szaller, Kritóf Németh, Gábor Ócsvári, István Markovits

Photos: Ágnes Kinga Buza, Ferenc Divós, László Bejő, Jaroslav Kolařík, photo archive Fakopp, photo archive EKO-TREK, and photos of various producers with permission – indicated right after the image

Design and layout: Marta Płonka

Dobre Kadry. Research and Training Centre Ltd.

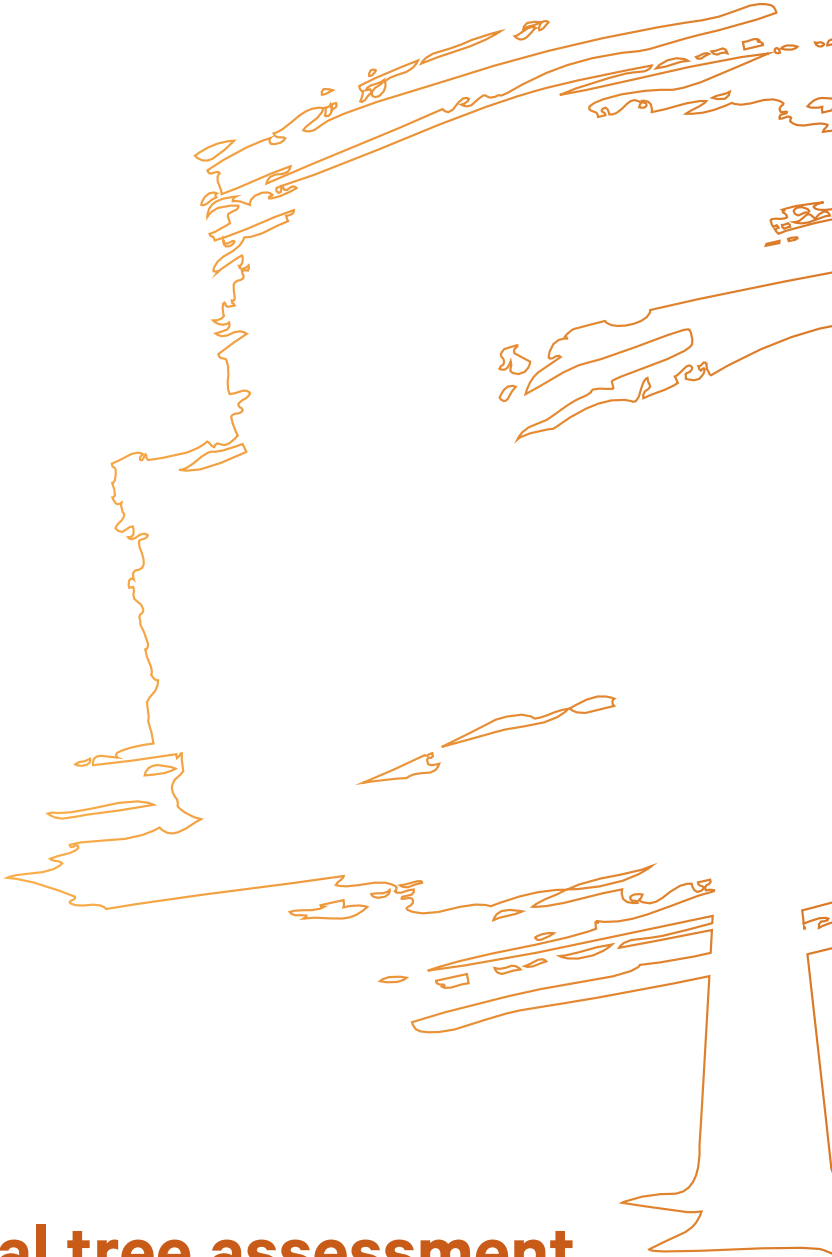
Jęczyńska Street 10/1, 53-507 Wrocław

Phone: +48 71 343 77 73, +48 71 343 77 74, fax: +48 71 343 77 72



Creative Commons License

© Copyright Dobre Kadry. Research and Training Centre Ltd. / FAKOPP ENTERPRISE
Wrocław 2021



TREE ASSESSOR

Instrumental tree assessment

Advanced tree assessment –
manual for professionals

This project has been founded with support from the European Commission under the Erasmus+ Programme Strategic partnerships in the field of education and vocational training



Table of contents

INTRODUCTION	8
I. TREE BIOMECHANICS – ADVANCED	10
1. Basic concepts	11
a. Safety factor	11
b. Drag factor (drag coefficient or aerodynamic drag factor)	12
c. The weight of a tree	13
2. Data and physical quantities used for the calculations	14
a. Tree data including the ones collected during measurements and tests	14
b. Basic physics data used for the calculations – data for wind	15
c. Wind loads by EUROCODE and terrain categories	15
3. Wind load	15
a. The second moment of inertia	16
4. Self load – weight and bending	17

5. Measured data and conclusions	18
a. Data from tomography	18
b. Data from static pulling tests	18
c. Data from dynamic “pulling” test	21
d. Tree or green wood properties from tables	22
6. Other stresses – shear and growth	22
7. Calculations / equations for the Safety Factors	24
Physical terms	30
Equations	31
II. INSTRUMENTAL ASSESSMENT: DECAY	32
1. Increment borer and fractometer	33
2. Resistance drilling	33
3. Acoustic and ultrasound signals in wood and one-line acoustic measurements	35
4. Acoustic tomographies	37
5. Electric impedance / resistivity tomography	43
6. Calipers	45
7. Other decay detection devices	46
INSTRUMENTAL ASSESSMENT: DECAY – CASE STUDIES	47
1. Acoustic tomography via 7 years	47
2. Examination of giant trees (circumference above 350 cm)	48
3. Huge, decayed trees (circumference over 400 cm)	50
4. Tomograms just below a fork	51
5. Partially frozen trunk	52
6. Why not use your pen to make sound signals?	54
7. Examination of a wound reaction	56
8. Safety of a tree in a parking lot	56
9. Impedance and acoustic tomographies	57
10. Transport activity measurement – an experimental use of impedance tomography	59
INSTRUMENTAL ASSESSMENT – LIMITATIONS OF DECAY DETECTION	60
INSTRUMENTAL ASSESSMENT – THE ADVANTAGES OF USAGE	60
III. INSTRUMENTAL ASSESSMENT: STABILITY	62
1. Tree stability in general	62
2. The pulling test	63
a. Equipment	63
b. Testing procedure	68
c. Evaluation of the results	75
d. Advantages and limitations of the pulling test	78
3. The Dynamic test	79
a. Equipment	82
b. Testing procedure	85
c. Evaluation of the results	86

d.	Factors influencing the reliability of dynamic testing	87
e.	Advantages and limitations of the dynamic test	89
f.	The reliability of the dynamic test	90
4.	Factors influencing tree stability testing	92
a.	Foliage	92
b.	Precipitation	93
c.	Frozen ground	94
d.	Seasonal changes	94
d.	Measurement direction	94
VI.	ROOT DETECTION METHODS – INSTRUMENTAL,	
	NON-DESTRUCTIVE POSSIBILITIES	96
1.	Ground probe	96
2.	Acoustic methods	97
3.	Ground penetration radar	100
4.	Electrical Resistivity Tomography	103
5.	Case studies	105
5.1.	Root mapping compared to excavation	105
5.2.	Root mapping linked to stability?	106
V.	REMOTE INSTRUMENTAL TREE ASSESSMENT	109
	Introduction	109
	Positional analysis	110
	Picture analysis	112
	Spectral analysis	112
	Neural networks and artificial intelligence	113
	LiDAR	113
	Drones	114
VI.	DENDROCHRONOLOGY	117
1.	History and principles	117
2.	Overlapping and master chronology	118
3.	Sampling and usage	119
	REFERENCES	122



Introduction

Tomography and pulling test are the most well-known advanced instrumental techniques in tree assessment. They are used for decades all around the world from Japan to Spain, from Columbia to Germany, from the UK to Australia and of course, well-spread in Poland and Hungary as well.

Before starting the following informative chapters, let me make you remember that these instruments are tools. They are useful for their purpose.

A few years ago, I had a very strange pain in my tooth. So, I went to the dentist, who sent me to a panoramic dental X-ray. He did not send me to blood test, he did not send me to PET-CT, however these are very useful diagnostic tools.

He could select the right tool and my problem was found. My doctor worked as a dentist for over four decades, but it was the second time he saw something like my case. So, he had sent me to a specialist. And I had a happy end :)

Acoustic measurements, dynamic measurements,... are great tools, but you have to be able to choose the proper one. One of them can not solve all the situations, different cases need different approach and examination.

Keep it in your mind, and do not hesitate to ask for help or consultation. Get your tree to its happy end.



*Agnes Kinga Bekefi-Buza, PhD
Editor*



I.

Tree biomechanics – advanced

Tree biomechanics is a really wide field of science, researched by many people from many aspects, like modelling trees in wind, trees reaction to bending forces, researching the formation and/or density and other conditions of wood materials and so on.

Some experts simplify the topic to “trees and wind” highlighting one main element of it. It is true that understanding and predicting the behavior (the safety) of a tree during a storm or gale is one of the most important practical topics, as we should strive to minimize the risk of injury or damage resulting from tree failure. Trees cannot walk away, they grow where they germinated (unless they are transplanted), and they have to adapt to the conditions. They can respond to the challenges by growing, by building the proper structure and they can also bend or let the branches move while staying at the same place. move in their place.

The basic knowledge which is useful in practice is included in the chapter “Foundations of Tree Biology, Ecology and Biomechanics”, while the tools used for measuring in the field are presented in the chapters “Instrumental assessment: tree stability” and “Instrumental assessment: decay”. Here we focus on physical principles, definitions and calculations.

Even if the topic sounds to be a little dry, the focus is still on practical usage. If we understand the background, the principles, we can use our tools better, catch if there is something gone wrong and explain or summarize these topics better to non-professionals.

In this chapter the main question will be if the tree is safe. How can we answer this question? Safety factors and load calculations (wind, self-load, bending,...) will be presented as well as the models used for calculations and the physical concepts. The principles of static and dynamic pulling tests will be included as well with the interpretation of the data. A whole subchapter will guide the reader through the usability of dynamic wind loads as it is a new and growing area.

A quick review of the equations and quantities (if you need just a short recall of the topic) can be found at the end of the chapter.



1. BASIC CONCEPTS

Tree biomechanics has been studied for decades, the names of the German scientists Wessolly, Erb and Mattheck are relatively well-known, they are also authors of exhaustive and well-illustrated books in this topic. (Wessolly and Erb: Tree Static and Tree Inspection, 2016; Mattheck: Aktualisierte Feldanleitung für Baumkontrollen mit Visual Tree Assessment, 2007)

The basic concept of static can be presented with the “static triangle” based on the work of Wessolly. This shows that the tree has two ways to stand loads, the material of the tree can have the proper conditions, of the shape of the tree can be load-bearing. (See Figure 1.1.)

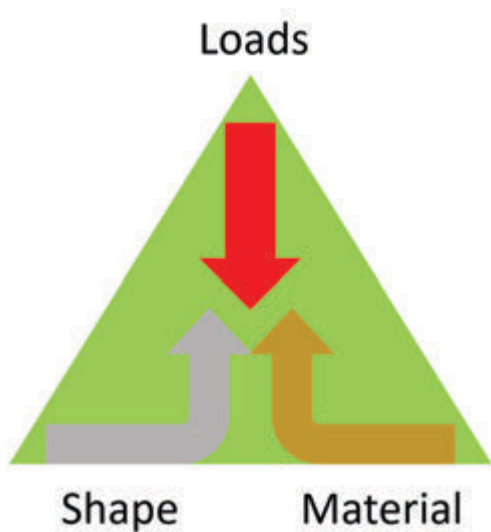


Figure 1.1.

The “static triangle” (based on Wessolly and Erb, 2016), source: own work

To quantify if the tree shape and material can hold more or not than the estimated load, Safety Factor is introduced. To help in understanding the concepts detailed in later subchapters, the drag factor and the weight of the tree are also described in this chapter.

A. SAFETY FACTOR

It is a number or percentage showing the ratio between load bearing capability and the loads (e.g.: 3.12 or 312 %). The equation for it is very simple (however calculating the capacity or the loads can become highly demanding).

$$SF = (\text{load bearing capacity}) / (\text{loads})$$

Please note that Safety factors (SF) can be higher than 1 or 100%. It should be more than 100% for a healthy and safe tree. This is not a chance or a probability. It is just the ratio. 100% or 150% still does not mean that it is sure that the tree will not fail during the next heavy storm. A tree used to be considered safe if the safety factor is above 150% or even above 200%. It is because there are simplifications during the calculations. It is possible to model a whole tree with all of the branches and leaves, but this kind of modelling is not part of daily practice and even with the perfect model, wood properties should be estimated.

Safety factor has no measurement unit (like meters or kg) because it is a ratio. Which also means that the two divided quantities should be from the same kind (e.g. it is not possible to make a ratio of force and moment).

Safety factors can refer to a trunk layer or to the root system. As they are based on data collected during a measurement (e.g. pulling test, tomography) they can only refer to the measured parts. There is no “safety factor for a whole tree”, there are safety factors for the root system considering uprooting and there are ones for layers of the trunk considering trunk failure. If – for any reason – a general safety factor should be given, the lowest value must be chosen. The arborist is responsible to choose the most critical part, layer of the tree, based on the visual evaluation, and execute the proper measurement.

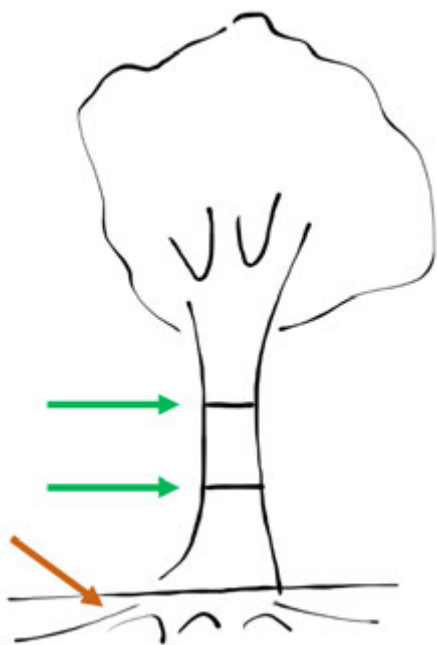


Figure 1.2.

Safety Factor can refer to the measured layers of the trunk (green arrows) or to the root system (brown arrow)

Till recent days there is no something like “branch safety factor”. Tree branches can move with high amplitudes during storms and even if there is no problem, decay in their woods, they may fall to decrease the load on the tree. When windy conditions are analyzed, wind speed is the main factor in the load calculation. Please note that the value of the safety factor belongs to a specific wind speed, and it decreases when the wind speed increases. Setting the maximal expected wind speed correctly – considering the conditions of the area – is critical. (For example, during one measurement we obtained a safety factor 3.1 for 120 km/h wind gust while it was only 1.7 for 160 km/h winds for the same tree.) Interpretation of safety factors: under 1 or 100% there is a severe risk of failure as the calculated load bearing capacity is smaller than the

calculated load; there is a “grey zone” if the safety factor is between 1 and 1.5 (or 2), 100% and 150% (or 200%), usually it means that something should be done (like reducing the crown area and/or the height of the crown); while if the safety is above 1.5 (or 2), 150% (or 200%) the tree is considered to be safe.

Interestingly, for a healthy tree the safety factor of the root system and the safety factors of the trunk layers (considering 120 km/h winds) are usually quite close, and usually a little more than 300%. Healthy trees strengthen both main parts.

B. DRAG FACTOR (DRAG COEFFICIENT OR AERODYNAMIC DRAG FACTOR)

Drag coefficient can be used in different approaches, one if there is a flow (like wind) and there is a fixed object which bears the force made by the flow. The other situation is that when the object moves in a fluid or air.

Of course, an object can move in a flow or wind as well, but as the focus is on tree safety, we will assume that the tree stands in its position and moves only as a reaction to wind gusts.

wind direction

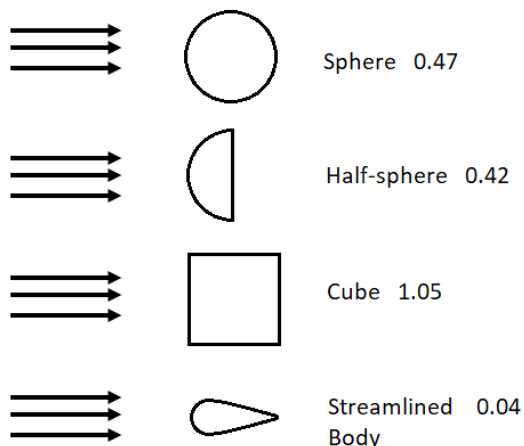


Figure 1.3.

Some examples of drag coefficients

From this point of view, the drag factor or coefficient shows how big is the effect of the flow on this object, as it disturbs the flow. Figure 1.3. shows some examples to illustrate the practical meaning of it. (Shape is not the only factor effecting drag factor, it also depends on the velocity, on the fluid or air conditions, the surface, the direction,...)

The term drag factor will be used instead of drag coefficient in the following text, as it was used by Wessolly and became known among arborist. Drag factors for trees were measured by Wessolly and Erb and published in 1998 as part of the "Stuttgart table of wood strength". This table includes the proposed aerodynamic drag factors for 45 tree species. According to this research the measured drag factors were between 0.12 and 0.30 while for most of the trees it varied in a smaller range (0.2-0.25).

Usually these values are used as initial points for safety calculations. Drag factor is a multiplier during wind load estimations.

weight above a certain level (the mass of the root system will not be included anyways).

As trees differ so much in shape according to their living conditions, it would be quite challenging to measure the weight of the trunk, branches and leaves for all the individual trees. Hence, a simplified model will be used. This model in most of the cases overestimates the weight by 5-15%. (Regarding safety, the overestimations of loads and the underestimations of capabilities is prudent.

The model of a tree is a wooden rod which has the same density and height as the modelled tree. The diameter of the rod is constant, this is the DBH (Diameter at breast height, the diameter measured at 1.3 m above ground) of the tree.

$$m_{\text{tree}} = \rho_{\text{tree}} H D_{1.3}^2 \pi / 4$$

m_{tree} – the weight of the tree

ρ_{tree} – density (kg/m³) of green wood
(living tree material)

H – height of the tree (m)

$D_{1.3}$ – DBH (m)

C. THE WEIGHT OF A TREE

The tree has to be able to bear its own weight, in this approach we will speak about the tree's

Remark: usually the load from wind is about 10-20 times bigger than the load from the weight, the errors coming from overestimating the weight of the tree used to be less than 1%.



2. DATA AND PHYSICAL QUANTITIES USED FOR THE CALCULATIONS

A. TREE DATA INCLUDING THE ONES COLLECTED DURING MEASUREMENTS AND TESTS

For safety evaluations and calculations, diverse sets of data need to be collected, depending on the focus (trunk or root system failure) and the interpretation of the assessment (tomography, static or dynamic pulling tests).

Let us have a look at the necessary inputs for calculating safety regarding trunk failure, based on tomography. In this case, height of the tree, diameter, crown surface and crown center, the height(s) of the tomography measurement, the degree and the direction of leaning (if the tree does not stand straight) are the ones. Density of living tree's wood and other properties like drag factor or the velocity of sound waves in the wood and yield strength depend on the species. As measuring these data in the field would take long time and special instruments should be involved, it is a simpler, but in this case critical, to recognize the proper species. Pulling test can be used for both root and trunk safety estimations. In both cases, the height of the rope on the examined tree, the angle of the rope (the distance of the anchor point can be used instead of the angle), crown surface and crown center should be recorded. Of course, the force used during the measurement and the inclination of the trunk basement / root collar and/or the elongation of the trunk is needed. If only safety regarding uprooting is interesting for us, no other measured data is needed, while if safety for trunk failure should be determined, the tree species will be necessary as the elastic limit is used during the calculations.

Crown surface and crown center can be estimated (by a person or table for estimating the shape and measuring the heights) or measured

from a photograph. In this case, the area should be marked. The photo can be taken without foliage, but the area should be the actual area of the whole crown including all the small branches and leaves.



Figure 1.4.
Crown area marked correctly

Dynamic measurements have a great advantage – they use actual wind. In this case, as the tree itself is measured during real wind gusts, the calculations can predict a risky wind speed, or can estimate if the tree will survive a certain wind or not. The calculation needs only the wind speeds and corresponding inclinations of the root collar if safety for uprooting should be determined. There is no need for the height or the crown surface or even for the species, because the tree itself is measured without

any assumptions. If safety against trunk failure is the question, the elongations of the trunk and the species (for the elastic limit) are the needed data.

Please note that different software may require different data (and have some assumptions). If the question arises if the trunk can split, the shear strength data is used for the calculation along with the geometry, density of wood and wind load.

B. BASIC PHYSICS DATA USED FOR THE CALCULATIONS – DATA FOR WIND

The safety evaluations contain data for wind load as well. Usually, a wind speed is required for the calculation. It can be in km/h or in m/s (or in miles/hour). 120 km/h (33.33 m/s) is used as a default value.

Temperature can be a significant parameter, as it affects the density of the air.

C. WIND LOADS BY EUROCODE AND TERRAIN CATEGORIES

Wind loads calculated according to EUROCODE are beyond the scope of this book. The standard EUROCODE EN 1991 divides the objects to 1 to 6 areas (depending on their height and the so-called terrain categories), calculates the wind load for all of them, and summarizes the loads at the end.

The wind speed differs depending on height, but it uses “base velocities” (they are included in the standard), velocities at other heights can be calculated from them. This information is available from a map with the area of the European Union presenting the base velocities. It is about 20-30 m/s in Poland, about 30-32 m/s in Latvia and about 26 m/s in Hungary depending on the region.

The terrain categories of the standard refer to the average height, the average wind load reduction of the surroundings. The categories are seashore (no lee at all, the wind reaches the object with its full energy), lakeside (very little reduction), agricultural (when other trees and plants can be around), village-like (where not very tall other close objects, houses can shelter the examined tree, at least partially) and city (where even high buildings are nearby).

Calculation constants of wind load changes if the terrain category is changed, the total load decreases from seashore to city.

Some software (like ArborSonic 5.3.118 and above) include calculations based on the EN 1991 standard.

Be aware that the wind load calculations presented in the following chapter usually lead to higher loads if the tree height is under 26 m compared to the EN 1991 and calculates less load if the tree is higher.

3. WIND LOAD

A simplified approximate calculation of wind loads is used for tree since the '80s (Jones, 1983) where the following equation (well-known in hydrodynamics) describes the force of the wind:

$$F_{\text{wind}} = 0.5 \rho_{\text{air}} c_{\text{tree specie}} A_{\text{tree}} v_{\text{wind}}^2$$

ρ_{air} – density of the air (depends on temperature, but it used to be assumed as 1.2 kg/m³)

$c_{\text{tree specie}}$ – the drag factor of the tree, specific for species

A_{tree} – the surface of the tree (m²) exposed to wind

v_{wind} – velocity of wind (m/s)

Please keep in mind that air density depends on geographical and the topographical situation and the seasonal and meteorological influences as well.

How can we use the force generated by the wind for safety calculations?

Various measurements will use it differently. Static pulling test requires the moment of wind, while for tomography the compression stress should be calculated (using the moment) while for evaluations based on dynamic measurements pressure will be used.

The moment of wind is:

$$M_{\text{wind}} = F_{\text{wind}} h_{\text{cc}}$$

h_{cc} – the height of the crown center (m)

The compression stress caused by wind gust at the base of the trunk is:

$$\sigma_{\text{wind}} = M_{\text{wind}} (z/I)$$

z – the distance from the neutral axis (this is the axis where there is no stress or strain during the bending) (m)

I – the second moment of inertia of the cross section (m^4) (detailed in the upcoming subchapter)

As tomography is usually measured in different heights and not only at the ground level,

we have to step back a little to the definition of moment (force times height) and use it to reach other levels as well:

$$\sigma_{\text{wind}} = F_{\text{wind}} (h_{\text{cc}} - h_{\text{layer}}) (z/I)$$

h_{layer} – the height of the layer of interest (m)

The wind pressure used for dynamic measurements' evaluation:

$$p_{\text{wind}} = F_{\text{wind}} / (c_{\text{tree spec}} A_{\text{tree}}) = 0.5 \rho_{\text{air}} v_{\text{wind}}^2$$

A. THE SECOND MOMENT OF INERTIA

The second moment of inertia or second moment of area describes how a 2-dimensional shape, area resists to bending or deflection. It is calculated by the following formula:

$$I_m = \iint_{x y} x^2 dx dy$$

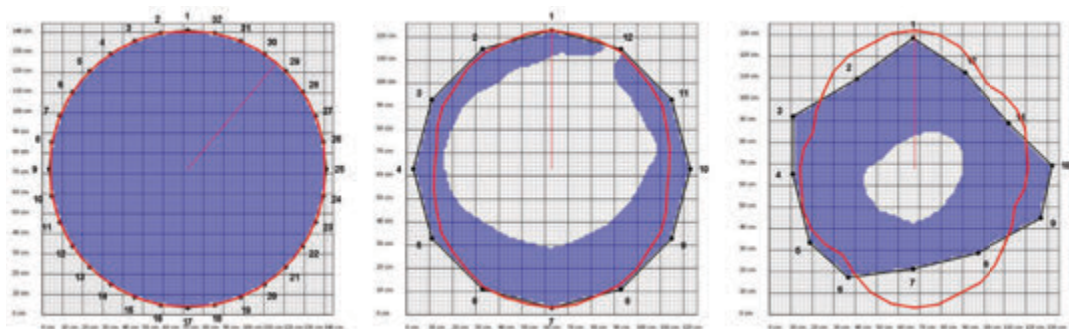


Figure 1.5.

The blue area represents the healthy wood in a cross section of the trunk, the distance of the red silhouette from the middle is proportional to the load, while the red radius shows the weakest direction

The calculations of safety can be done by simplifying the case (like supposing that the trunk is circular, in this case the second moment of inertia is $(\pi d^4) / 64$, where d refers to the diameter) or with the help of a software.

Using a software not only speeds up the calculation but it lets us see the load in different directions (second moment of inertia depends on the direction!). Examples of the effect of direction including healthy, circle-like trunk, decayed one and one irregular shaped are shown in Figure 1.5.

4. SELF LOAD – WEIGHT AND BENDING

The weight of the tree causes load, stress in its own, as the tree has to hold it, but on the other hand, if the tree is not straight but the trunk has an inclination, it causes an extra stress. Both of them are important for safety, as inclination of the trunk can modify loads and safety regarding the direction.

The stress from self load, the weight of the tree if there is no decay in a specific height:

$$\sigma_{\text{selfload}} = m_{\text{tree}} g / A_{\text{cross}}$$

here we can recall $m_{\text{tree}} = \rho_{\text{tree}} H D_{1.3}^2 \pi / 4$
make it more general using the area instead of the area of a circle and get

$$m_{\text{tree}} = A_{\text{cross}} H \rho_{\text{tree}}$$

H is the height of the tree, but we may be interested in a layer, which is not the ground layer, but above it. This will reduce the height (as the mass under the layer should not be held by that cross section)

substituting this the equation we get:

$$\sigma_{\text{selfload}} = (A_{\text{cross}} (H - h_{\text{layer}}) \rho_{\text{tree}} g) / A_{\text{cross}}$$

simplifying the equation by A_{cross} :

$$\sigma_{\text{selfload}} = (H - h_{\text{layer}}) \rho_{\text{tree}} g$$

H – height of the tree (m)

h_{layer} – height of the examined layer

ρ_{tree} – the green wood density of the tree (kg/m³)

g – standard gravitational acceleration of Earth (9.81 m/s²)

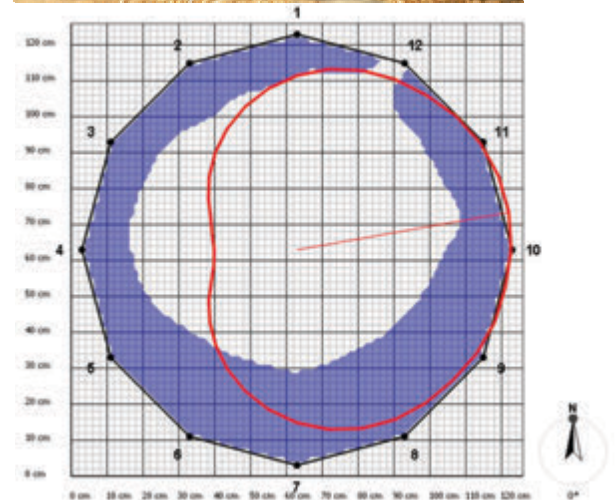


Figure 1.6.

The plane tree's trunk is leaning towards East, which makes wind from West the most risky

If there is a decay in the cross section, the stress should be multiplied by the ratio of the total cross section and the area of load bearing wood material (this is the area marked with blue on Figure 1.5. and 1.6.).

$$\sigma_{\text{selfload_decayed}} = [(H - h_{\text{layer}}) \rho_{\text{tree}} g] (A_{\text{cross}} / A_{\text{wood}})$$

A_{cross} – the area of the whole cross section (m²)

A_{wood} – the area of the load bearing part of the cross section (m²)

The stress caused by the leaning, the bending of the tree is

$$\sigma_{\text{bending}} = (m_{\text{tree}} g h_{\text{cc}} \sin \alpha) (z/I)$$

m_{tree} – mass of a tree (kg)

h_{cc} – the height of the crown center (m)

α – the angle of the trunk of the tree to the vertical

z – the distance from the neutral axis (this is the axis where there is no stress or strain during the bending) (m)

I – the second moment of inertia of the cross section (m⁴)

The stresses caused by the loads (wind, self-weight and lean) sum up and produce the stress which should be hold by a cross section of the trunk. The safety factor for the trunk will be presented in 5)b) and 7) subchapters.

5. MEASURED DATA AND CONCLUSIONS

In this part the data collected during measuring a tree with a proper, non-destructive instrument will be presented as well as the data which were measured during destructive methods and can be found in the proper tables. Both of them will be used to evaluate the safety.



A DATA FROM TOMOGRAPHY

In tomography, time and distance is measured, velocities are calculated from them and a 2D map of a layer is evaluated (for details please check chapter “Instrumental assessment: decay”). This so-called tomogram can show approximate extent of intact, healthy wood material, damaged, decayed ones, or hollows.

The value, which is a result of tomography and used for safety evaluations is the A_{wood} , the area of the load bearing part of the cross section, or $A_{\text{cross}}/A_{\text{wood}}$ if the area of the cross section is not trivial (and calculated by the program based on measuring the distances of the sensors).

(Of course, the software can contain many data from the location of the tree to the crown area, and safety calculations can be included.)

B. DATA FROM STATIC PULLING TESTS

During a pulling test, distance of the anchorage and height of the cable should be measured, while the measurement itself provide data on the applied force, inclinations and/or elongations.

The question here is to predict the force or the moment which could uproot the tree or lead to trunk failure. (The implementation of the test is detailed in the chapter “Instrumental assessment: stability”.)

Let us investigate the data for uprooting first. If a graph is made from the collected inclination-force data, a tangential function can be fitted to dots. (The data may need filtering according to the pull of the wincher as the tree is pulled and pulled again, and/or because of the relaxation of the tree after a pull.)

The tipping moment will be used for calculating the safety factor.

Elongation data can also be collected during pulling. The measured data are very small distances (micrometers). But what is interesting for us is the relative elongation (ϵ).

$$\epsilon = \Delta l / l$$

Δl – the change in the length (μm)

l – the original length of the elastometer

$$\varphi_{\text{calc}} = 0.333 \tan(1.35F/F_{\text{tip}}) + 0.333 (F/F_{\text{tip}})^2 - 0.1 (F/F_{\text{tip}})$$

φ_{calc} – the fitted inclination

F – is the measured force (N)

F_{tip} – the evaluated tipping force (N)

Using F_{tip} and the proper geometrical data, the uprooting moment can be calculated:

$$M_{\text{tip}} = F_{\text{tip}} L / \cos \alpha$$

L – the cable's (rope's) height on the examined tree (m)

α – the cable's angle (calculated from the proper distances)

The relative elongation-force graph shows linear correlation, which is basically true till the limit of elasticity. According to experiments the trunk breaks if the relative elongation is over the elastic limit (around 0.26% or 2.6%, species specific data is included in the Stuttgart table from Wessolly).

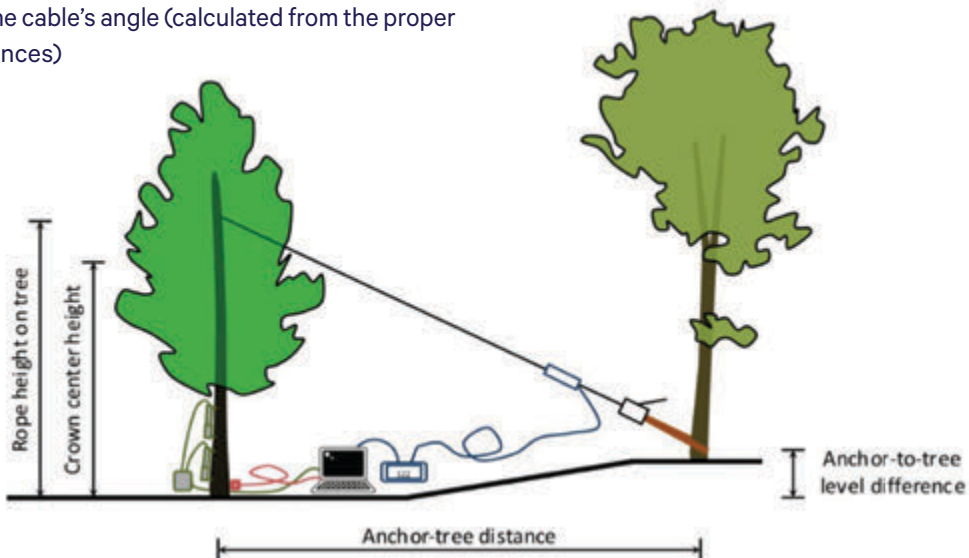


Figure 1.7.

The distances needed for the evaluation of safety from pulling test

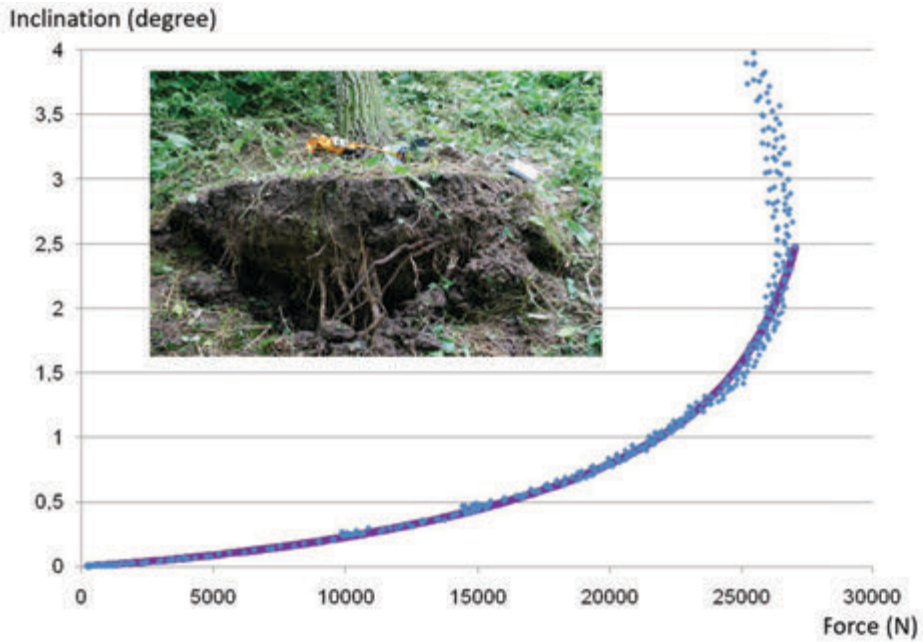


Figure 1.8.

Inclination and force data collected during uprooting (blue dots) and the tangent curve fitted to the data (purple line). Keep in mind that during a non-destructive pulling test the inclination does not go over 0.25 degrees.

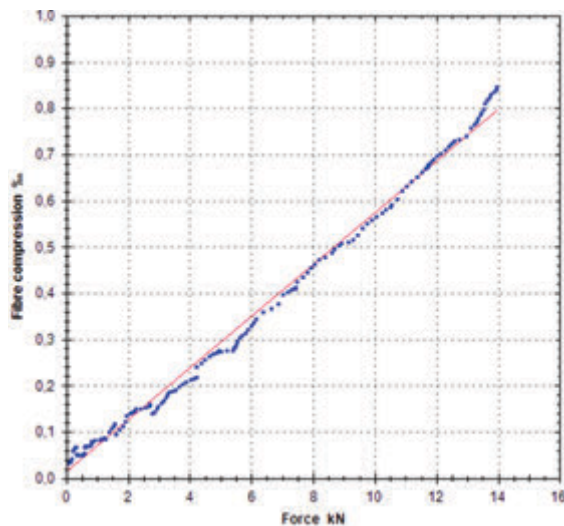


Figure 1.9.

Force and relative elongation (fiber compression, in %), measured during a pulling test (blue dots). The linearity of the trendline (red line) is observable.

The force value of the breakage can be read from the fitted curve and a moment can be calculated similarly to the case of uprooting, using the height of the rope and the angle.

This is M_{breaking} , the moment at which the trunk breaks.

C DATA FROM DYNAMIC “PULLING” TEST

The main idea of dynamic measurements is to use the wind, the real wind gusts as the load. By doing so, calculations become simpler, as the real situation is measured, including the surroundings drag factor, or the crown surface. During a dynamic investigation, wind speed and inclinations of the root collar and/or elongation(s) of the trunk are measured, these are just the same as during static pulling test.

The wind pressure is calculated from the measured wind velocity,

$$p_{\text{wind}} = 0.5 \rho_{\text{air}} v_{\text{wind}}^2$$

Pressure behaves similarly to pulling force during pulling, a similar tangent function can be fitted to the inclination-pressure dots and there is a linear correlation between the relative elongation (presented in the previous subchapter) and the wind pressure.

These lead us to p^{crit} the pressure estimated, with the tangent function, which could uproot the tree and to p_{breaking} the pressure which could break the trunk according to the measured elongations.

It is important to know and understand that the trees are flexible systems. As the wind blows, the tree sways, but also absorbs and keep some energy. When there is “too much” energy in the tree, it “explodes”. The tree releases the energy with a bigger sway. This phenomenon can be observed analyzing the data from dynamic measurement.

On the other hand, this phenomenon shows that there is no means to assign, to connect, to link the wind speed data measured at a specific moment to the inclination or elongation data measured at the same moment. The tree can still be in the absorbing period or it can release the energy while the wind is relatively low.

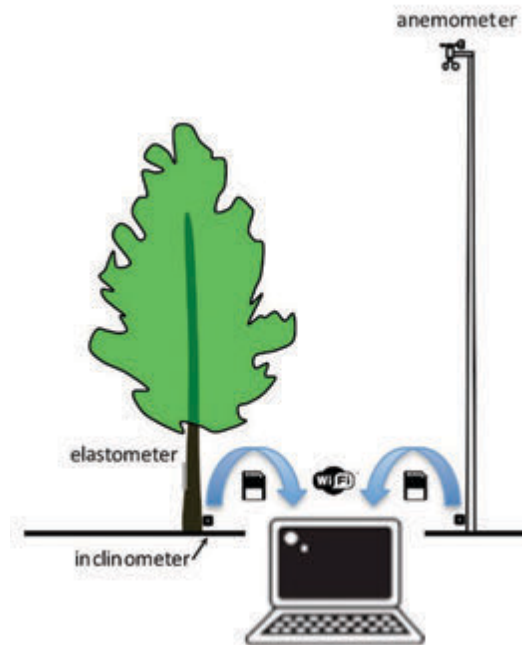


Figure 1.10.
A dynamic setup

According to the research made in this topic, the best is to check 10 minutes time windows and compare the wind and inclination / elongation data. Using the proper (statistical) math data pairs can be generated, and the proper function (tangent for inclination and linear for relative elongation) can be fitted.

(In practice, shorter time windows like 5 minutes, or even shorter can be used as well. As calculations need a minimal number of data pairs, if the window is shorter, the measurement should go on shorter as well. Using a 5 minutes data window, the shorted measuring period is about

1 hour. Measuring longer provides more data and better evaluation, measurements longer than 2 days are also possible.)

If someone would interpret a dynamic measurement, the anemometer used for the measurement should be able to detect even the wind gusts lasting for 1 s. So, the sampling rate should be at least 1 data/s, or 1 Hz.

The best position for the anemometer is at 10 m height, close to the tree, exposed to the wind. However, research shows that even if the anemometer is 5 km far, there can be a good fit for data. Wind data from meteorological sites may be useful during the evaluation. (In these cases, longer time window, like 20 minutes can be required for evaluation, which also increases the duration of the measurement.)

The minimum required velocity of wind gusts is 25 km/h. (As the tangent function is so flat at the beginning, if there are data pairs just around zero, the uncertainty of the fitting is relatively high.)

(The technique presented in this chapter is the dynamic measurement system developed by Fakopp. There are other products on the market, but, as long as we know, they require much higher wind speeds and much longer measurement time.)

D. TREE OR GREEN WOOD PROPERTIES FROM TABLES

Safety calculations need some wood properties which were determined during destructive tests and can be found in tables.

These are the drag factor, sound velocity in wood (and its dependence on direction), elastic limit, these were already presented, and compressive strength σ_{cst} (N/m²).

Compressive strength is the capability to withstand loads which can change the size of the material. This strength “holds” the weight of the tree and part of the wind load.

Note that yield strength can be also used during the calculation. Yield strength is the limit, under which no permanent deformation occurs. (It is similar to elastic limit, but it is not relative, the unit of it is N/m² or N/mm², not only a percent. Yield strength is called comparable strength in longitude in the Stuttgart table from Wessolly and Erb.)



6. OTHER STRESSES – SHEAR AND GROWTH

Shear stress in general is the stress from shear forces, which refers to the changes in shapes if we investigate smaller part of the material.

The failure caused by shear stresses on trees is when the trunk or other part splits longitudinally. In these cases, the load bearing capacity reduces significantly, these situations can be very dangerous.

$$\tau_{\text{shear}} = (F_{\text{shear}} S) / (I b)$$

F_{shear} – the shear force (N)

S – the first moment of area (m³)

I – the second moment of inertia of the cross section (m⁴)

b – width perpendicular to the shear (m)

S , I and b comes from the geometry (calculation of S is presented below).

Under the mass center of the tree:

$$F_{\text{shear}} = F_{\text{shear,wind}} + F_{\text{shear,selfload}}$$

$$F_{\text{shear,wind}} = F_{\text{wind}} \cos(\alpha)$$

α – the angle of the trunk of the tree to the vertical

$$F_{\text{shear,selfload}} = m_{\text{tree}} g \sin(\alpha)$$

m_{tree} – mass of a tree (kg)

g – standard gravitational acceleration of Earth (9.81 m/s²)

The first moment of area can be calculated by:

$$S = \int y_i dA$$

If we have a shape, an area, and an axis also, the first moment of area refers to the distance of the area, or its parts from the axis.

For circle $S = \frac{2}{3} R^3$.

Please note that the first moment of area should be calculated only – regarding the axis which is interesting for us – for the “upper” or “lower” (or one “sider”) part of the area.

The shear should be calculated for the axis at the middle of trunk as the highest stress occurs there.

(The shear stress has two indices, like τ_{RL} . The first index refers to the direction of the force while the second index shows the normal vector – which is perpendicular to the surface – of the area. With the presented equation τ_{RL} can be calculated, while the one causing splitting of trunk is τ_{LR} . However $\tau_{RL} = \tau_{LR}$ because of duality.) Shear stress can become critical in short trees with wide trunks, as it can be concluded from the work of Claus Mattheck.

Growth stress appears in trees as well, which makes the living tree a pre-stressed material.

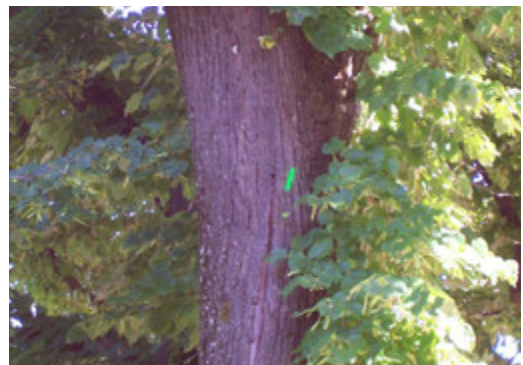


Figure 1.11.

In windy conditions the trunk becomes a little longer (because the tensile stress) on the side exposed to the wind while it becomes a little shorter (because the compression stress) on the leeward side. These two imaginary parts of the trunk wish to “slide” on each other. This stress causes the shear stress (orange line)

According to Brudi and his colleagues, this usually has a safety increasing effect, so usually the strength data measured on (dried) wood sample and used for safety calculations underestimates the safety, the moment or wind speed which can be survived by the tree.

7. CALCULATIONS / EQUATIONS FOR THE SAFETY FACTORS

Based on the previous chapters, the calculations of Safety Factors are clear. There are six separate cases, regarding tomography, pulling and dynamic tests, and splitting.

Safety Factor for trunk failure based on tomography (for the measured layer and only if the trunk is not split):

$$SF_{\text{trunk_tomogram}} = \sigma_{\text{cst}} / (\sigma_{\text{wind}} + \sigma_{\text{selfload}} + \sigma_{\text{bending}})$$

Safety Factor for root system failure based on pulling test:

$$SF_{\text{root_pulling}} = M_{\text{tip}} / M_{\text{wind}}$$

Safety Factor for trunk failure based on pulling test:

$$SF_{\text{trunk_pulling}} = M_{\text{breaking}} / M_{\text{wind}}$$

Safety Factor for root system failure based on dynamic test:

$$SF_{\text{root_dynamic}} = p_{\text{crit}} / p_{\text{wind}}$$

Safety Factor for trunk failure based on dynamic test:

$$SF_{\text{trunk_dynamic}} = p_{\text{breaking}} / p_{\text{wind}}$$

Safety Factor for trunk splitting (based on geometry):

$$SF_{\text{split}} = \sigma_{\text{shear}} / \tau_{\text{shear}}$$

(σ_{shear} is the shear strength of the examined species, from previous studies, tables or standard)



Table 1.1.

SPECIES	MOISTURE CONTENT	SHEAR PARALLEL TO GRAIN (KPA)
Alder, red	green 12%	5300 7400
Ash, black	green 12%	5900 10800
Ash, blue	green 12%	10600 14000
Ash, green	green 12%	8700 13200
Ash, oregon	green 12%	8200 12300
Ash, white	green 12%	9300 13200
Aspen, bigtooth	green 12%	5000 7400
Aspen, quaking	green 12%	4600 5900
Basswood, American	green 12%	4100 6800
Beech, American	green 12%	8900 13900
Birch, paper	green 12%	5800 8300
Birch, sweet	green 12%	8500 15400
Birch, yellow	green 12%	7700 13000
Butternut	green 12%	5200 8100
Cherry, black	green 12%	7800 11700
Chestnut, American	green 12%	5500 7400
Cottonwood, balsam poplar	green 12%	3400 5400
Cottonwood, black	green 12%	4200 7200
Cottonwood, eastern	green 12%	4700 6400
Elm, American	green 12%	6900 10400
Elm, rock	green 12%	8800 13200
Elm, slippery	green 12%	7700 11200
Hackberry	green 12%	7400 11000
Hickory, pecan	green 12%	10200 14300

SPECIES	MOISTURE CONTENT	SHEAR PARALLEL TO GRAIN (KPA)
Hickory, true, mockernut	green 12%	8800 12000
Hickory, true, pignut	green 12%	9400 14800
Hickory, true, shagbark	green 12%	10500 16800
Hickory, true, shellbark	green 12%	8200 14500
Honeylocust	green 12%	11400 15500
Locust, black	green 12%	12100 17100
Magnolia, cucumber tree	green 12%	6800 9200
Magnolia, southern	green 12%	7200 10500
Maple, bigleaf	green 12%	7700 11900
Maple, black	green 12%	7800 12500
Maple, red	green 12%	7900 12800
Maple, silver	green 12%	7200 10200
Maple, sugar	green 12%	10100 16100
Oak, red – black	green 12%	8400 13200
Oak, red – cherrybark	green 12%	9100 13800
Oak, red – laurel	green 12%	8100 12600
Oak, red – northern red	green 12%	8300 12300
Oak, red – pin	green 12%	8900 14300
Oak, red – scarlet	green 12%	9700 13000
Oak, red – southern red	green 12%	6400 9600
Oak, red – water	green 12%	8500 13900
Oak, white – bur	green 12%	9300 12500
Oak, white – chestnut	green 12%	8300 10300
Oak, white – live	green 12%	15200 18300

SPECIES	MOISTURE CONTENT	SHEAR PARALLEL TO GRAIN (KPA)
Oak, white – overcup	green 12%	9100 13800
Oak, white – post	green 12%	8800 12700
Oak, white – swamp chestnut	green 12%	8700 13700
Oak, white – swamp white	green 12%	9000 13800
Oak, white – white	green 12%	8600 13800
Sassafrass	green 12%	6600 8500
Sweetgum	green 12%	6800 11000
Sycamore, American	green 12%	6900 10100
Tupelo, black	green 12%	7600 9200
Tupelo, water	green 12%	8200 11000
Walnut, black	green 12%	8400 9400
Willow, black	green 12%	4700 8600

Table 1.1.

Some hardwood species' shear strengths based on Wood handbook—Wood as an engineering material

(<https://www.fpl.fs.fed.us/documnts/fplgtr/fplgtr113/ch04.pdf>)

Mechanical Properties of Wood David W. Green, Jerrold E. Winandy, and David E. Kretschmann, From Forest Products Laboratory. 1999. Wood handbook—Wood as an engineering material. Gen. Tech. Rep. FPL–GTR–113. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 463 p.

Table 1.2.

SPECIES	MODULUS OF ELASTICITY (N/MM2)	COMPARABLE STRENGTH IN LONGITUDE (N/MM2)	ELASTIC LIMIT (%)	PROPOSED AERODYNAMIC DRAG FACTOR (CW)
Abies alba	9500	15	0,16	0,2
Acer campestre	6000	25,5	0,43	0,25
Acer negundo	5600	20	0,36	0,25
Acer pseudoplatanus	8500	25	0,29	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
Alnus glutinosa	8000	20	0,25	0,25
Betula pendula	7050	22	0,31	0,12
Carpinus betulus	8800	16	0,18	0,2
Castanea sativa	6000	25	0,42	0,25
Cedrus deodora	7650	15	0,2	0,2
Cercis siliquastrum	0	15	-	0,2
Chamaecyparis lawsonia	7350	20	0,27	0,2
Fagus sylvatica	8500	22,5	0,26	0,25-0,30
Fraxinus excelsior	6250	26	0,42	0,2
Larix decidua	5035	17	0,32	0,15
Liriodendron tulipifera	5000	17	0,34	0,25
Picea abies	9000	21	0,23	0,2
Picea omorika	9000	16	0,18	0,2
Pinus pinaster	8500	18	0,21	0,2
Pinus sylvestris	5800	17	0,29	0,15
Platanus x hybrid	6250	27	0,43	0,25
Populus alba	6400	20	0,31	0,2
Populus nigra	6520	20	0,31	0,2
Populus nigra 'Italica'	6800	16	0,24	0,3
Populus x canescens	6050	20	0,33	0,2-0,25
Pseudotsuga menziesii	1000	20	0,2	0,2
Pyrus communis	5800	17	0,29	0,3
Quercus robur	6900	28	0,41	0,25
Quercus rubra	7200	20	0,28	0,25
Robinia monophyla	5200	20	0,38	0,15-0,2
Robinia pseudoacacia	7050	20	0,28	0,15
Salix alba	7750	16	0,21	0,2
Salix alba 'Tristis'	7000	16	0,23	0,2
Sequoiadendron giganteum	4550	18	0,4	0,2

SPECIES	MODULUS OF ELASTICITY (N/MM2)	COMPARABLE STRENGTH IN LONGITUDE (N/MM2)	ELASTIC LIMIT (%)	PROPOSED AERODYNAMIC DRAG FACTOR (CW)
Sophora japonica	6450	20	0,31	0,15
Sorbus aria	6000	16	0,27	0,25
Tilia cordata	8300	20	0,24	0,25
Tilia euchlora	7000	17,5	0,25	0,25
Tilia platyphyllos	8000	20	0,25	0,25
Tilia tomentosa	8350	20	0,24	0,25-0,30
Tilia x hollandica	4500	17	0,38	0,25
Ulmus glabra	5700	20	0,35	0,25

Table 1.2.

Wood strengths based on Wessolly and Erb

Handbuch der Baumstatik und Baumkontrolle. Patzer Verlag, Berlin, Germany, 1998.



PHYSICAL TERMS

SF – safety factor (no dimension)

m_{tree} – mass of a tree (kg)

ρ_{tree} – density (kg/m³) of green wood (living tree material)

H – height of the tree (m)

$D_{1.3}$ – DBH (m)

F_{wind} – force caused by wind (N)

ρ_{air} – density of the air (depends on temperature, but it used to be assumed as 1.2 kg/m³)

$C_{\text{tree specie}}$ – the drag factor of the tree, specific for species (no dimension)

A_{tree} – the surface of the tree (m²) exposed to wind

v_{wind} – velocity of wind (m/s)

M_{wind} – moment of wind (Nm)

h_{cc} – the height of the crown center (m)

σ_{wind} – compression stress caused by wind gust (N/m²)

z – the distance from the neutral axis (this is the axis where there is no stress or strain during the bending) (m)

I – the second moment of inertia of the cross section (m⁴)

h_{layer} – the height of the layer of interest (m)

p_{wind} – pressure caused by wind (N/m²)

g – standard gravitational acceleration of Earth (9.81 m/s²)

A_{cross} – the area of the whole cross section (m²)

A_{wood} – the area of the load bearing part of the cross section (m²)

α – the angle of the trunk of the tree to the vertical

φ_{calc} – the fitted inclination

F – is the measured force (N)

F_{tip} – the evaluated tipping force (N)

L – the cable's height on the examined tree (m)

α – the cable's angle (calculated from the proper distances)

Δl – the change in the length (μm)

l – the original length of the elastometer (μm)

σ_{cst} – compressing strength (N/m²)

M_{breaking} – the moment at which the trunk breaks.

p_{crit} – the pressure, which could uproot the tree

p_{breaking} – the pressure which could break the trunk

F_{shear} – the shear force (N)

S – the first moment of area (m³)

b – width perpendicular to the shear (m)

σ_{shear} – the shear strength

EQUATIONS

SF = (load bearing capability) / (loads)

$$m_{tree} = \rho_{tree} H D_{1.3}^2 \pi / 4$$

$$F_{wind} = 0.5 \rho_{air} c_{tree\ species} A_{tree} v_{wind}^2$$

$$M_{wind} = F_{wind} h_{cc}$$

$$\sigma_{wind} = M_{wind} (z/l)$$

$$\sigma_{wind} = F_{wind} (h_{cc} - h_{layer}) (z/l)$$

$$p_{wind} = F_{wind} / (c_{tree\ species} A_{tree}) = 0.5 \rho_{air} v_{wind}^2$$

$$I_{circle} = (\pi d^4) / 64$$

$$\sigma_{selfload} = m_{tree} g / A_{cross}$$

$$m_{tree} = A_{cross} (H - h_{layer}) \rho_{tree}$$

$$\sigma_{selfload} = (A_{cross} (H - h_{layer}) \rho_{tree} g) / A_{cross}$$

$$\sigma_{selfload_decayed} = [(H - h_{layer}) \rho_{tree} g] (A_{cross} / A_{wood})$$

$$\sigma_{bending} = (m_{tree} g h_{cc} \sin \alpha) (z/l)$$

$$\phi_{calc} = 0.33 \tan(F/F_{tip}) + 0.5 (F/F_{tip})^2 - 0.1 (F/F_{tip})$$

$$M_{tip} = F_{tip} L / \cos \alpha$$

$$\epsilon = \Delta l / l$$

$$p_{wind} = 0.5 \rho_{air} v_{wind}^2$$

$$\tau_{shear} = (F_{shear} S) / (I b)$$

$$F_{shear} = F_{shear,wind} + F_{shear,selfload}$$

$$F_{shear,wind} = F_{wind} \cos(\alpha)$$

$$F_{shear,selfload} = m_{tree} g \sin(\alpha)$$

$$S = \int y_i dA \text{ (the first moment of area)}$$

$$S_{circle} = \frac{2}{3} R^3$$

$$S_{Ftrunk_tomogram} = \sigma_{cst} / (\sigma_{wind} + \sigma_{selfload} + \sigma_{bending})$$

Safety Factor for trunk failure based on tomography (for the measured layer and only if the trunk is not split)

$$S_{Froot_pulling} = M_{tip} / M_{wind}$$

Safety Factor for root system failure based on pulling test

$$S_{Ftrunk_pulling} = M_{breaking} / M_{wind}$$

Safety Factor for trunk failure based on pulling test

$$S_{Froot_dynamic} = p_{crit} / p_{wind}$$

Safety Factor for root system failure based on dynamic test

$$SF_{trunk_dynamic} = p_{breaking} / p_{wind}$$

Safety Factor for trunk failure based on dynamic test

$$S_{Fsplit} = \sigma_{shear} / \tau_{shear}$$

Safety Factor for trunk splitting (based on geometry)



II.

Instrumental assessment: decay

Decays are important signs of tree health. Sometimes decays are visible as they grow from a wound or reach the bark from the inside, but there are decays and hollows only inside the tree as well. Decay detection starts with the visual assessment, as there are signals (e.g. fruiting bodies of fungi) referring to decays and the sound of the diagnostic, rubber mallet may change if the decayed area is significant. Locating the decay and estimating the affected area is possible in different levels, using non-destructive or little destructive tools and instruments.

This chapter presents increment borer and fractometer as simple tools, one-line acoustic measurements to find significant decays, resistivity drill which also give information on one line at a time, and tomographies bringing detailed tomograms of the examined layer.

The usage of calipers will be summarized as well. The link between decayed areas and safety or safety factors will be presented also.

Case studies focusing on acoustic tomography are also included as this technique is about to become part of daily usage.



Please always remember that all these techniques do not give information about the whole tree, only about the measured height, layer. Visual assessment is the basic and should help to decide if usage of any instruments is necessary or not. If it is necessary, the examined heights, parts should be selected based on the visual evaluation.

1. INCREMENT BORER AND FRACTOMETER

Increment borer is wood sampling tool, it is a drill with a hole and a tray inside, which makes us able to collect a wood sample from the trunk. This sample can be examined, even visual information can be very useful, affected, destroyed wood may be seen, if the tree is decayed.



Figure 2.1.
Sampling with increment borer



Figure 2.2.
A (healthy) wooden sample in the groove,
in the channel of the increment borer

Sampling with an increment borer usually takes a few minutes but sometime greater physical effort is needed. The friction causes heat, as getting the sample, both the increment borer and the sample can be very hot as well.

This technique can not be categorized to the non-destructive testing methods, usually a hole with 10-15 mm diameter and considerable depth is the result of the sampling. The hole must be treated properly to keep the tree healthy.

The advantage of the increment borer is the sample itself, on which detailed analysis can be performed. (Increment borer samples can help us to estimate the latest years' growth as well.) Fractometer is a handy tool which is designed to evaluate the increment borer's sample even on the field. The fractometer bends and breaks the sample and gives information about its strengths. Strengths depend on species (usually a table comes with the device with values of different species), on direction of bending (if the bending is in fiber direction, or perpendicular to it) and the state (healthy or decayed) of the wood.

2. RESISTANCE DRILLING

Resistivity drilling is a special, thin (few mm-s) but usually quite long drill which can go inside the tree and measure the resistance against the drilling itself. The little changes in this resistance, that how hard or easy it is to go ahead for the drill, can refer to the changes in wood quality. Decays can be found by this technique but also the growth-rings can be seen on the resistogram (Figure 2.3). or can be digitally visualized and saved, depending on the used instrument. The technique can find or verify the presence of a decay, or a ring shake.

Resistograms can be printed on a piece of paper. During the drilling, the wood (and the drill) becomes very hot. This may sterilize the wood, but the treatment of the hole is essential.

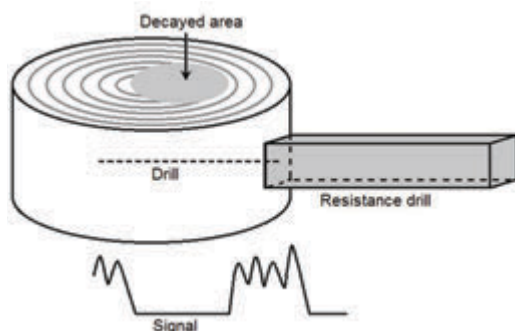


Figure 2.3.

Schematic image of resistance drilling.

As the drill penetrates to the wood the changes in the material give a specific signal. Growth rings and decays appear on the resistogram.

One measurement takes about 5 minutes, but usually several drillings are needed for each examined layer, height, as one drilling gives information only about one line.

This technique is recommended after one-line acoustic measurements and tomographies, as it works best as control. And – according to the research of Lin and his colleagues – the resistivity drilling may break existing compartmentalization zones within the tree and let fungi reach the healthy parts (Lin et al. 2013).

Usually the drill itself is heavy, holding straight perpendicular to the surface of the bark needs effort.

If a huge decay is found inside the tree, the drill can bend inside the decay. It is recommended to stop drilling after a longer part showing the “empty”, hollowed signal.



Figure 2.4.

Resistance drill during a presentation, after drilling through the log (only a part of the resistogram is visible on the screen, but the result can be scrolled and evaluated)

3. ACOUSTIC AND ULTRASOUND SIGNALS IN WOOD AND ONE-LINE ACOUSTIC MEASUREMENTS

Sound propagates well in wood materials as it can be heard listening to different musical instruments. As the atoms, molecules vibrate they make the surrounding ones move as well, this is how the signal, the sound wave propagates. The particles in the wood material are bound together so it is relatively easy to make the neighbors vibrate.

The sound wave is less fast in air or in less quality wood. This condition can be used to have information from the quality of the wood in a non-destructive way.

The sound signal goes “fast” (cc. 2000 m/s perpendicular to fiber) in the healthy wood (the exact value depends on the specie as well), while it goes “slow” (cc. 340 m/s) in air. As the difference is so high, even if the sound signal has to get around a decay in the healthy wood, it will arrive first to the other side comparing to the signal going through the decayed area. This phenomenon is illustrated in Figure 2.5. In the other hand if you compare a decayed and a healthy case, of course, the sound wave in the intact wood will be the fastest.

The simplest case is called 1D or TOF (time-of-flight) measurement as there is only a signal producer (or start) sensor and a receiver one (or stop).

Be aware of that acoustic methods use the fastest signal, which is the one going through the wood towards the detector in case of healthy material and which is the “getting around” signal if the wood is decayed. If the wood is decayed, we got no information from the decay.

There are also materials in which ones sound can travel as fast as in healthy wood, or faster. For example, if there is ice or concrete in a decayed or hollowed area, the signal can go through directly and the tree can be categorized as a

healthy one. To avoid this kind of mistakes, it is not recommended to implement acoustic measurement if the inside of the examined can be frozen. (Even if the actual air temperature is above 0 Celsius, be aware of the latest day’s weather as well and consider if the tree could freeze or not.)

The propagation time depends not only on if the tree is healthy or not. It – of course – also depends on the distance between the sensors. To make the values comparable the velocity is calculated from the time and distance data and used for analysis.

Velocity data were measured in laboratories and on field and can be found in tables for many species. Or a reference velocity can be attained by measurements on the healthy part of the same tree being investigated.

The sound velocity depends on the specie, on the health issue of the examined tree and on the direction.

One-line measurements can give a rough estimate of the size the decay (if the tree is decayed). For this the measured (V_{mes}) and reference sound velocity (V_{ref}) values are needed. With the following formula the relative decrease of velocity (RDSV) of sound can be attained in %.

1D measurements usually taken in radial direction, on a line or lines which go through the center (see Figure 2.5.). Or TOF measurement can be done along the trunk to evaluate wood quality, which is a tool to help selecting the best quality woods on plantations.

$$RDSV = (V_{ref} - V_{mes}) / V_{ref} * 100$$



Figure 2.5.

An example of TOF (time-of-flight) or 1D acoustic measurement. The propagation time is measured between a signal producer and receiver. If there is a decay, the sound signal “gets around” it, and the measured time increases

DECAYED AREA RATIO GIVEN IN %	RELATIVE VELOCITY DECREASE IN %
0	0
5	0
10	0
15	0-10
20	10-20
25	10-20
30	20-30
40	20-40
50	30-50
>50	>50

Table 2.1.

The relation between the relative velocity decrease and the decayed area ratio of the examined layer

Sound and ultrasound signals behave similarly, there are devices using each of them. The practical differences are:

- ultrasound is generated by the sensor/signal producer, it should not be hit by any hammers
- ultrasound sensors must be very well coupled to the wood material, the sensor may need some gel or it can be necessary to hold and push them strongly into the wood during the measurement
- sound waves are generated by hitting the sensors/measuring points by a metal hammer.



Figure 2.6.

Measuring the redwood trees (bark thickness 7-10 cm) in a park (left and right), long (12 cm) and normal (6 cm) nailed sensor (middle)

The acoustic sensors should be well coupled as well, the tip of the sensor must reach the wood material. Which means it must be longer than the thickness of the bark. For many species, a sensor with 6 cm nail is more than enough, but in some cases or ages a longer nailed sensor should be used.

For example, when we had to measure the redwood trees (cc. hundred years old) in a park, we used the sensors with 12 cm nails. See in Figure 2.6.

4. ACOUSTIC TOMOGRAPHIES

Acoustic and ultrasound tomographies are based on the same physical phenomenon as it described in the previous chapter. In this case of tomography, there are several sensors around the trunk or limb and acoustic signals' penetration is measured between all of them. The measurements give information about a line and 2D tomograms can be calculated based on these data.

As Figure 2.7. shows the increase of the measurement lines lead also to smaller not-measured areas. The resolution and the liability of the

calculated tomograms increase if more sensors are used. However, it is not recommended to place sensors with less than 5 cm distance between them.

The tomogram is calculated by the software during several steps including time and direction corrections as the wood material is inhomogeneous and the penetration of the sound signals depend on the direction as well. (This is why 1D measurement are done on the line going through the middle or along the trunk and not at any other directions.)

The image reconstruction could be done on paper as well but according to the amount of steps and information is not part of nor training either practice or practical exercises.

The measured layer should be perpendicular to the growth of the tree which usually means that is should be horizontal. It is also recommended to measure the height of the examined layer, not only to know where the measurement was taken but also for load estimations and for 3D tomogram.

Using the proper geometry pattern of the measured layer affects the results as if the distances between the sensors are not the real ones, the calculated velocities are affected as well.

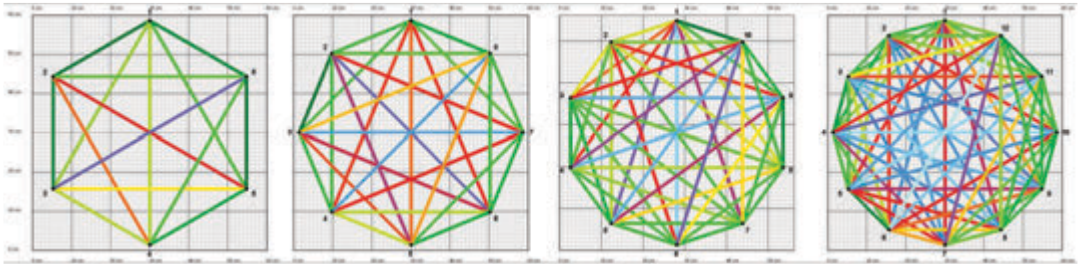


Figure 2.7.

If there are several sensors around the trunk, there will be more and more measurement pathways, measurement line from one to another

The software offers different geometries like circular, elliptical, irregular. It is recommended to use irregular geometry.

The irregular geometry needs information on the positions of the sensors (while the “regular” geometries tell you where to place the sensors for optimal resolution). Usually, the distances of some sensors should be measure which can take several minutes (according to the number of sensors). To speed up this part of the measurement it is recommended to use a digital caliper. (But it can be done with a mechanical caliper as well, just it takes more time.)

Using the not proper geometry may underestimate the decayed area and overestimate the safety even with 40% or even more. Never use circular or elliptic geometry when the trunk is visibly far from a circle or an ellipse.

Better resolution can be achieved by using more sensors or by using more “measurement points” like Ludwig sensors.

Examples are presented in Figure 2.9. and Figure 2.10.

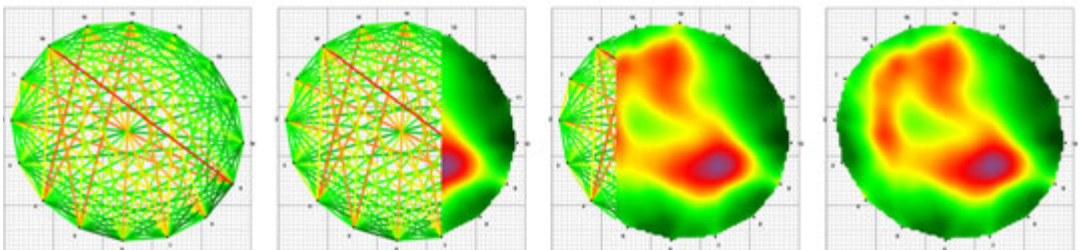


Figure 2.8.

Measurement lines and the calculated tomogram

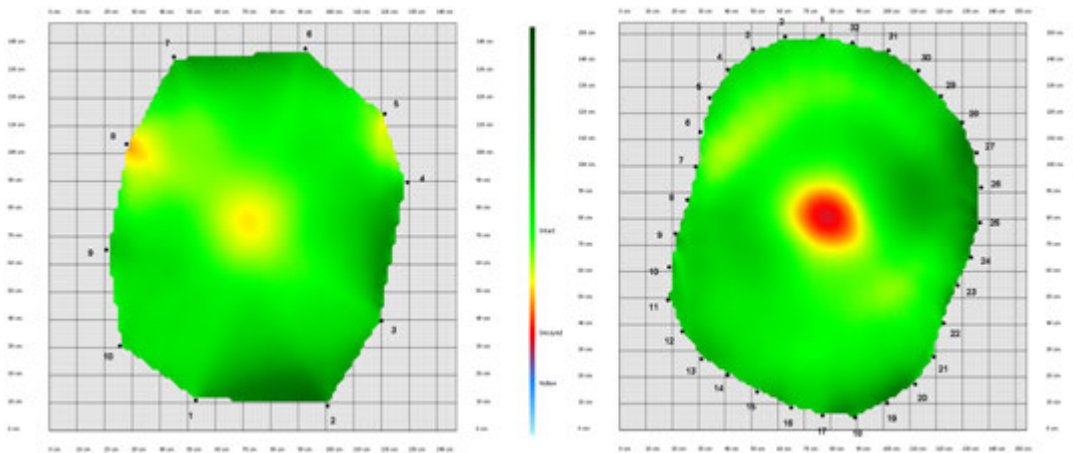


Figure 2.9.

A plane tree measured with 10 sensors (left) and with 32 sensors (right)

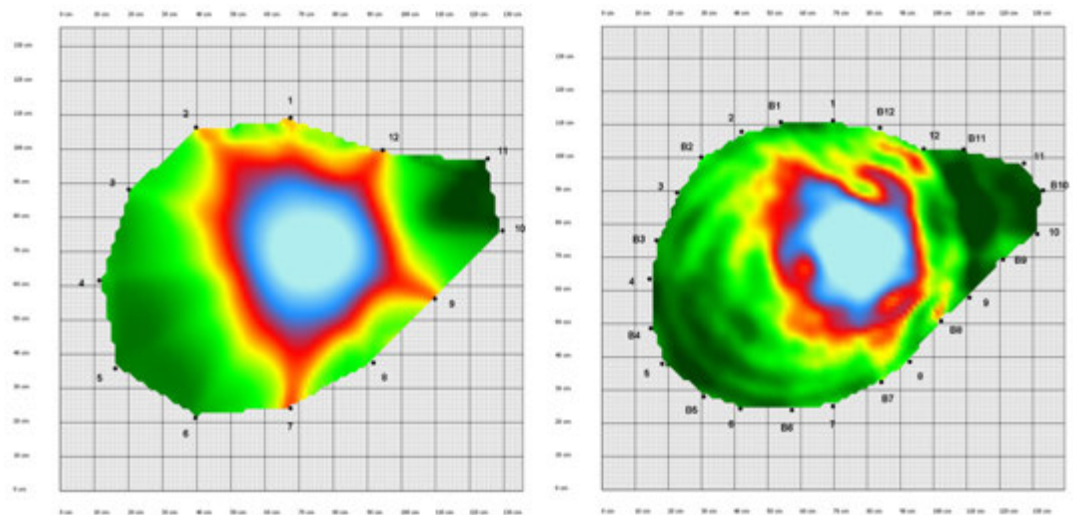


Figure 2.10.

Another plane measured with 12 sensors alone (left) and with 12 sensors, and with 12 Ludwig sensors (which ones do not detect the sound signals, only generate them) (right)

Tomography for a layer in a comfortable height implemented by 2 people takes about 10 minutes, while the whole process including safety evaluation and preparation of report is longer. Of course, measuring several layers of at heights

which can not be reached from ground level can increase the measurement time significantly. Working in pairs is optimal as the task can be well divided among two people.

If several layers were measured on the same tree, a 3D image can be interpolated from the layer's tomograms (see on Figure 2.11.).

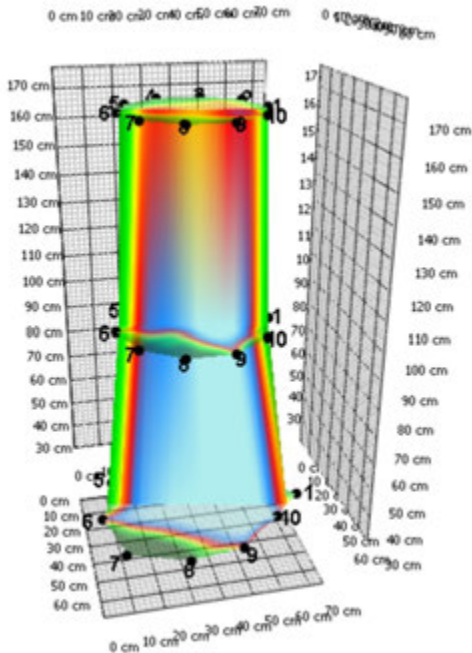


Figure 2.11.
The interpolation calculated from
the tomograms of the measured layers

THE RECOMMENDED STEPS OF A TOMOGRAPHY MEASUREMENT:

- select the weakest layer(s) of the examined tree based on visual evaluation;
- decide if it is possible to use regular (circular, elliptic) geometry, if yes, measure the proper data (circumference, ...) and place the sensors into the proper positions indicated by the software;
- if you use irregular geometry, place the sensors onto the trunk following the shape of it and measure the proper distances between the sensors;
- set up the device, place the sensor in a layer perpendicular to the growth direction of the

trunk (this layer is usually horizontal, but in case of significant trunk tilting the measured layer should be leaning as well);

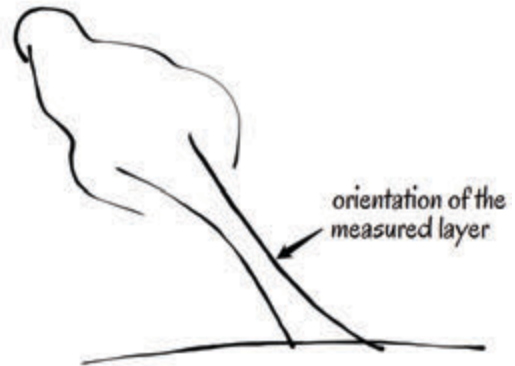


Figure 2.12.
The measurement should be done
perpendicular to growth direction

- check if the sensors are deep enough, if they went through the bark for achieving proper acoustic coupling;
- remove the measuring tape;
- connect the sensors to the battery (you may need connect some cables as well), turn on the device;
- measure by hitting all the sensors/measuring points at least 3 time (it is recommended to hit at 5 times);
- turn off the device;
- save the data;
- let the software calculate the tomogram to have a quick view of it, to check the measurement if it was performed well;
- immediately warn the customer / owner of the tree if there is a chance of serious damage / injury based on the tomogram;
- measure another layer if it is necessary;
- take a photo from the whole tree from at least as far as high the tree is. In this way the distortions can be reduced;
- remove and clean the device;
- go to the next tree;

- do biomechanical / safety analysis if it is needed and possible (depending on software);
- prepare the report and send it to the customer / owner / office...

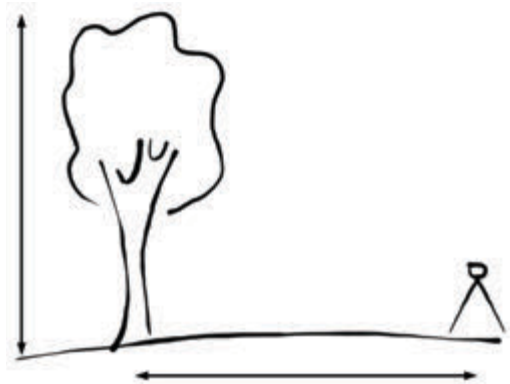


Figure 2.13.

The photo should be taken at least as far from the tree as high it is

ADVICE ON USING TOMOGRAPHY:

- make a proper visual evaluation to decide if tomography is needed or not. There are cases when the conditions of a tree are obvious

and there is no need to spend time with tomography;

- do not do tomography if the water inside the trunk/limbs can be frozen. Low temperature can affect the device as well, the cable can become rigid and vulnerable;
- do not do acoustic tomography during heavy rain;
- do not do acoustic tomography when the temperature is above 40°C;
- do not do acoustic and impedance tomography on the same tree at the same time. Do one of them after the other;
- acoustic coupling is important, please hit the sensors/nails deep enough to reach the wood. Sensors/nails should go through the bark. (as you can see it in Figure 2.5.);
- if you use metallic measure tape, remove it before starting the measurement. It can cause acoustic shortcut and bring false data, as the sound travels much more faster in the metal than in the wood;
- use the real geometry whenever it is possible. Using a simplified geometry affects the estimation of the decayed area and the safety factor as well;

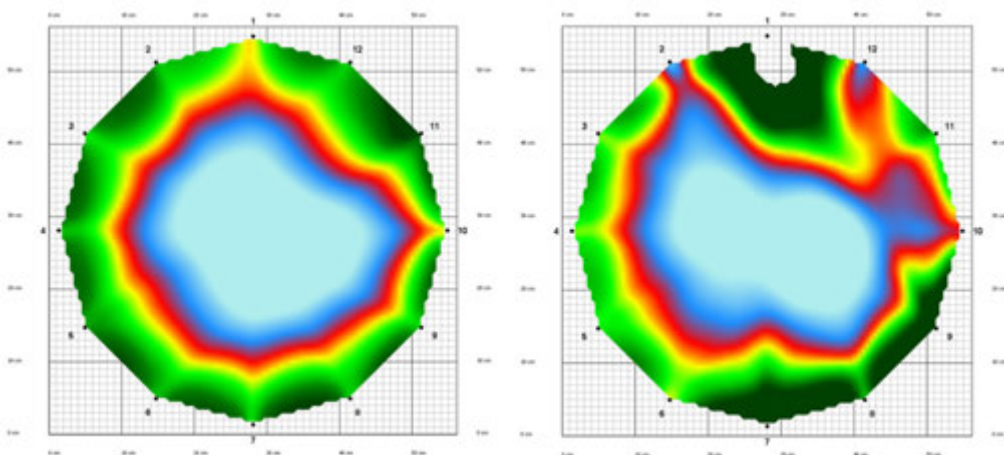


Figure 2.14.

The tomogram of a decay (left) the same layer measure when the metallic measuring tape was left on the tree

- check the battery before going to the field, have enough battery for the measurements;
- it is recommended to have a foldable table to be able to put the device onto it;
- keep the sensors' tips clean, sterilize them if there is a chance of infection;
- it is recommended to have a little alcohol or benzine to be able to remove resin from the device;
- the tips of the sensors/nails can be very pointed, be careful during the setting up and removing, to not to hurt yourself or others;
- place the first sensor in the north direction if it is possible;
- when you have to climb higher it is recommended to use a light device/measure by tablet or smartphone, but it could be a simple way to measure any time;
- during the measurement have at least 3 measurements on each sensors/measuring points;
- limbs can be measured and their tomographic image can be calculated but no safety of the limb is provided via tomography;
- if the trunk is splitting, the calculated safety is significantly higher than the realistic one;
- be aware of the fact that the software has information on the measured layer(s). Safety factors belongs to the examined layers not to the whole tree;
- save your data, there may not be any autosave function;
- participate on a training about the tomographic device before you start work on your own.



5. ELECTRIC IMPEDANCE/ RESISTIVITY TOMOGRAPHY

The idea of using electric signals to get information about the inner conditions of a trunk goes back to Alex Shigo who developed the so-called shignometer device. It provided information about the resistance of the trunk, but interpreting the results was difficult.

Electric impedance or resistivity tomography is successfully used in geophysics for decades, so the idea of electric measurements returned to the field of tree evaluation.

While acoustic signals can be approached or imagined as straight lines, electric field “lines” are closer to curves and cylindrical lines. The interpretation of the measurement is more complex. A tomogram is made with iteration steps. It means that the software figures out a situation, a tomogram which would result the same measurement results as we’ve got during the measurement.

Impedance tomography can find the inhomogeneities in a material. (Figure 2.15.)

During a measurement, electrodes are placed onto the tree. (The electrodes have to go through the bark.) Electricity is conducted to the tree by two conducting electrodes, while the voltage is measured by two detecting electrodes. Inhomogeneity changes the voltage which can be measure and it can refer to more or less water or ion concentrate, red heart (false heartwood) and damages or the presence of fungi. Discoloration of wood, water transport, the sapwood, and the heartwood can be studied by impedance tomography.

As the measured quality, the electric resistivity differs from acoustic signals’ velocity, the tomogram also differs significantly from the ones calculated in acoustic tomography.

Early changes in wood can be caught. The impedance tomography shows differences even when the density is still has not changed during a fungi attack, it can catch the infection before the other tomography methods.

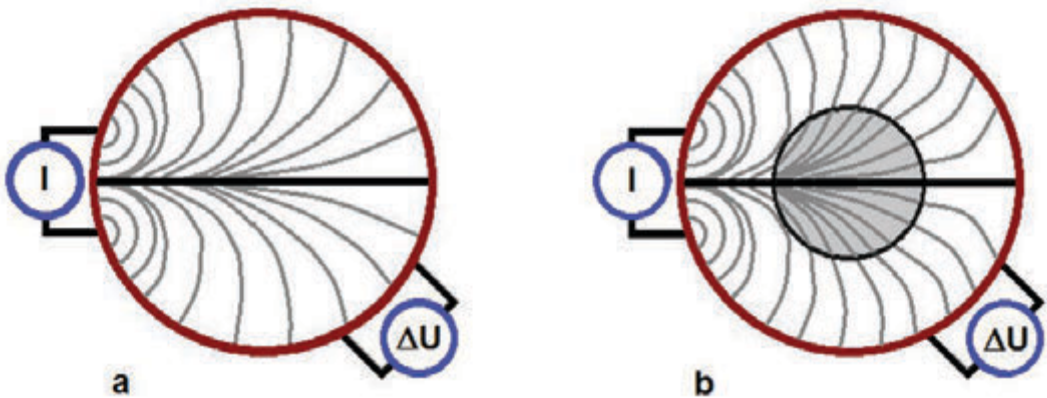


Figure 2.15.

- Schematic image of equipotential lines during an impedance tomography measurement. Current is conducted (“I”) to a homogeneous material while the voltage is measured (“ ΔU ”). The voltage measurement can go around and the role of the electrodes can be changed. A model about the conductivity or resistivity of the material can be made.
- Schematic image of impedance tomography of a trunk. The change in the material changes the equipotential lines and the measured voltage.

To be able to catch the change, the patterns of the healthy wood should be measured. The pattern of healthy resistivity tomograms depends on the examined species as well.

Let's see an example (and see more in the case studies including comparison of acoustic and impedance tomography)!

STEPS OF AN IMPEDANCE TOMOGRAPHY:

- choose the layer which is interesting (there is a chance of fungi activity, dead knots,...);
- place the stainless-steel electrodes (nails) onto the tree, drive them through the bark;
- start the computer software;
- register the positions of the nails (impedance tomography is very sensitive for geometry);

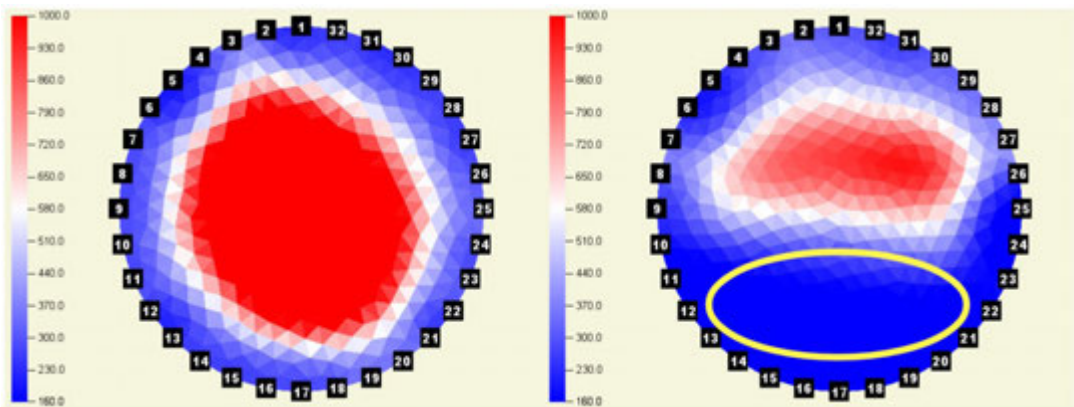


Figure 2.16.

Healthy spruce (left) with a higher resistivity area in the middle. The decrease of the resistivity (on the right, the marked area) refers to the presence of more free, movable ions, which refers to active fungi. Both trees are Norway spruces.

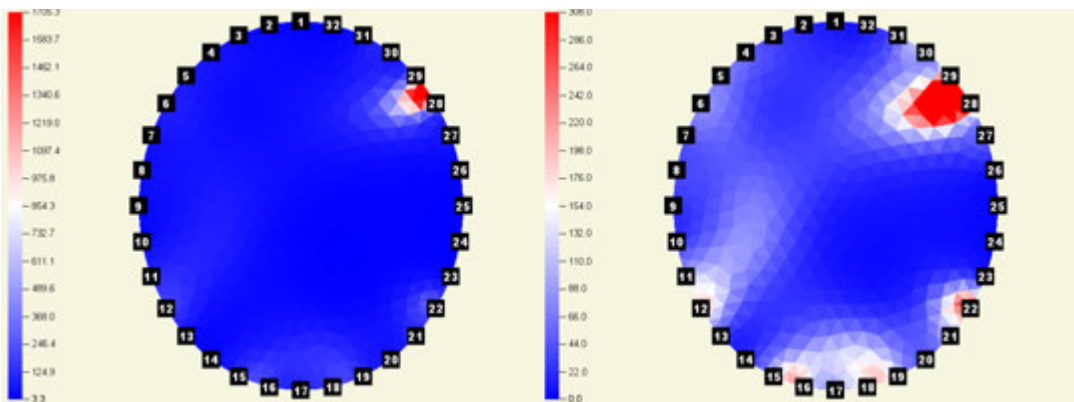


Figure 2.17.

A healthy chestnut tree with wound reaction. (Healthy chestnut tree's pattern does not have a circular higher resistivity area in the middle.) The tomogram with autoscale (scale from 3.3 to 1705.3) is on the left. To highlight the wound reaction the scale was set to 0.0 to 308.0 (right).

- place the crocodile clips onto the nail, connect the cables;
- turn on the device and connect it to the computer;
- start the measurement and let the computer handle the process, the measurement can take several minutes;
- when the measurement finished, turn off the device and save your data;
- let the software calculate the tomogram;
- compare the tomogram's pattern to a healthy tree's tomogram of the same specie.

PRACTICAL CONSIDERATIONS WHILE MEASURING IMPEDANCE TOMOGRAPHY:

- usually autoscale works well as the patterns should be compared not the actual resistivity values;
- scale can be modified to highlight smaller changes, to have a more detailed image of the interested area;
- this technique is very sensitive for the geometry, please always measure and use the real geometry;
- the device should be well charged (low charge can cause misleading tomograms);
- tomograms are comparable only if the amount of used electrodes is the same (and the so-called max. electrode distance is the same as well);
- resistivity has seasonal changes (related to temperature) but it should not affect the patterns.

Measuring one layer at comfortable height with 16 electrodes takes about 15 minutes.

6. CALIPERS

Distance and geometry measurements are quite important for both 1-line acoustic measurement and tomographies.



Figure 2.18.
Mechanical caliper

Mechanical or electrical calipers with at least 0.5 cm accuracy can be used for measuring the distance between the sensors. (Of course, calipers can measure any distances in their range, the tree's diameter, or the lengths of the axis if the trunk is ellipse-like.)

Mechanical calipers are cheap and a handy tool for 1-line measurements.

The advantage of the electric calipers used in the tree assessment is that they usually have a Bluetooth connection with the measuring device, computer, or smartphone.



Figure 2.19.
Using an electric caliper

The connection can speed up the registration of irregular geometries. The measured distance usually can be sent with just one push on a button, which is on one of the arms of the caliper.

ADVICE ON USING CALIPERS:

- choose the correct range for the measured tree
- charge the caliper
- don't force the caliper

7. OTHER DECAY DETECTION DEVICES

Beside the presented, and relatively well-known and widespread methods, there are developments as well.

Tree radar for trunks is a technique using ground penetration radar or similar for trunks. During the measurement, a hand-held radar goes around the trunk at the interesting height(s).

The echo differs for different material (like air) and tomogram-like images can be calculated from the data.

There were several trials using optical detection. Infrared cameras may find decay which are very close (less than a few cm-s) to the surface. Recording the bark movement and its' distortions (with a marker) and find correlation if there is a decay or not, is also a research field. Some techniques, like using a portable CT to examine the inner status of a trunk, are rarely used.

Please be aware of that there are several device developers and producers as well, the photos and images of the chapter are here to help understanding the principles for the techniques and to demonstrate the usability. The most well-known company differs from geographical area to geographical area, but if you are interested in the producers looking at the homepages of Fakopp, Rinntech and Argus Electronic can give you good starting point.



Instrumental assessment: decay – case studies

1. ACOUSTIC TOMOGRAPHY VIA 7 YEARS

In 2013 a honey fungus (*Armillaria mellea*) attacked Norway spruce (*Picea abies*) was selected for research in a botanical garden. Between 2013 and 2019 the tree was measured repeatedly at 30 cm, 100 cm, and 170 cm heights with acoustic tomography. (The data from 2017 were lost.)

It might be surprising that the decayed area decreased a bit at 30 cm height for a few years, but as the tree grew wider, the total area became bigger while the decayed area was isolated so it could not grow so fast.



Figure 2.20.
Fruiting bodies of honey fungus

Height	2013	2014	2015	2016	2018	2019
30 CM	63%	61%	61%	62%	66%	67%
100 cm	52%	55%	53%	60%	58%	57%
170 cm	23%	42%	46%	52%	48%	67%

Table 2.2.

The measured decayed area compared to the total area of the layer

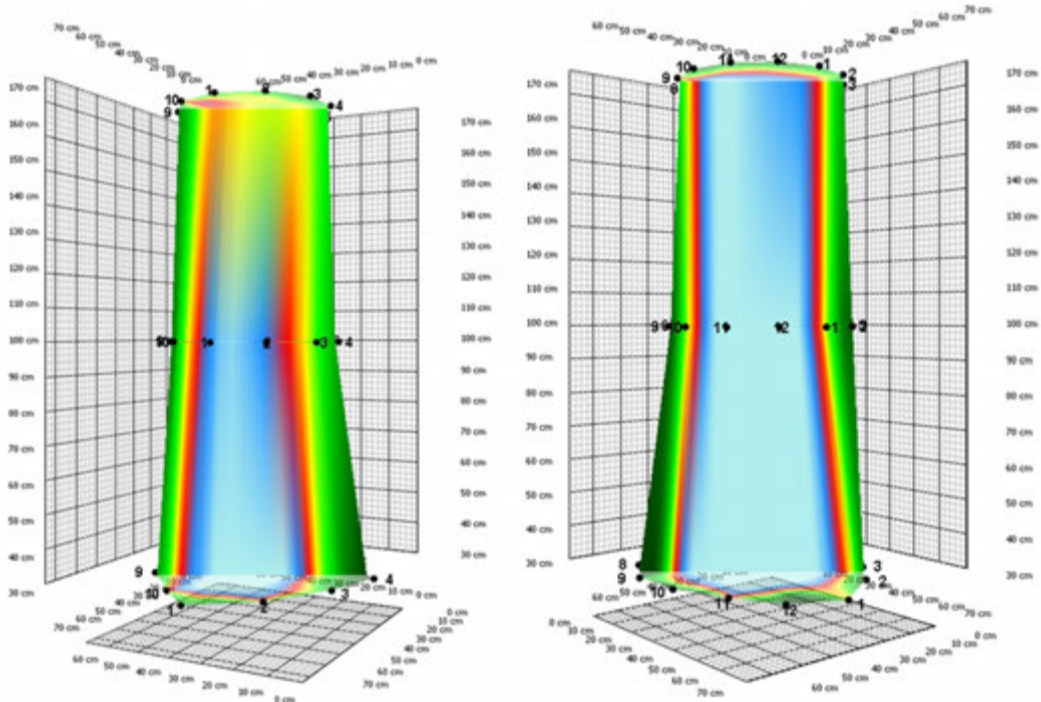


Figure 2.21.

3D model of the trunk in 2013 (left) and in 2019 (right). The decayed area could expand more in horizontal direction, while it could grow very moderately to the sides at 30 cm height.

Safety factors for trunk breaking (for 120 km/h wind gusts) were also determined from the data. The lowest (2018, 170 cm) was 249%. It shows that the risk of trunk failure in this height is quite moderate. The tree still stands (spring 2021). This tree could fight for itself even against the relatively dangerous infection.

2. EXAMINATION OF GIANT TREES (CIRCUMFERENCE ABOVE 350 CM)

In the botanical garden of the University of Sopron 3 huge trees, 2 redwoods and a plane were examined to check their conditions.

The first redwood ($c=380$ cm) stands in the garden, surrounded by other trees, the other redwood ($c=472$ cm) stands next to building and the plane tree stands in the middle of an area. The redwoods have 6-10 cm thick barks, so they were measured with the 12 cm long nailed sensors. The first tree showed a 1% decay, while the other is healthy.

The plane was measured with the normal, 6 cm long sensor. The plane first was measured with circular geometry, then it was checked with irregular geometry as well.

A few months later it was also measured with 32 sensors. (Check Figure 2.9. for the tomograms of with 10 and 32 sensors. The decayed area changed from 1% to 4% as the geometry and the resolution increased.)

This measurement was done for testing the device, but the images of the different measurement are interesting to compare, even if we are aware of that the decay is very small and central.



Figure 2.22.
Tomography on the first redwood

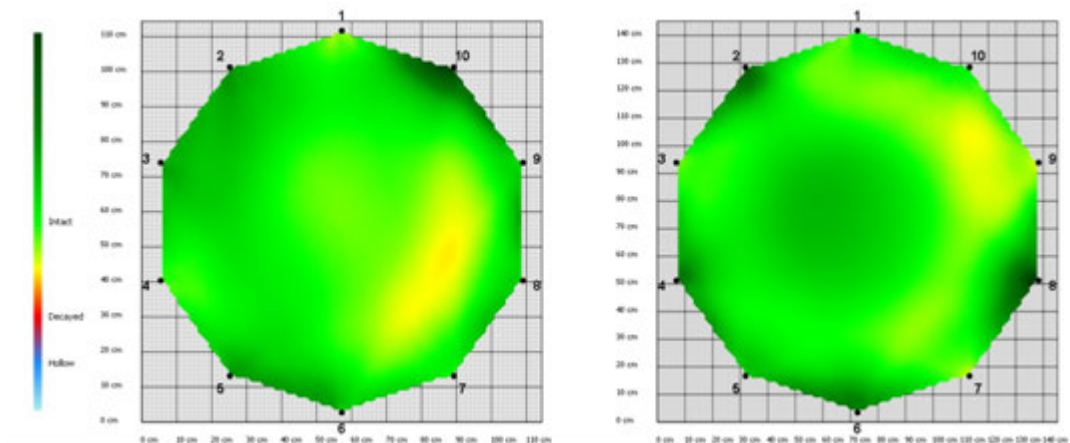


Figure 2.23.
The tomograms of the first (left) and second (right) redwood trees.

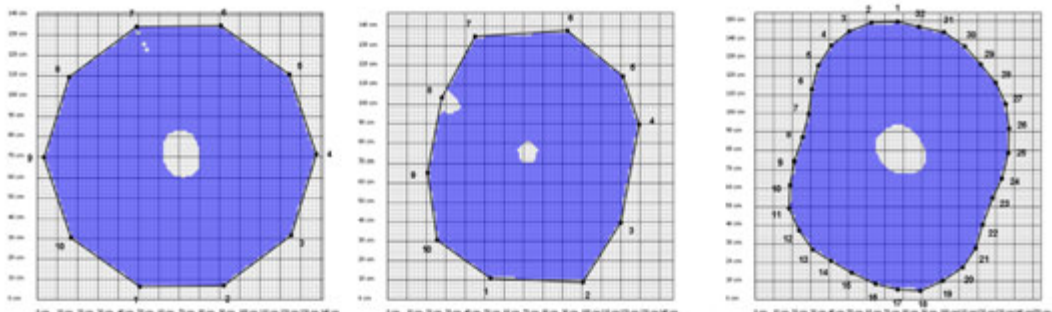


Figure 2.24.
The estimated decayed area of the plane tree

3. HUGE, DECAYED TREES (CIRCUMFERENCE OVER 400 CM)

Acoustic tomography is limited by the attenuation because the signal generated at one sensor must reach the other sensor. Different trees have different material, yet the hugest trees measured by tomography are above 10 m in circumference. If there is a decay inside a large tree, the sound signal goes around it, which means more possibility to be weakened or to faded.

Three examples were collected to present this situation.

The first tree is an oak, standing near a hotel on the edge of the forest (Sopron, Hungary). Circumference at the measurement's height was 402 cm. The decayed area was 33%.

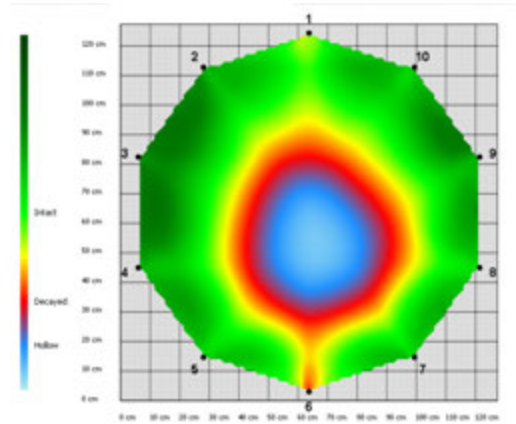


Figure 2.26.

The measured tomogram of the oak tree



Figure 2.25.

The measurement just finished,
tomogram is shown on a smartphone

The second tree is a poplar, standing in a park area (Hidegseg, Hungary). Circumference at the measurement's height was 448 cm. The decayed area was 76%.

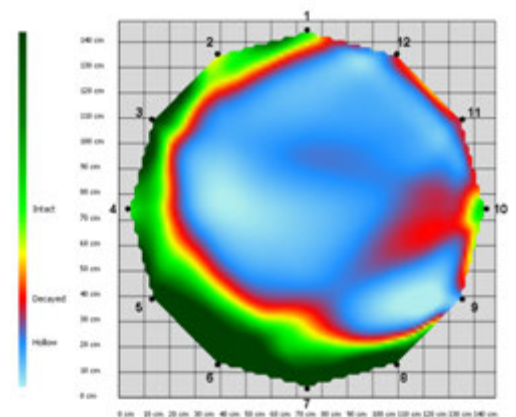


Figure 2.27.

The tomogram of the poplar at Hidegseg

The third tree is a poplar again, it stands near by a route (Nagylozs, Hungary). The crown was reduced according to the conditions of the tree. Circumference at the measurement's height was 664 cm (diameter little above 2 m). The decayed area was 82%.



Figure 2.28.
Poplar at Nagylozs

4. TOMOGRAMS JUST BELOW A FORK

An oak tree standing next to a house was examined on demand the of the owner. The tree had a fork from its stamp.



Figure 2.30.
Measuring one trunk of the forked oak

The work was successful, the tomogram could be calculated. Even biomechanical evaluation was done for the tree, the safety was extremely high (over 1000%) because of the significantly reduced crown.

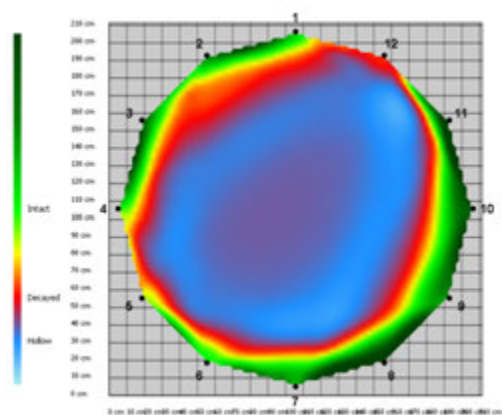


Figure 2.29.
The tomogram of the poplar at Nagylozs

Both trunks and the base were measured with tomography. In the trunks the decayed area was between 47% and 55% (measured at 65, 75 and 100 cm).

The base (at 30 cm height) was examined two ways, first with the sensors around the whole base. During the second measurement the parts were measured separately.

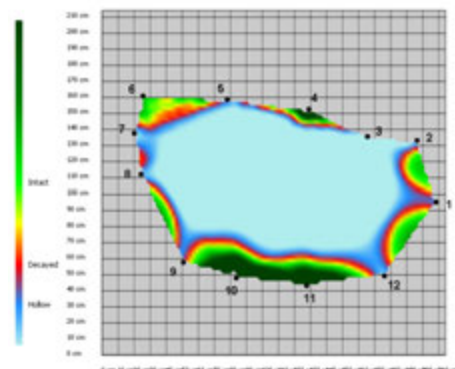


Figure 2.31.
The tomogram just below the fork

When just below fork was measured as one trunk, the decayed area was 86%.

When the two parts were measured separately, the decayed areas were 63 % for both left and right parts. The tomography overestimated the decayed area during the first measurement as the sound had to get around the overgrown bark as well.

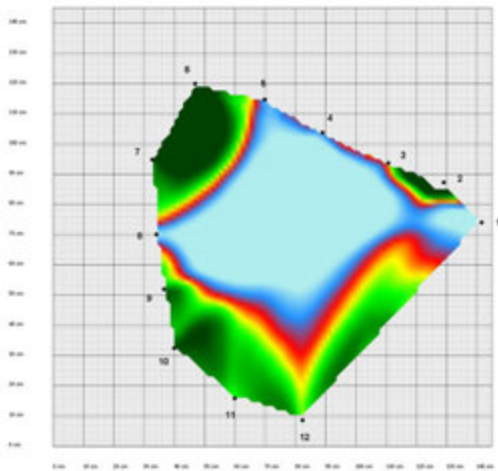


Figure 2.32.
Tomogram of the left part

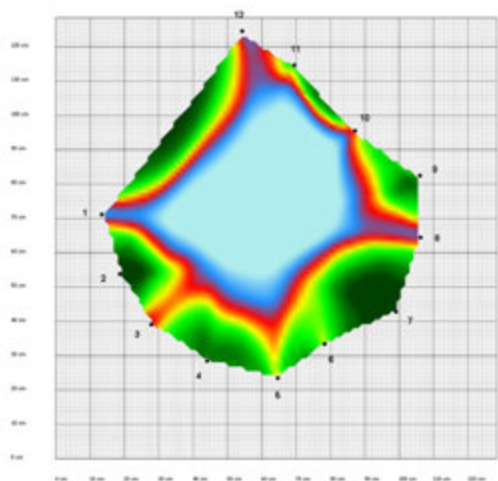


Figure 2.33.
Tomogram of the right part

5. PARTIALLY FROZEN TRUNK

The maintainer of a park demanded tree examination including tomography. The temperature was below zero Celsius (in the previous days as well), the park was covered by snow and frost. As the examination was urged, the plane tree was examined visually (a main branch around 5 m height was removed, and the pruning cut started decaying), and acoustic tomogram was also measured at 95 cm height. At this time, 41% decayed area was found.

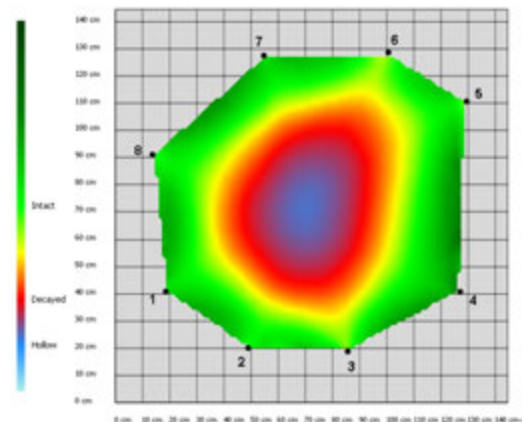


Figure 2.34.
The tomogram of the trunk at 95 cm under frozen condition

According to the tree expert's opinion the measurement was repeated about two weeks later when the temperature was higher for several days, so the water in the trunk should not be frozen any longer. The sensor's positions were exactly the same. The repeated measurement showed only 1% decay.

The phenomenon was explained as the outer part of the trunk was frozen in the first case, so the sound could travel fast in sides (the velocities

were checked, they were around 2000 m/s, while the sound velocity in healthy wood for plane is about 1300-1400 m/s) while in the middle of the trunk the signals were slower (they were about 1400 m/s). This led to the decay-like tomogram.

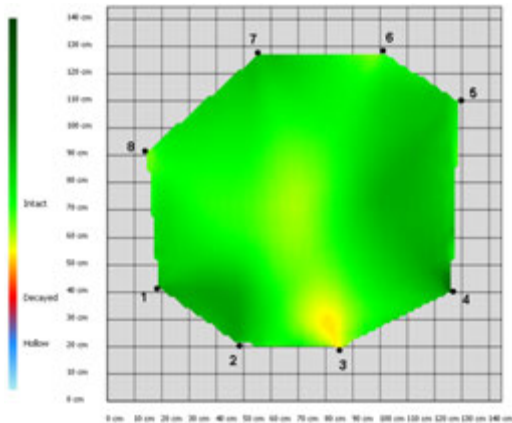


Figure 2.35.
The tomogram of the trunk at 95 cm
under “normal”, not-frozen conditions

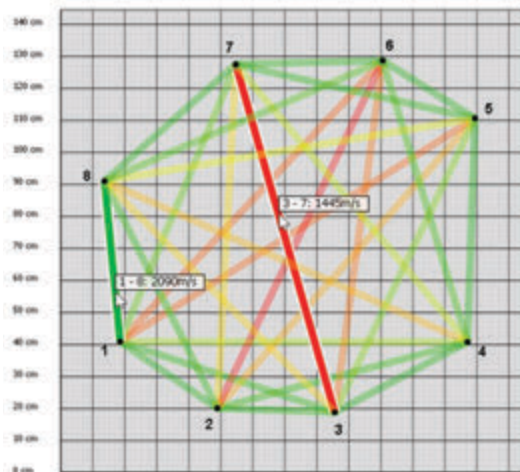


Figure 2.36.
Graph view of the first measurement. The
velocities on the side are higher than it would be
normal for plane tree because that part was frozen

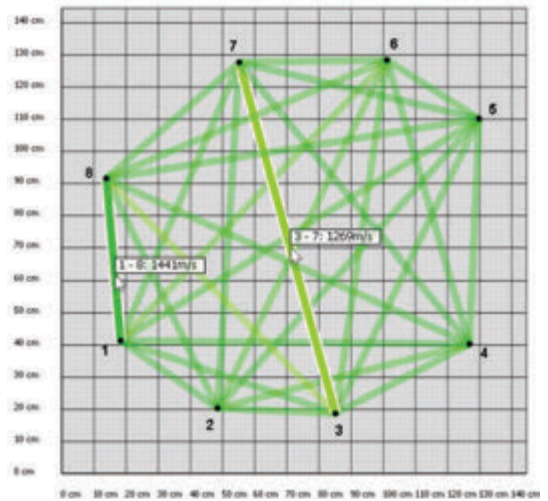


Figure 2.37.
Graph view of the second measurement,
when the trunk was not frozen any more.
Velocities refer to healthy plane wood.
(Please keep in mind that velocities for
healthy wood depends on the species!)

Reverse situation could also happen, when a decayed tree was measured but there was ice in the decay, the tomogram showed no decay at all. When the tree was measured again (temperature was above zero) the decay was visible on the tomogram.

Remark for the presented measurement: as there was a decayed pruning cut, the trunk was decayed above 2 m height, but when the measurement was done, it did not already reach down to 95 cm.

6. WHY NOT USE YOUR PEN TO MAKE SOUND SIGNALS?



Figure 2.38.
Tools used for sound generation

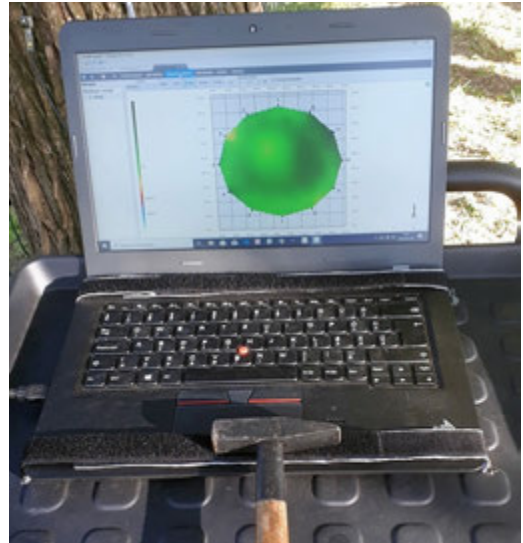


Figure 2.39.
The control measurement

The tree examination team of Fókert (organization caring about 700 thousand trees in Budapest) had the idea to figure out what happens if they don't have the metal hammer with themselves to generate sound signals. In their experiment, 12 different tools were used to generate signals.

They used the metal hammer included in the tomogram's package as a control. The other "signal generators" were:

- a plastic pen
- the rubber head of a hammer (type: 'Wiha')
- the 'superplastik' head of a hammer (type: 'Wiha')
- an aluminum hammer
- a bronze headed hammer
- a so-called 'SK-hammer', a little steel in a plastic head
- the varnished black locust (Robinia) handle of a hammer
- an ash hammer
- a piece of pine
- a plastic soldering rod
- a steel secateurs (type: 'Kunde')



Figure 2.40.
The worst tomogram was measured using a pen

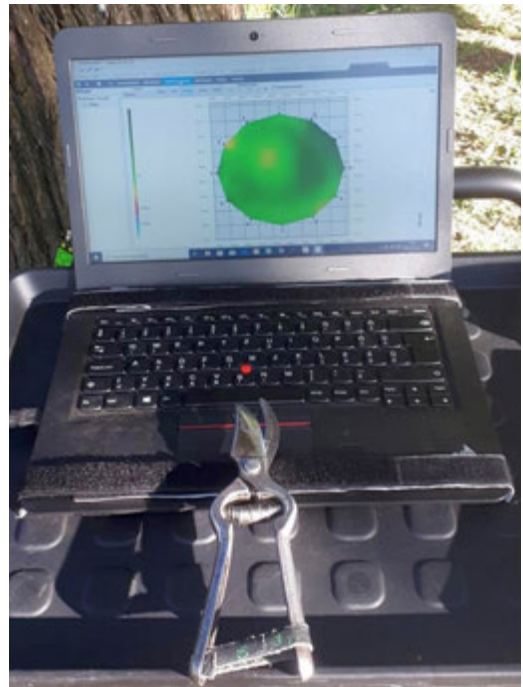


Figure 2.42.
The tomogram 'made by' steel secateurs



Figure 2.41.
Tomogram measured using the 'SK-hammer'
for sound generation (up) and the
head of the 'SK-hammer' (down)

The worst sound velocities (compared to the control) were measured using a pen, the worst tomogram was calculated from the data. Measuring with a wooden hammer or rod or handle are also not the best ideas.

The sound velocities were better using a robber, a bronze or plastic hammer or with a plastic soldering rod. While measuring with an aluminum hammer or with steel secateurs showed only little differences.

The best tool for measuring (if the steel hammer is not available) seemed to be the so-called 'SK-hammer', a little steel in a plastic head.

7. EXAMINATION OF A WOUND REACTION

A plane tree in a botanical garden had suffered from a freeze wound several years ago.



Figure 2.43.

The tested plane tree, the overgrew wound is marked with red

The tree was examined by tomography, a decay was found. The test was repeated to check if more precise geometry could show more details of the decayed area.

The second results showed not only more details about the decay, but a very strong wooded part appeared as well. This area was exactly the area of the wound which was overgrew during the years.

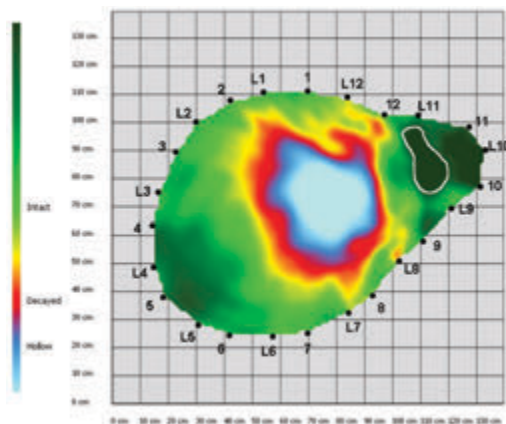


Figure 2.44.

The detailed tomogram, the reaction wood is highlighted

8. SAFETY OF A TREE IN A PARKING LOT

A plane tree with fracture was standing in a parking lot.



Figure 2.45.

The fracture wound on the tree

The decay was visualized by a tomogram and safety regarding trunk failure was calculated using a photo from the tree.



Figure 2.46.

The crown area selection for safety calculation

The safety factor with wind loads calculated based on the EN1991 European standard was 70%. To reduce the risk a simulation of crown reduction was done.

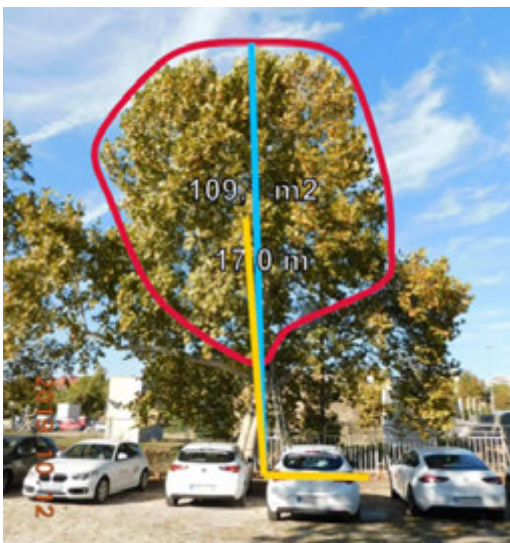


Figure 2.47.

Crown area reduction simulation

The safety factor increased only a little to 80% in the simulated case. The European standard calculated with higher winds in higher areas, keeping the top area did not decrease wind load sufficiently.

9. IMPEDANCE AND ACOUSTIC TOMOGRAPHIES

Impedance tomography can find active fungi attack, it may forecast decays, or show the problematic areas before it could be seen on the acoustic tomogram. In the other hand, impedance tomography can confirm the suspicion of the presence of fungi in a decayed area.

According to the research on the University of Applied Sciences and Art in Gottingen, even white rot fungi can be found (Bieker et al., 2009). As white rot “eats” lignin but let cellulose stay in the material, sound waves may get through without significant delay, the acoustic tomogram may not show the decay caused by white rot fungus, especially at the first phases of the decay.

Measurements on spruce, ash, poplar, chestnut, cedar, and oak trees showed similar phenomenon.

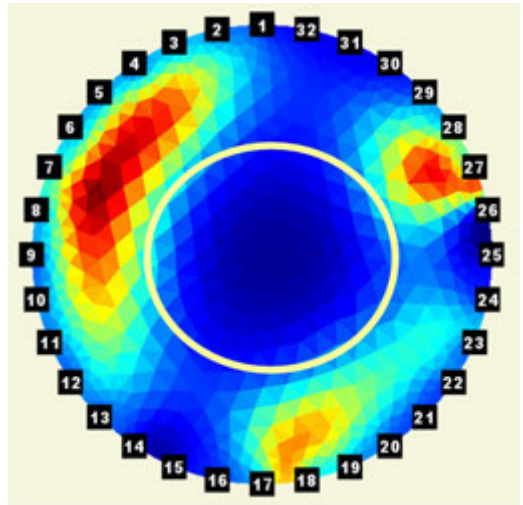
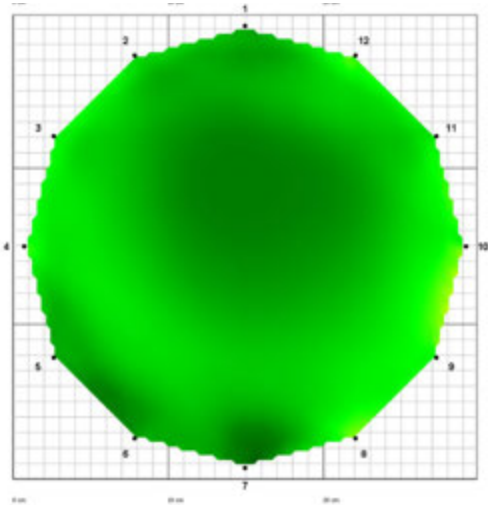


Figure 2.48.

An ash tree (top left) was attacked by an *Armillaria* specie (top right – the fruiting bodies of the fungi). The tree was in bad conditions (e.g. losing the foliage). The acoustic tomography (bottom left) showed no decay or problematic area. A low resistivity area is highlighted on the impedance tomogram (bottom right). This refers to the presence of the fungi. (Source: own work)

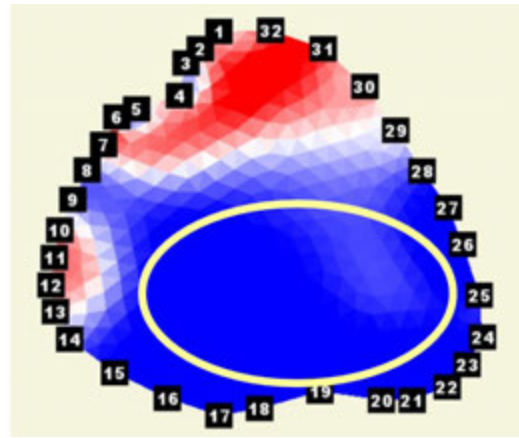
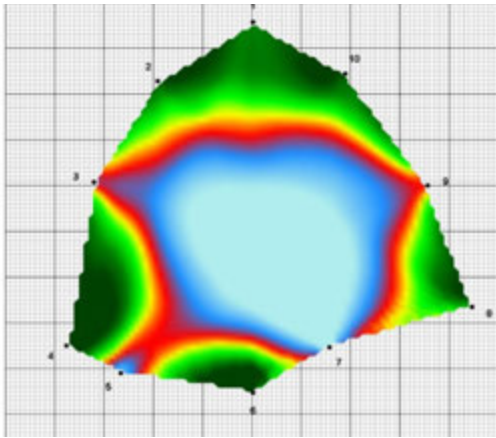


Figure 2.49.

The acoustic tomography (left) shows significant decay. The low resistivity (blue) area shows more fungi, which refers to the presence of fungi (right). Measurements were done on Norway spruce tree.

10. TRANSPORT ACTIVITY MEASUREMENT – AN EXPERIMENTAL USE OF IMPEDANCE TOMOGRAPHY

When a tree is “awake” transportation between the roots and foliage is going on as well especially during spring when the new leaves are growing.

Impedance tomograms were measured on a beech tree in every hour for 25 hours. Of course, the tomograms did not change a lot – as fungi does not grow so fast. But the little changes were compared to the light intensity and an interesting relation was found. It seems that the changes in resistivity follows the changes in light.

For the comparison, the resistivity values were negated (multiplied with minus one) as the resistivity become lower when the light was higher. Later this technique might become useful for checking the vitality of a tree, nowadays it is great research topic.

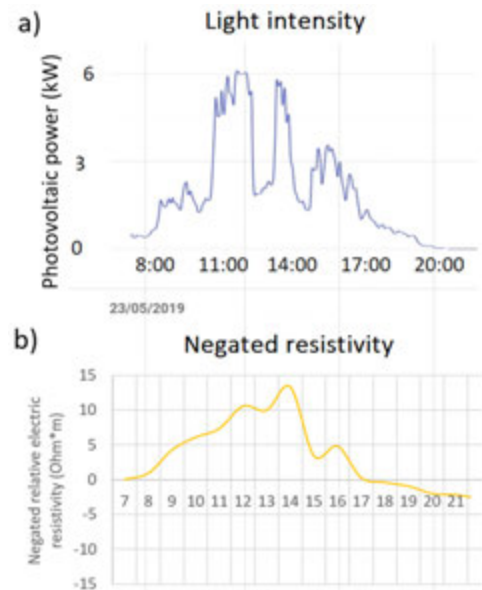


Figure 2.50.

Changes in measured resistivity (b) followed the changes in light intensity. (a).

X axis is time in hours for both. (The graph presents the period of daylight only, while the whole measurement took 25 hours.)

Instrumental assessment – Limitations of decay detection

Acoustic techniques assume that if there is a decay or other stability decreasing situation (like a crack) the sound wave “has to” go around, the velocity compared to the healthy case decreases.

As it was mentioned before, in case of white rot fungi, the sound can still go with its normal speed, and tomogram can mislead the examiner. Similar can happen in case if larvae or insects feed on the wood, the sound may find its way even if there are many holes and tunnels in the wood.

The sound may travel with the normal speed again in cases when there is not only wood material is present. For example, if a decay was filled with concrete. Or if the tree over grew a pillar or column of a fence or other building. These materials can behave similar to the frozen case – the sound may travel faster, and the involved part may be presented as healthy wood on the tomogram.

Sometimes the opposite happens – the sound goes slower and a decayed area is on the tomogram, while there is no decay at all, but there is a crack, a ring shake or an included bark. Regarding safety these cases does not mislead a lot the examiner, as a crack decreases load bearing capacity just like if there was a decay.

Instrumental assessment – The advantages of usage

The advantages are so visible – the tomograms provide more information on the inside of the trunk than any visual assessment. Even a very quick one-line measurement can warn the user about serious, yet invisible damages and save property or avoid injuries.

In the other hand tomograms can be presented and shared easily, the images can be understood, and it can help the communication of the work of the tree assessor.





III.

Instrumental assessment: stability

The stability of trees is an important issue in an urban environment. Trees provide many benefits, including shading, windbreak, decoration, relaxation, improved air quality and reduced temperatures. Unfortunately, urban trees sometimes also pose various risks. Falling branches, trunk breakage or uprooting do not only lead to nuisance and clean-up expenses. They may result in considerable damage to public and private property, and also in personal injury, or, in extreme cases, death. The accurate assessment of tree stability and safety is therefore crucial in preventing these highly undesirable outcomes.

This chapter will provide a detailed description of two instrumental methods of tree stability assessment. These were developed based on the principles of biomechanics described in chapter I. We will introduce the basic concept, practical tools, implementation and evaluation of the traditional pulling test as well as the novel dynamic stability testing procedures. The reliability, advantages and drawbacks of these techniques will also be discussed. Finally, there we will look at some factors that affect tree stability and its assessment that we need to keep in mind when testing and interpreting the results.

1. TREE STABILITY IN GENERAL

The main, if not the sole cause of trees falling down is the horizontal wind loading on the tree crown. Trees are analogous to cantilever beams, and the wind load creates bending that may cause the trunk to break, or the roots that anchor the tree to be pulled out of the ground (uprooting). The purpose of tree stability testing is to determine if this is likely to occur to a given tree.

The first issue that we need to clarify is what do we mean by tree safety? What does it mean when we say a tree is safe?

The answer may seem obvious on the face of it: the tree should not fall down due to uprooting or breakage under any circumstances. However, this is an impossible expectation; sufficiently heavy wind loads may cause even the safest tree to fall. Therefore, tree stability is always determined based on the expected high wind conditions, and safety is determined relative to a so-called reference wind velocity value (the highest wind expected in the particular geographical location).

As explained in chapter I, the stability of trees is determined by comparing the highest wind loads that are likely to act upon the tree to the highest load that the tree can withstand without breaking or uprooting. In very simple terms, if the former is higher, the tree is likely to break or be uprooted in high winds, and therefore is unsafe.

This sounds simple enough in theory. However, there are difficulties and uncertainties in determining both the maximum expected wind load, and the critical wind load that the tree can withstand. These complications will be discussed in detail in the section on pulling tests.

One of the problems that complicate the issue of tree stability is that wind loading is not a constant, static type of load. High winds, especially, tend to come in gusts interspersed by periods of lull. Trees are complex structures, and their response to this type of dynamic loads tend to be erratic. This is why the traditional method to test tree stability (i.e. the pulling test) is based on static loading. The pulling test is much easier to control and handle computationally, but is a poor representation of tree behaviour in dynamic wind loads.

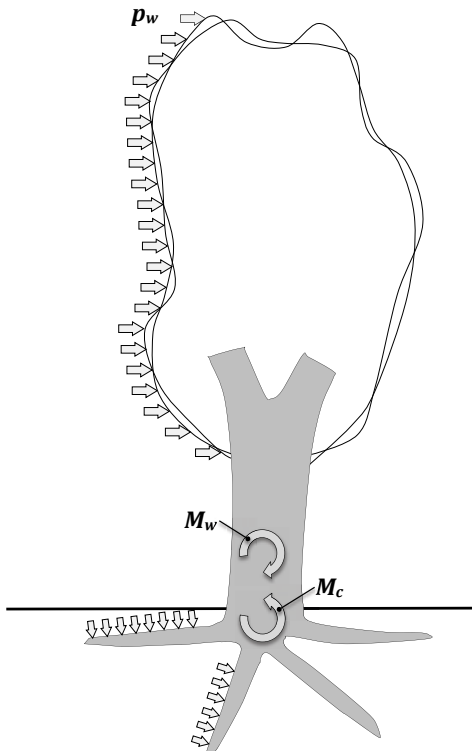


Figure 3.1.
The balance between wind loading (M_w)
and the anchoring moment (M_c)

A way to handle tree testing under actual wind load emerged recently, based on a statistical approach. We will describe the philosophy, advantages and limitations of both of these tests in the following chapters.

2. THE PULLING TEST

The pulling test is a tree-friendly non-destructive stability assessment method that was derived from the results of Wessolly's and Sinn's research (Sinn 1983, Wessolly 1991).

As described in chapter 1.5), the pulling test is based on affixing a cable in the crown of the tree (preferably close to the crown centerpoint), and exerting a gradually increasing lateral load, while continuously measuring the inclination of the tree collar and/or the deformation of the tree trunk. Tree stability and trunk breakage safety can be evaluated based on the inclination and deformation data, respectively.

A. EQUIPMENT

Figure 3.2. shows the typical testing setup of the pulling test, with the main components of the system shown.

CABLE AND WINCH

Lateral force is exerted on the tree using a steel or synthetic cable (e.g. dyneema) of sufficient length (usually at least 20 meter) and loading capacity. Depending on tree geometry and the height at which the cable is mounted in the crown, considerable load is required to reach the desired inclination or deformation. This requires a winch that has a ratchet mechanism that multiplies the force of the operator to exert sufficient tension on the cable. Both the cable and the winch should be strong enough to withstand the load needed for the pulling test (usually 1.5 to 3.5 tons.)

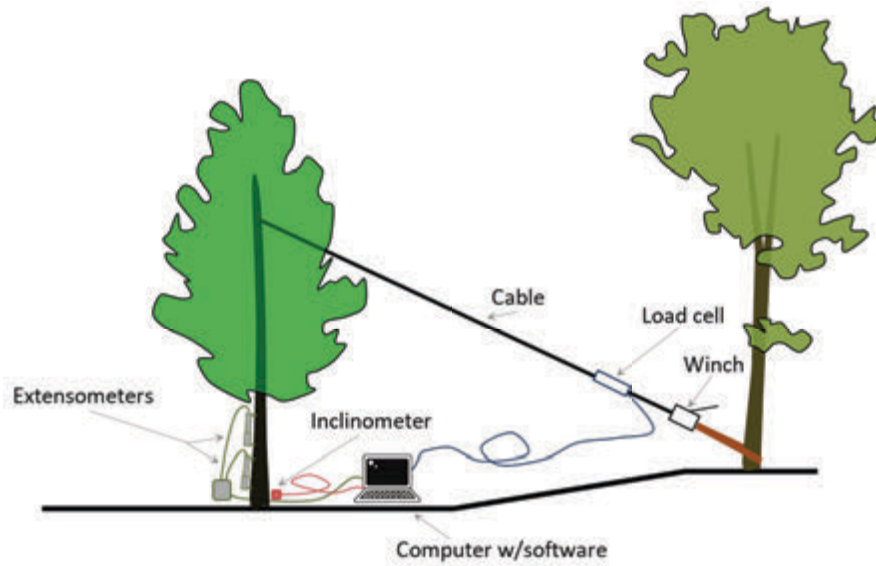


Figure 3.2.
The testing setup and main components of the pulling test



Figure 3.3.
Cable, winch and strap used for
creating lateral load on the tree

The cable needs to be mounted in the crown of the tree (around the trunk or a large branch), and the winch anchored to a point near the ground (often around the trunk of another tree). Since there is significant load on it, the cable is very likely to cause damage to the tree(s). To avoid this, operators usually use a wide, soft belt or strap to go around the tree.



Figure 3.4.
Using a strap to protect the tree



Figure 3.5.
Checking the load rating on the protective strap



Figure 3.6.
Cable-mounted calibrated load cell

Obviously the strap or belt should also be strong enough to withstand the tension on the cable. Straps used for the pulling test should be rated, and the rating checked before testing.

LOAD CELL

The accurate measurement of the cable tension (i.e. the lateral load exerted on the tree) is crucial for creating the load-inclination or load-deformation curve, and, ultimately, assessing the safety of the tree. Tension is measured using a calibrated load cell.

The load cell may be mounted on the cable or placed in-between the strap and the cable. The instrument provides accurate real-time load readings with sufficient frequency (at least 1 reading per second), which is recorded and displayed by the evaluation software. The load cell needs to be rugged, reliable and weather proof.

INCLINOMETER(S)

Tree stability assessment requires accurate inclination measurement of the tree collar (the base of the tree, close to the ground.) Inclination measurement requires a so-called inclinometer with appropriate sensitivity (± 0.001 degree) and measurement range.

The inclinometer is typically secured to the base of the tree via a mounting plate screwed to the



Figure 3.7.
Load cell placed in-between the strap and the cable (courtesy of Argus Electronic GmbH)

tree collar. The instrument itself is connected to the mounting plate through a leveling apparatus (usually a ball-and-socket joint). During measurement, the inclinometer is connected to the computer via a data cable or Bluetooth to forward the inclination values to the measurement software with sufficient frequency.

EXTENSOMETER(S)

For assessing trunk breakage safety, the deformation of the trunk needs to be measured. This requires a very sensitive device for measuring the deformation (± 0.001 mm) of the trunk. Deformation is measured either the same side



Figure 3.8.
Inclinometers mounted on the root collar
(courtesy of Argus Electronic GmbH and
FAKOPP Ltd.)



Figure 3.9.
Mounting plate for inclinometer with
biaxial levelling apparatus

or on the side opposite the cable (compression or tension zone, or possibly both). For this, we typically use so-called LVDT (Linear Variable Differential Transformer) type extensometers. LVDT extensometers can measure the relative elongation of the tree trunk very precisely.

An LVDT extensometer consists of a stationary casing, and a moving core. Both of these need to be secured to the tree, after which their relative displacement can be measured very precisely. The relative displacement values are, again, sent to the evaluation software, which generates the load-deformation curve.



Figure 3.10
Extensometer mounted on the tree trunk
(courtesy of Argus Electronic GmbH)



Figure 3.11.
Extensometer in locked (left) and open (right)
position. (1 – cable, 2 – casing, 3,4,5 – locking
mechanism, 6 – moving core, courtesy
of FAKOPP Ltd.)

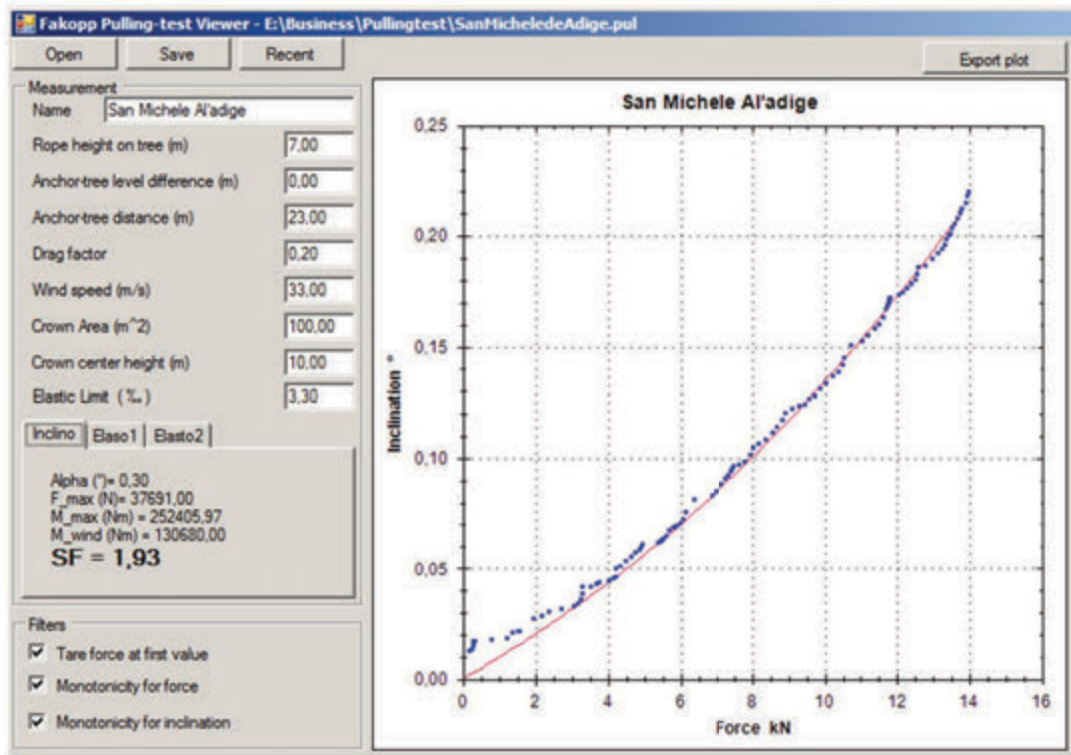


Figure 3.12.

Example of a pulling test software output screen

THE PULLING TEST SOFTWARE AND COMPUTER

Both the implementation of the test and the evaluation of the results requires appropriate computer software. There are several versions of the pulling test software available on the market (usually shipped along with the pulling test apparatus). Depending on the software, they are usually capable of:

- Calculating horizontal loads based on the geometric parameters entered;
- Simultaneous load, inclination and extension measurements;
- Generating load-inclination and load-deformation curves;

- Automatic Safety Factor calculation for uprooting and trunk safety based on the entered geometric parameters, drag factor, elastic limit and reference wind velocity values;
- Exporting the results into reports and/or in tabulated format.

Simultaneous data collection and evaluation during the test is important, in order to know when to stop the testing without causing damage to the tree. This requires a portable computer (laptop or tablet) that receives the data and alerts the operator to stop the test when the appropriate inclination or deformation is

reached. System specifications depend on the particular testing software used, but the demand is usually moderate.

In addition to the load-inclination and/or load-deformation diagrams, the evaluation of the results also requires certain geometric parameters, like crown surface area or crown centerpoint height. This may be determined by estimation, but this requires a lot of practice and is likely to be inaccurate. Nowadays experts usually use digital photographs taken of the tree and analysed by a computer software (which may be the same or a separate software from the pulling test.) For more on this, see the evaluation section.

LADDER OR CLIMBING GEAR

Depending on the height of the tree, we may also need a ladder, or need to climb up in the tree to secure the strap that the cable is attached to at a sufficient height. If we use the former, it is best to have a lightweight, telescopic or collapsible aluminium ladder. Tree climbing gear may be a more flexible and less cumbersome alternative, but its use requires expertise and experience. In either case, safety is an utmost priority.

B. TESTING PROCEDURE

Figure 2 shows a generalised schematic of the testing setup. In this chapter, we will provide a step-by-step operation guide concerning how to prepare and implement the pulling test. Before setting up and starting the test, some general rules that need to be observed:

- Pulling test requires a relatively calm day with wind speeds below 25 km/h. High winds can interfere with the testing, and result in false readings.
- The stability and strength of trees may be different depending on direction. Trees tend to be strongest in the so-called prevailing wind direction (the point of the compass



Figure 3.13.

Lightweight collapsible ladder (left) and climbing gear (right, courtesy of Dr. Lajos Puskas)

where the wind most frequently blows.) For optimal results, testing direction should be the same, or at least close to the prevailing wind direction.

- Test setup, implementation and dismantling requires from 30 to 60 minutes per tree. You need to plan accordingly.
- During setup and testing we need to observe the appropriate safety measures (see at the end of this section.)

First, pulling test equipment needs to be transported to the testing location. Since many components of the equipment (like the cable, winch, ladder and/or climbing gear) are heavy and/or awkward to carry, this usually requires an assistant, who can also aid in the setup and testing. Preparations to the test include the following steps:

1. FIXING THE CABLE IN THE CROWN

The first step of the testing is securing the cable in the crown. As mentioned in the previous section, to avoid damage to the tree, the cable is not hooked directly around the tree. Instead, we use a soft, wide strap that goes around the trunk, and hook the cable into the strap.

The strap usually goes around the trunk of the tree, at sufficient height in the crown. The higher the fixing point, the lower the load required on the cable, because the lever arm is longer. This is especially useful when testing old, large diameter trees that require significant torque to produce the desired inclination and/or deformation. On the other hand, securing the strap high up in the tree may require much climbing, or using long ladders.



Figure 3.14.
Running the strap around the trunk of the tree



Figure 3.15.
Hooking the cable into the strap

2. INSTALLING THE WINCH

After one end of the cable is secured in the tree, the other end needs to be fed into the winch. The winch itself is attached to an anchorage point near the ground. This may be the trunk of another tree (close to the base), a tree stump, or any object that is safely anchored in the ground. If we use another tree, then, again, we need a soft strap to go around it so as not to injure the trunk of the tree.



Figure 3.16.
Feeding the cable into the winch



Figure 3.17.

Winch attached to the anchorage point via wide strap

We should choose an anchor point on the side of the tree opposite the prevailing wind direction. This is not always easy, since we may not have a convenient anchor point in exactly the right direction, but we should strive to find one as close to it as possible.

We should also pay attention that the cable should not be too steep, otherwise we cannot exert enough horizontal load, and push the tree into the ground. When taut, the cable's angle should be max. 30 to the horizontal.

Attention: winches are powerful instruments designed to create heavy tension on the cable. Operators should be familiar with the workings of the winch and be very careful to avoid serious personal injury!

3. MOUNTING THE LOAD CELL

Depending on the particular system used, the load cell should either go between the strap and the cable, between the winch and the anchoring strap, or mounted on the cable.

When using a cable-mounted load cell, the instrument goes over the cable, somewhere above where the cable enters the winch. It should

not be too close to the winch, since we will have to feed the cable further into the winch to exert the required pulling load. It should also not be too high up on the cable so that we do not have difficulty attaching it. When the cable is nearly taut, a distance of approx. 50 to 60 cm should be sufficient.



Figure 3.18.

Attaching the cable-mounted load cell to the cable



Figure 3.19.

Load cell should be at a sufficient distance from the winch

4.

MOUNTING THE INCLINOMETER(S)

The inclinometer goes on the root collar, i.e. on the base of the tree as close to the ground as we can practically place it. For stability assessment, we need to measure the inclination of the root collar. If the inclinometer is mounted higher on the trunk, we will register higher inclination and lower Safety Factor values than is the case in reality.

Depending on the type of inclination sensor used, first we usually need to attach the mounting plate to the tree. This is typically done by screws (the damage to the tree is minimal), or sometimes using straps.



*Figure 3.20.
Attaching the mounting plate to the tree collar*

After mounting the plate, we attach the inclinometer instrument itself. Finally, depending on the type of inclinometer used, we usually need to level the instrument, otherwise we may exceed the measurement range. It should be level in all directions. We can use a small spirit level for this, but there are also mobile phone

applications available cheaply (or even free of charge) for this task.

Some of the mounting plates also have built-in spirit levels to aid levelling (Figure 22).



*Figure 3.21.
Levelling the inclinometer using a small spirit level (top) or a cell phone application (bottom)*

If we have a healthy, relatively large diameter tree, one inclinometer is usually enough to measure the inclination of the root collar. However, smaller diameter, or diseased trees deform relatively easily, and, even if the sensor is placed close to the ground, the added deformation of the trunk may read to false readings. In such cases two or even more inclinometers may be used simultaneously.



Figure 3.22.
Mounting plate with built-in spirit level



Figure 3.23.
Using several inclinometers on the same tree

Note that the root collar of very young, small diameter trees show large deformation (bending) during testing. We are measuring this in addition to root inclination, which results in amplified inclination and reduced SF. For this reason, we should avoid testing young trees below 40 cm trunk diameter.

5.

MOUNTING THE EXTENSOMETER(S)

The extensometers are to be mounted on the tree trunk, at the position where the tree is most likely to break. If there is no indication of any weakness in the trunk, we can mount it at breast height. When using more than one extensometer, we can check several positions on the trunk.



Figure 3.24.
Mounting the extensometer on the side of the trunk, in the closed position

Mounting the extensometer is usually a simple task that requires attaching the casing and the moving core to the trunk of the tree, at the desired position, with one screw or nail each. The extensometer should be locked for mounting (see Figure 3.11.), after which we can open the locking mechanism for the test itself. We can attach the extensometer on the same side of the tree where the cable is attached (compression zone) or on the opposite side (tensile zone). The extensometer should not be mounted laterally, because we will register lower readings, or (in the so-called neutral zone) no deformation at all. After mounting all of the measurement instruments, they need to be connected to the computer.



Figure 3.25.
Extensometers mounted on the side of the tree,
in the open position

6. TESTING

After completing the preparations, we are now ready to start the test. First, we need to launch the pulling test software, and input some basic geometric data and other parameters, as follows:

- Tree geometry: crown surface area and crown center height
- Measurement setup geometry: anchor-to-tree distance, rope fixing height, anchor-to-tree level difference
- Reference wind velocity
- Aerodynamic drag factor
- Linear elastic limit (for trunk safety only)

Tree geometry and is usually determined by taking a digital image of the tree, and analysing it. This requires a clear digital image of the tree, with a reference distance marked on the image. The operator needs to know and enter the actual measurement of the reference distance. The longer the distance the more accurate the geometric parameters will be – it is best if we can measure and enter the tree height.

The software calculates the crown surface area and crown centerpoint height from the picture. The software may estimate crown geometry as a geometric shape (e.g. an oval), or the operator

may mark the approximate contour of the crown, and the software calculates the area and centerpoint position.



Figure 3.26.
Image of a tree with the crown contours (red)
and a reference length (height of the tree, blue)
marked.



Figure 3.27.
Testing in progress

After providing all of the required data, we may start the test. Throughout the test, we create gradually increasing tension in the cable, by winding the winch slowly and evenly. This generates torque in the tree, causing the trunk to bend and the tree collar to tilt.

Testing should be arrested when we reach an inclination of 0.25 degrees, to protect the tree from harm, and especially to prevent the tree from falling and causing injury or damage to nearby trees or structures. (Trees do not usually uproot or break below 2 degrees of inclination, so this should be well within the safe region. Nevertheless, we should minimize risks by confining bystanders to a safe distance and wearing protective gear.)

The inclination of the tree collar should be monitored throughout the test to determine when we need to stop testing. The testing software usually gives visual and/or auditory warning upon reaching .25 degrees of inclination or the load limit of the winch.



Figure 3.28.

Computer screen showing the measured parameters. The computer warns the operator if the inclination or load limit is reached



SAFETY WARNINGS:

The pulling test requires significant loads, and may be dangerous if proper protocol is not observed. Rope failure can cause serious injury, so follow the safety instructions below:

- The leader of the pulling test team is responsible for the safe execution of the test.
- Only trained personnel is allowed to perform the pulling test
- The pulling device, including belts, cable and winch must be intact. Inspect the equipment before the test for any damages.
- All devices must be protected from high moisture, frost and extended periods of sunlight exposure.
- The work area should be closed off from the public. Unauthorized persons must not be allowed to come near, pass under or climb over the cable.
- Pulling test team members should wear protective gear, including hard hats and steel-toed shoes. Protective gloves are also advisable when handling the cable and winch, climbing tree, etc.
- Pulling test team members need to stay at least 2m from the cable, except for the winch operator.
- 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.
- Above 1 kN of load, the winch operator should use an extension arm, and stand as far as possible from the cable.
- Stop the pulling test after reaching 0.25 degree of inclination.
- If the tree starts creaking, stop the pulling test immediately! (Do not confuse this with the noise caused by the rope adjusting its position in the tree.)
- Follow all of the safety instructions listed in the pulling device manual.
- Pulling test must not be performed in rain, or in freezing temperatures.

NOTE:

it is also possible to test trees all the way to failure (by either uprooting or breakage), if damaging the tree is not a problem (e.g. if the tree is diseased and slated for removal.) This requires creating significant torque, by either using a long lever arm (i.e. securing the cable high up in the tree) or considerable load on the cable. In such case, safety is of the utmost importance; bystanders should be well out of the way, the winch should be at a safe distance, and operators should wear strong protective gear! Such tests are very useful especially for research purposes.

C. EVALUATION OF THE RESULTS

Based on the parameters entered at the beginning of the test, and the load-inclination and/or load-deformation curves, the pulling test software evaluates the results automatically, which is convenient for the operator. It is important for us to understand the meaning, and be able to interpret the results:

WIND LOAD

The software calculates the maximum expected torque from wind loading (M_{wind}), based on the entered crown geometry, reference wind velocity and drag factor values, using the formulas introduced in chapter I. This is the torque that the tree will have to withstand without uprooting or trunk breakage.

LOAD-INCLINATION CURVE AND UPROOTING TORQUE

The load-inclination data points follow a special, second-order tangential relationship introduced in chapter I. Figure 1.8. demonstrates this relationship very well. It shows the load-inclination curve of a tree tested all the way to failure, so the uprooting moment (F_{tip}) is clearly visible from the graph, and the uprooting torque is easy to calculate.

However, when assessing tree stability, we only test to .25 degrees of inclination, and we only get the first part of this curve. The way we determine M_{tip} from this curve is by fitting the tangential curve on the available data points, and extrapolating the curve to F_{tip} . (Figure 3.29.). (Note that the load values shown in Figure 3.26. are the horizontal component of the load on the cable, which the software calculates based on the entered geometric data.)

LOAD-DEFORMATION CURVE AND TRUNK BREAKAGE TORQUE

As discussed in chapter I, the load deformation curve of the trunk follows a linear relationship up to the so-called linear elastic limit. The tree does not actually break at this limit, but there is irrecoverable damage done to the trunk. Therefore, safety calculations are based on the elastic limit, rather than the ultimate load. In this case, again, we only measure the early stage of the load-deformation curve, and the software extrapolates the load to the entered linear elastic limit to calculate the critical horizontal load ($F_{breaking}$, see Figure 3.30.) and from that, the torque required for trunk breakage ($M_{breaking}$).

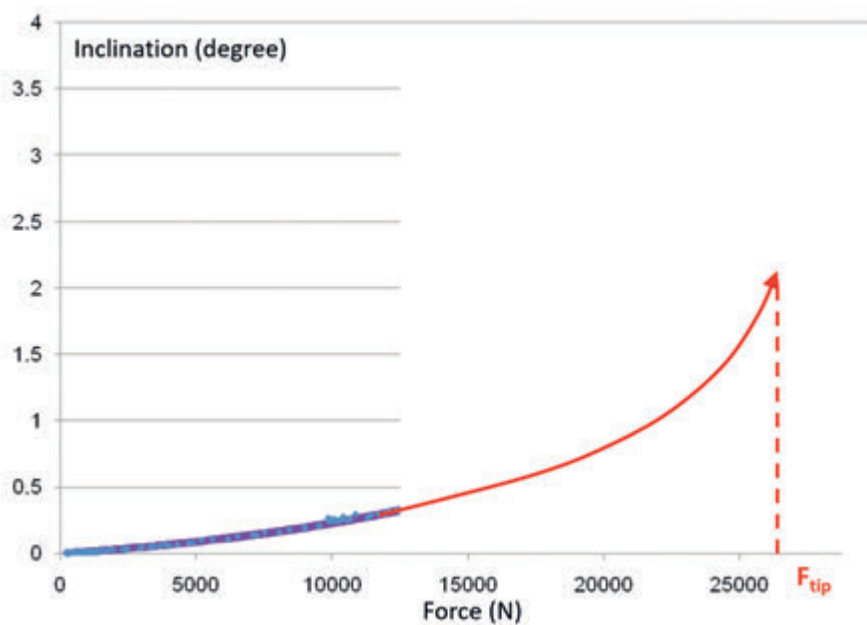


Figure 3.29.

Determining the uprooting force (F_{tip}) from the early part of the load-inclination graph by extrapolation, using the special second order tangential relationship

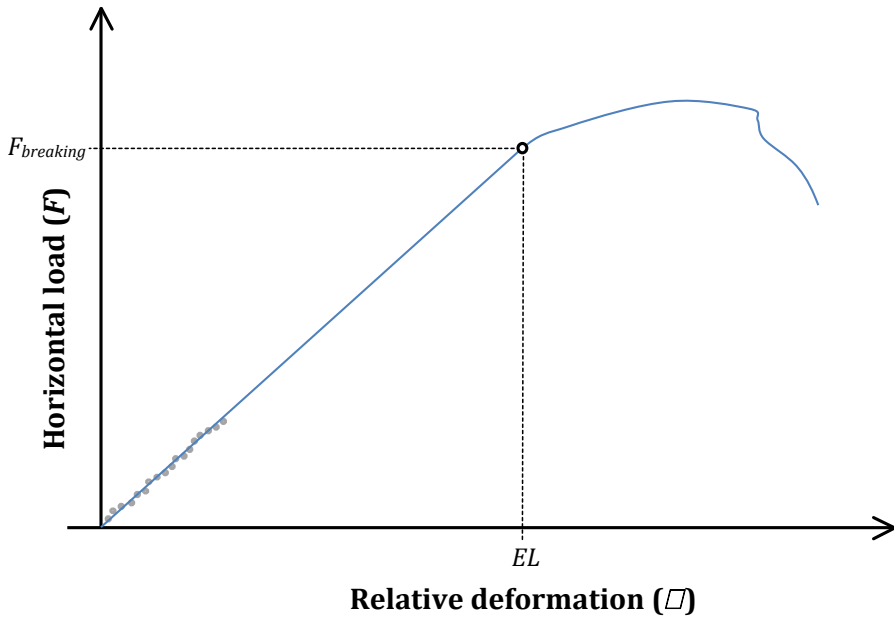


Figure 3.30.

Determining the trunk breakage force (F_{breaking}) from the early part of the load-deformation graph by linear extrapolation to the elastic limit (EL)

The linear elastic limit (EL) is a species-specific value that is available for many species from the Stuttgart table of wood strength (see chapter I)

SAFETY FACTOR

The software calculates the Safety Factor (SF) of the tree by simply dividing the tipping moment (M_{tip}) or the breaking moment (M_{breaking}) by the wind load moment (M_{wind}) for uprooting safety and trunk breakage safety, respectively. For the interpretation of the Safety Factor, see chapter I. There are a few things that are important to keep in mind when interpreting the Safety Factor:

- Wind load moment, and therefore the Safety Factor is always calculated relative to a reference wind velocity. A tree with a relatively

high Safety Factor at this wind velocity may not be safe in stronger winds!

- Trunk breakage safety factor is valid for the section of the trunk where the extensometer was located during the test. If a weaker section of the trunk should exist, the tree may still break at or below the reference wind velocity. Evaluation certainty may be improved by measuring more sections of the trunk, or combining the test with other forms of assessment (e.g. acoustic tomography.)
- The Safety Factor values are valid in the circumstances under which the measurement took place. Factors like foliage changes, frozen ground, soil moisture content may affect the safety of the tree. If the Safety

Factor is below 1, the tree is unsafe, requires intervention. Above 1.5, the tree is considered safe. Since there is some uncertainty in the determination, if the SF is between 1 and 1.5, there is a moderate risk of uprooting or breakage, and the tree should be monitored to see if it is safe. For a more detailed discussion, see section 4) at the end of this chapter.

D. ADVANTAGES AND LIMITATIONS OF THE PULLING TEST

The pulling test (sometimes also referred to as the 'elasto-inclino method') has been in widespread use by tree inspection experts since the 1980's. It was developed based on solid biomechanics principles, and is considered the standard method for tree stability inspection. It is, however, not without its drawbacks and limitations.

ADVANTAGES OF THE PULLING TEST:

- Accepted and approved method for tree stability and trunk breakage safety evaluation;
- Works well in calm weather (wind velocities below 25 km/h);
- Operator has complete control over testing conditions (direction, loading rates, etc.);
- Good correlation between measured parameters provides a high level of confidence in the results.

DRAWBACKS AND LIMITATIONS:

- Uncertainties in geometric parameters: determining tree crown geometry can be somewhat tricky. It is done either by estimation, which has a high likelihood of imprecision, or by digital image analysis. The latter

method relies on the operator marking the boundaries of the crown on the image, which is somewhat subjective, and, at the current level of advancement, the software cannot take the coverage of the area into account. It also requires a reference length value, which may introduce another source of inaccuracy.

- Uncertainties in species-specific parameters: some constants needed for the evaluation, like the linear elastic limit, or the aerodynamic drag factor come from literature data, as species-specific values. However, there are often very significant differences between trees of the same species (so-called ontogenetic differences) that may considerably alter these values.
- Uncertainties in wind intensity: differences in the terrain, shading from other trees or artificial objects, and vertical wind intensity variations may significantly affect the actual wind intensity that individual trees experience in high wind conditions, and may affect the actual safety of the tree.
- The pulling test cannot be used in windy weather (wind velocities above 25 km/h.)
- Testing requires heavy and cumbersome equipment and much preparation.
- Lastly, the pulling test is based on a static loading scenario. The response of the trees to the gradually increasing static load exerted by a cable may be markedly different from the erratic, dynamic wind gusts that act on the complicated system of leaves, twigs, branches and trunk of the tree. A more realistic, dynamic loading scenario may offer better insight to the safety and stability of trees.

3. THE DYNAMIC TEST

Currently, the most accepted method of tree stability assessment is the static pulling test, even though there are many disadvantages and limitations, as discussed in the previous section. The biggest issue is that it is a poor way of modelling the response of trees to actual wind loads (Moore and Maguire 2004). It would be much better to measure the trees' response to actual wind loading.

Unfortunately, the behaviour of trees under actual wind load conditions is far from straightforward. Trees – especially open-grown trees, typical of urban situations – constitute a complex system of trunk, primary and secondary branches, twigs and leaves (James et al. 2006, 2014, see Figure 3.31.).

The behaviour of such trees under dynamic loading conditions is very erratic. In fact there seems to be no direct relationship between momentary wind velocity and the inclination

of the trunk. There is often little movement when wind velocity peaks, and the tree can sway strongly in a relative lull (see Figure 3.32.). Due to the complex interaction of the different components, the actual response of the tree is practically impossible to model or predict at our current scientific capabilities (Sellier and Fourcaud 2009). In fact, the behavior of the various components – trunk, branches, twigs – is not unlike that of a multiple damped pendulum (Bejo et al. 2017).

The branches and the trunk constitute a nonlinear vibrating system that behaves very erratically. The behavior of such systems is extremely sensitive to the initial boundary conditions, and is virtually impossible to predict long term. This type of behavior is called chaotic motion, and multiple pendulums are also dubbed chaotic pendulums for this reason. This is why there appears to be no direct relationship between momentary wind velocity and the inclination of the trunk. In fact, in high

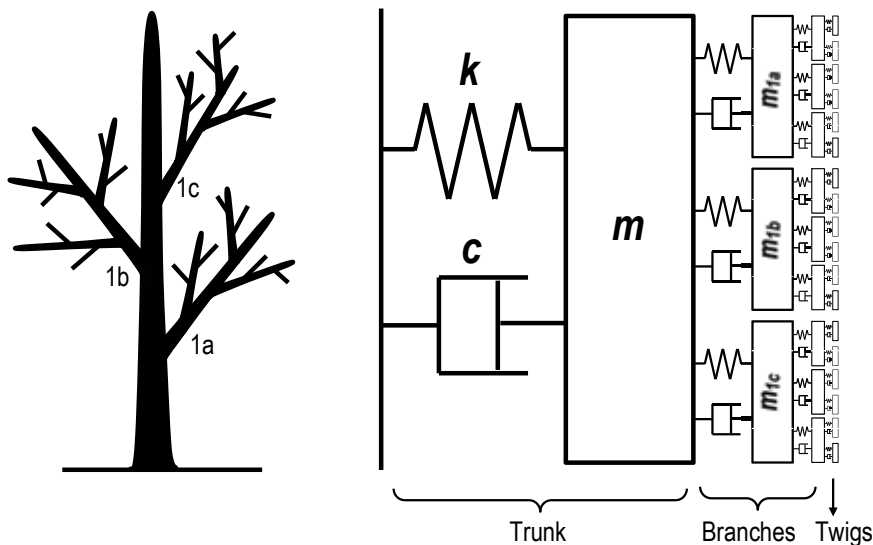


Figure 3.31.

The model of a tree as a complex, interconnected system of different components (based on James et al. 2006)

wind gusts the tree often remains relatively stable, while sometimes in a relative lull significant loss of stability is observed (see Figure 3.32.). This phenomenon goes well beyond a simple time lag; it appears almost completely random (Divos et al. 2015).

However, chaotic systems may be studied using statistical methods (Strogatz 2014). While there is no direct relationship between momentary wind load and inclination, average wind speed and average inclination values taken over longer periods (e.g. 1, 5 or 10-minute intervals) exhibit a similar relationship as that found between load and inclination during static testing.

Dynamic testing is based on the same principles as the static test, except the static horizontal load is replaced by statistical parameters of actual wind loading. For example, the wind load and inclination diagrams introduced in Figure 3.29. can be broken down into longer intervals, and statistical parameters (e.g. the average over a 5 or 10-minute period) can be calculated, as

shown in Figure 3.33. It is evident from these diagrams that, while momentary values cannot be correlated, the averages (indicated by red lines in the figure) are in relatively good agreement.

By measuring the wind intensity and root collar inclination over longer periods of several hours, grouping them into batches of several minutes, and calculating the averages, similar load and inclination data pairs can be obtained as the ones used for evaluating pulling test results. As explained in chapter I, wind load-inclination and wind load-elongation data points follow the same trend, as in the case of static loading (tangential curve and linear, respectively). There are only two important differences:

- Data points are not consecutive but random;
- Instead of horizontal force, wind velocity or wind pressure is measured.

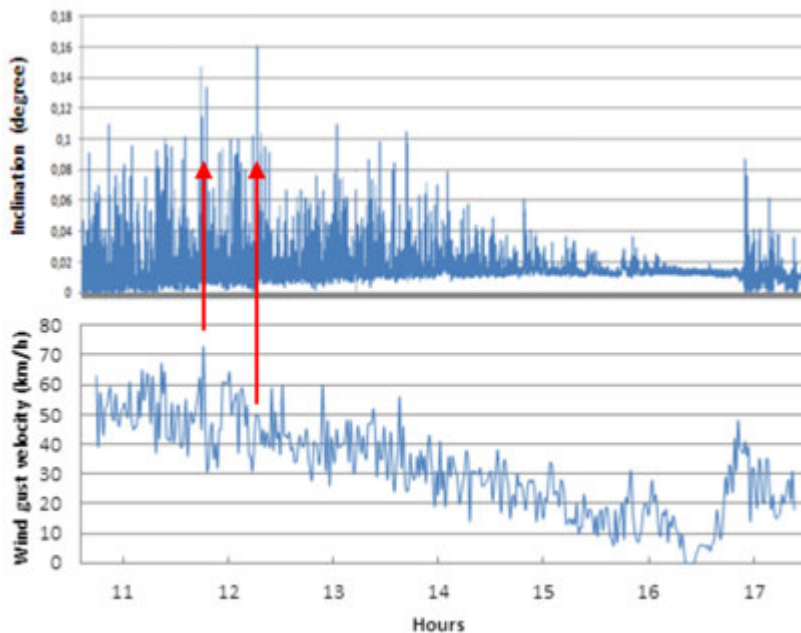


Figure 3.32.

Momentary inclination and wind velocity data shows no immediate correlation between the two factors (Bejo et al. 2017)

The first issue is inconsequential since curve fitting can be executed regardless of the order of the points, as long as enough data points are available. The second issue means that the calculation of the Safety Factor is slightly different, since wind load is substituted for the static load employed to determine M_{tip} . Therefore, the safety factor can be expressed, as follows:

$$SF = \frac{M_{tip}}{M_{wind}} = \frac{p_{tip} A_{tree} c_w h_{cc}}{p_{wind} A_{tree} c_w h_{cc}}$$

Notice that by substituting wind pressure for the calculation of the tipping and maximum wind moments (M_{tip} and M_{wind} , respectively), the crown area (A_{tree}) and, crown centerpoint height (h_{cc}) cancel out in the equation, since these parameters are the same whether we are considering maximum or uprooting/breakage wind pressure.

The situation is less straightforward in case of the species-specific drag factor (c_w), which depends on wind intensity, and does not affect low-wind section of the curve as much as the high wind area. However, because the drag factor is lower in high wind, using the same, high c_w value throughout the curve results in conservative estimation. This way, we can cancel out the drag factor too.

Thus, the equation is reduced to the ratio of the tipping wind pressure to the maximum wind pressure (the wind pressure belonging to the highest expected wind velocity). Tipping pressure (p_{tip}) is determined from the pressure-inclination curve the same way as F_{tip} is determined from the load-inclination curve. The safety factor determined this way is not only simpler to calculate, but likely to be more relevant to the dynamic loading situation that trees experience in the wind.

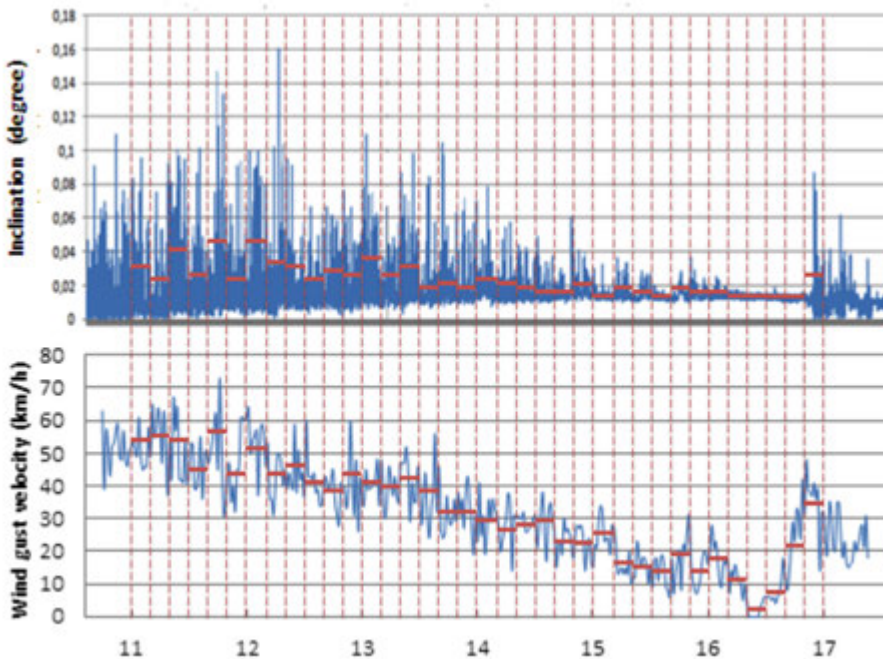


Figure 3.33.

When grouping wind gust velocity and inclination data into batches, and calculating the averages, the correlation improves

A. EQUIPMENT

Figure 3.34. shows the testing setup required for dynamic stability testing. The system consists of the following components:

ANEMOMETER

The anemometer is an instrument for measuring and registering the wind velocity and direction at or near the tree to be evaluated. The closer the anemometer is to the tree, the better. Ideally the anemometer should be clear of buildings or other objects that may obstruct the wind, at a height of 10 m.

There are two different types of anemometers currently in use:



Figure 3.35.
Ball type anemometer

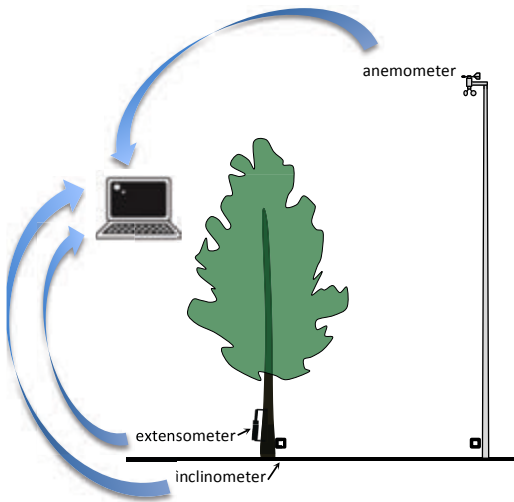


Figure 3.34.
Test setup for dynamic tree stability assessment

Ball type anemometers are straightforward instruments that have rotating cups to measure wind velocity, and a windcock or weathervane to determine wind direction.

Sonic anemometers emit ultrasonic signals in various directions and measure the time required

for the signal to reach the opposing sensor (the so-called Time-of-Flight, or ToF). In still weather, the time of flight is the same in all directions. In windy weather, if the signal travels with the wind, ToF is shorter, and it gets longer against the wind. Ultrasonic anemometers usually have two sensor pairs in orthogonal directions, and can determine both the velocity and the direction of the wind. They are less prone to failure because they contain no moving parts. As mentioned in chapter I, the anemometer must provide wind velocity readings with sufficient frequency (usually 1 data/second.)



Figure 3.36.
Ultrasonic anemometer



Figure 3.38.
Anemometer mounted on mobile telescopic mast

Anemometers may be permanently installed, for example on top of buildings, or we may use mobile anemometers if permanent anemometers are not available. Mobile anemometers are mounted on top of collapsible or telescopic masts. Masts must be tethered so that the wind won't topple them.



Figure 3.37.
Anemometer permanently mounted
on top of a building

It is very important that wind velocity, inclination and/or deformation data is perfectly synchronised during evaluation. Since the data is usually not sent directly to a computer but recorded by the instrument, accurate time data must also be recorded.

Depending on the geographical location, wind velocity and direction data may be available publicly from nearby weather station. In such cases, temporal resolution should be sufficient (at least 1Hz), and the associated time data must be provided too.

INCLINOMETER

For registering the relatively small movements of the tree collar in lower winds of 25-50 km/h, very sensitive inclinometers are needed (in the 0.001° range). The inclinometer must have its own power source (enough for several hours of operation), and be equipped to store the relatively large amount of inclination data. Some models are equipped with Bluetooth or are wi-fi enabled for easy data transfer. The instrument should also record the accurate time along with inclination.



Figure 3.39.

High precision inclination recorder with mounting plate and power source



Figure 3.40.

Cheap, lower resolution sensors for easy operation and long-term tree inclination monitoring (courtesy of Argus Electronic GmbH)



Figure 3.41.

Solar charger equipped inclination sensor with remote monitoring capabilities allow several months of unsupervised operation (courtesy of Argus Electronic GmbH)

Cheaper versions of the inclinometer are also available. These instruments have a lower resolution, and require larger tree collar movements (i.e. high winds) to create accurate readings. The primary advantage is the lower price. Some versions of these instruments do not require levelling, may be equipped with solar cells for automatic charging, and may even allow remote monitoring, for several months of uninterrupted and unsupervised operation.

EXTENSOMETER

Dynamic testing also allows the evaluation of trunk safety. This requires high sensitivity extensometers. These instruments are similar to the one used for the pulling test, except that they need to be able to record the deformation data along with the time of the measurement, and have their own power source, similarly to the high precision inclinometer mentioned in the previous section.

EVALUATION SOFTWARE

The evaluation software used for dynamic tree stability and trunk safety determination is similar to that used for the pulling test. After importing the data, the software groups it into batches, calculates the statistical value(s) (average or some other parameter) for each batch, creates data pairs, and fits the appropriate model (second order tangential function or straight line, for inclination and deformation, respectively), for calculating the tipping or breakage pressure.

B. TESTING PROCEDURE

The testing procedure for dynamic tree stability and trunk safety evaluation is somewhat similar, but much simpler than that of the pulling test. It consists of the following steps:

- **Appropriate measurement conditions:** in dynamic testing, we have much less control over the measurement conditions than in static testing. Dynamic testing requires wind speeds of 25 km/h. It is best if the wind direction is close to the prevalent winds, and other conditions (like soil moisture content, presence of foliage, frozen soil, etc.) matter as well. It is best to monitor the weather forecast and choose the time of measurement accordingly.
- **Erecting the mast:** if a mobile mast is used, it should be erected before installing the inclinometers and/or extensometers. The anemometers should be at a height of at least 10m, preferably in an open area, clear of buildings, tall trees or any other obstruction. After the mast is up and the instrument is operational, it needs to be turned on and data collection started.



Figure 3.42.
Erecting the mobile mast

- **Installing the inclinometer(s):** the procedure is the same as described in the section on the pulling test procedure. The key difference is that the inclinometer is not connected to a computer, but collects time and inclination data after the instrument is turned on. If a dual-axis inclinometer is used, it doesn't matter where the inclinometer is installed, but on young trees, or trees with a weakened trunk, using several inclinometers may be a smart idea.



Figure 3.43.
Extensometers mounted in orthogonal positions to allow calculating the deformation on the upwind or downwind side of the tree.

- **Installing the extensometer(s):** the extensometers are, again, installed in a similar manner as described at the pulling test procedure. For best results, the extensometers should be either on the same or opposite side of the tree relative to the wind direction. Unfortunately, the exact wind direction is not necessarily known when starting (and it may change in the course of) the measurement. Therefore, experts often use two extensometers in orthogonal positions on the tree trunk. The evaluation software can calculate the maximum tension or compression on the tree trunk based on the two readings.

Regardless of wind direction, intensity, tree-anemometer distance or any other factor, the longer the measurement the better. Measurement duration may be limited by the length of the windy period, or the capacity of the batteries used. The measurement usually takes at least three hours or more, which means that dynamic testing is more time-consuming than the static test. On the other hand, with this technique, several trees may be tested simultaneously. One may easily test ten trees or more at the same time; the only limitation is the number of inclinometers and/or extensometers available, since mounting usually only takes a couple of minutes.

Simpler, cheaper inclinometers described in the previous section usually allow longer testing times (even several months, if the remotely accessed, solar charger equipped instruments are used.) The downside is the inferior sensitivity, where meaningful data requires testing in high wind conditions.

After the completion of the test, data is collected from the instruments. Depending on the particular instrument, data may be collected by removing the memory card, through Bluetooth or wifi, or even remotely through the internet.

C. EVALUATION OF THE RESULTS

After importing the wind velocity, inclination and/or deformation results, the software groups the data into batches. One batch contains all of the data measured over a 1, 5 or 10 minute measurement period (as specified by the user). The longer the period (or so-called statistical evaluation window), the better the data points will fit the applied model, but the fewer data points we have. A 5-minute statistical window is usually optimal, depending on measurement duration.



Figure 3.44.

Sample dynamic tree stability evaluation output

As evident in Figure 3.44., data points do not fit the estimation curve nearly as well as in the case of the static pulling test, which introduces a degree of uncertainty in the dynamic test. On the other hand, this technique measures the response of the trees to actual wind loading, rather than to a static load, and many of the uncertainties associated with the pulling test are eliminated.

The correlation coefficient in Figure 3.44. provides information on the goodness of fit. The closer this value is to 1, the better the fit, and the more reliable the evaluation. Several factors influence the correlation. These will be described in a later section.

The software calculates the Safety Factor much the same way as described previously for the pulling test evaluation. The only exception is that the second order tangential fit or straight line is fit on the averages (or other statistical parameters) of the 1, 5 or 10 minute batches of data, rather than momentary values. After fitting the curve, the software performs the

extrapolation the same way as shown in Figure 3.29 and 3.30.

One simplification during the evaluation is that the operator does not need to provide the crown area, crown centerpoint height and drag factor values, because these cancel out in the evaluation, and the Safety Factor is simply calculated as the ratio of the tipping or breakage pressure to the maximum wind pressure during high winds. However, for trunk breakage safety, the program still needs the species-specific elastic limit value.

D. FACTORS INFLUENCING THE RELIABILITY OF DYNAMIC TESTING

As mentioned before, one drawback of the dynamic tree evaluation is that the data points do not fit the trendlines nearly as well as in the case of the static pulling test. The goodness of fit – as expressed by the correlation coefficient – is a key issue in this type of testing. We can be reasonably confident in the results if the correlation coefficient is at least 0.75.

There are a number of factors that influence the correlation between wind intensity and the measured inclination/deformation. Unfortunately, many of these are out of our control, but we may strive to choose conditions that provide the best results.

1. WIND INTENSITY

The most important condition for the application of the dynamic technique is windy weather. Depending on the type of instrument used, the minimum wind velocity to measure meaningful data may be as low as 25 km/h. However, the higher the wind velocity, the more intensively trees sway, and the more reliably we can measure inclination and deformation.

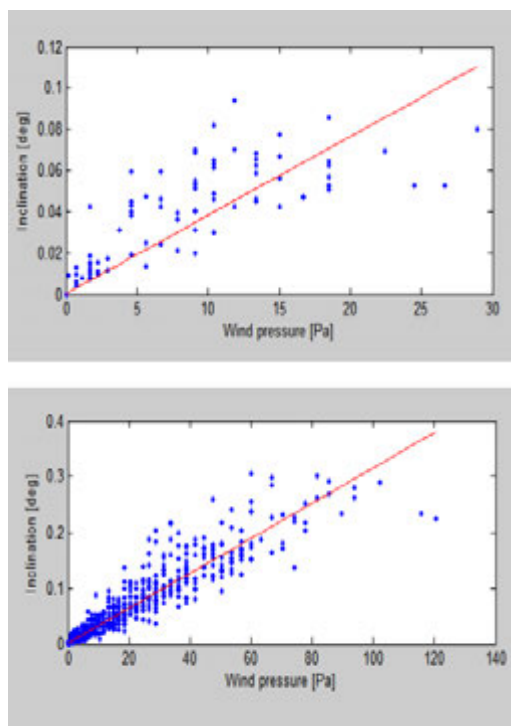


Figure 3.45.

Wind pressure and inclination data collected in low (25 km/h, top) and in high winds (65 km/h, bottom)

Also, in high winds we have higher inclination and/or deformation levels, which improves the accuracy of curve fitting, the accuracy of the estimated p_{tip} and $p_{breaking}$, and ultimately the accuracy of the Safety Factor.

Unfortunately, wind intensity is obviously out of the operator's control. Nevertheless, we should strive to choose periods of peak wind velocity for collecting dynamic load, inclination and deformation data.

2. MEASUREMENT DURATION AND STATISTICAL WINDOW SIZE

Generally, the longer the so-called statistical window – the length of the period over which data are batched together and statistical parameters

are calculated – the better the data points fit the pressure-inclination or pressure-deformation models, and the better the correlation (see Figure 3.46.). However, the longer the statistical window, the less data points we get for the same measurement duration. We need to balance these two issues to get the best results.

It is possible to use a long statistical window and still have enough data points. This requires longer measurement periods. E.g. if we choose a 10 min statistical window and want to have at least 50 data points, we need more than 8 hrs worth of data. In case of 5 min statistical window, the same number of points require only 4 hrs of measurement, but the correlation coefficient will be somewhat lower.

Just like with wind intensity, we do not usually have control over measurement duration. If we have good batteries, we may run the measurement for 10 hrs or longer, but this also depends on the weather. The wind may die down earlier, in which case we may have only 3 to 4 hrs worth of data. In such case, we usually need to decrease the statistical window to 5 min or less to have enough data points.

(In Figure 3.46., note that we get diminishing returns when increasing the statistical window length above 2 minutes. A 5-minute statistical window length is generally a good compromise between more accuracy and a larger number of data points.)

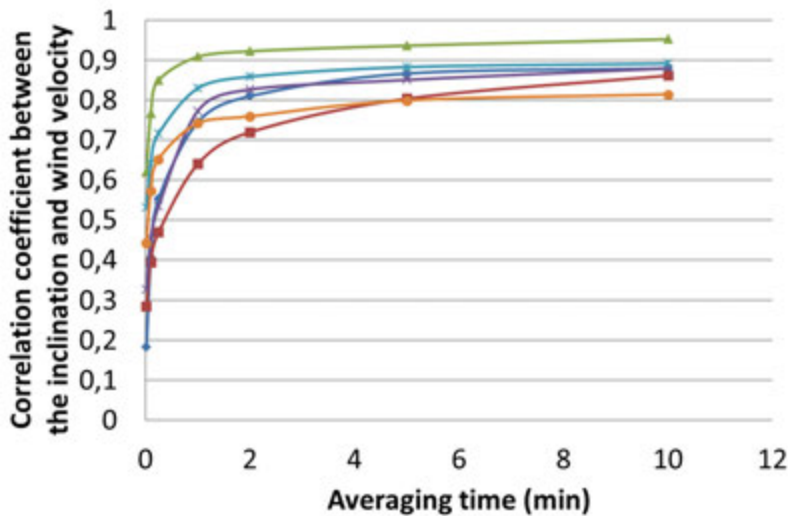


Figure 3.46.

The relationship between statistical window length and the correlation coefficient

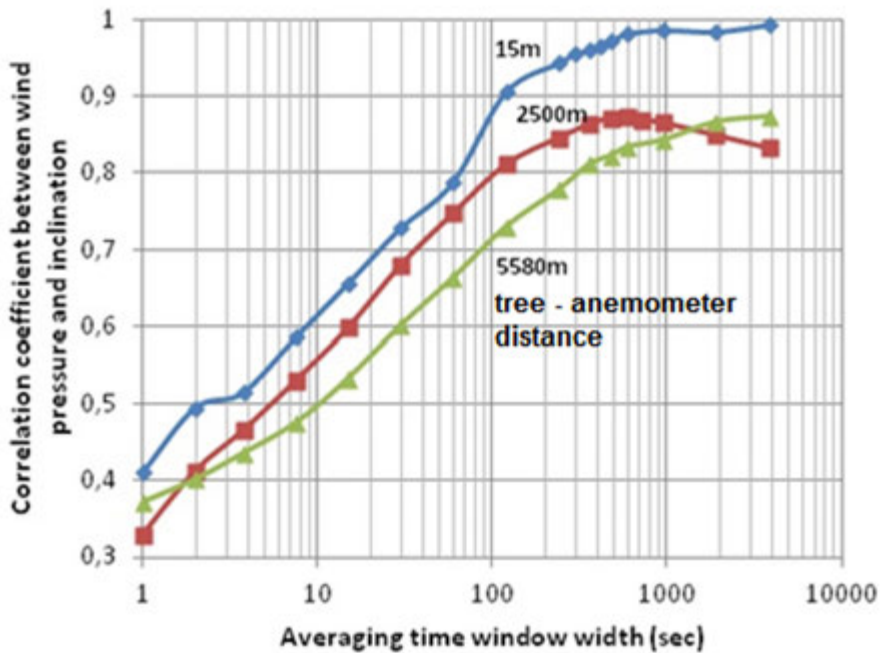


Figure 3.47.

The effect of various tree-to-anemometer distances on the correlation coefficient

3. TREE-TO-ANEMOMETER DISTANCE

Local weather – including wind intensity and direction – tend to be fairly consistent in a radius of several hundred meters, or even a few kilometres, depending on geographical location. Nevertheless, wind does tend to vary especially in high winds and storms. Therefore, it is best to measure wind velocity as close to the tree(s) under examination as possible.

Figure 3.47. illustrates the effect of anemometer-to-tree distance. The accuracy of the analysis drops by approx. 10% as we move to a distance of 2.5 km, and another 10% as we move even further. Nevertheless, meaningful analysis is still possible, even if the anemometer is several kilometres away. We may compensate for the drop in accuracy by using a longer statistical window.

This is especially useful if we want to measure several trees at the same time (sometimes located in some distance from one another), or if we use a permanently installed anemometer or data from a nearby weather station.

E. ADVANTAGES AND LIMITATIONS OF THE DYNAMIC TEST

As discussed before, dynamic tree stability and trunk safety testing is a relatively new technique. The development and the validation of this novel method is still underway, but, so far, results are encouraging.

The advantages of dynamic tree stability testing are, as follows:

- Measurements are performed under realistic, dynamic loading conditions. This type of measurement is better for examining the

safety of the tree in dynamic high wind condition than is static loading.

- Measurement equipment is simpler and lighter. No need for lugging around heavy and cumbersome equipment like cables, winch, straps, load cell, ladder, etc.
- Operation safety. Even if all possible safety measures are observed, the pulling test presents several safety issues related to climbing the tree or ladder, operating the winch, cable breakage, etc. (Note that fatal problems, arising e.g. from trees falling down are extremely unlikely during the pulling test, but non-fatal injuries are still a serious risk.) The dynamic test is virtually risk-free, unless setting up the test in stormy weather, which is not advisable.
- Data analysis is simpler; there is no need to measure and provide tree and measurement geometry, or looking up the aerodynamic drag factor. This also eliminates the uncertainties related to the determination of these parameters.
- Environmental factors, like nearby buildings or trees that provide shading from the wind, affect the dynamic measurement the same way as they affect tree safety. Such factors cannot be considered during the pulling test, which may result in underestimating the safety of the tree.
- Several (10 or more) trees can be measured simultaneously.
- Dynamic measurements can be performed in wind while the static measurement requires still weather.

The limitations and drawbacks of dynamic testing include the following issues:

- Dynamic testing is a novel method that has not been accepted and adopted in the industry yet. The validation of the new technique is underway. The next section presents some information concerning the reliability of the new method.

- Dynamic testing data points, generated statistically by grouping several minutes' worth of data together, do not fit the respective tangential and linear models for inclination and deformation as well as pulling test data. This introduces a level of uncertainty in determining the parameters and the safety of the tree.
- Dynamic testing is only possible in windy weather. Minimum wind velocities of at least 25 km/h are essential for generating any kind of meaningful results. However, higher wind velocities are preferable for improved reliability and precision.
- Dynamic testing takes longer (at least 3 hrs) than the static test (approx. half an hour to an hour.) The fact that we can test several trees simultaneously counterbalances this limitation.
- We have less control over the testing conditions during dynamic testing. Wind load levels and wind direction, especially, may not be ideal at the time of measurement. Other environmental parameters – like soil moisture content, foliage, frozen ground, etc. – may also not be favourable. (More on this in section 4).
- Finally, since the measurement is not monitored continuously, instruments may be exposed to damages due to weather, animal interference, theft or vandalism.

F. THE RELIABILITY OF THE DYNAMIC TEST

As mentioned earlier, dynamic testing is a relatively new approach that has not been tested as extensively as the static pulling test. For this reason, experts are yet to accept the dynamic method as a standard for tree stability testing. It is not easy to demonstrate the reliability of the dynamic test. The only way to prove the Safety Factor's accuracy is if the tree gets blown

down (and the wind velocity is known). We may also measure the actual tipping or breaking moment by pulling the tree over in a static test, but, as discussed before, wind loading works differently from the static load, so the tipping/breaking moment measured this way may be different from the dynamic wind load required for toppling the tree.

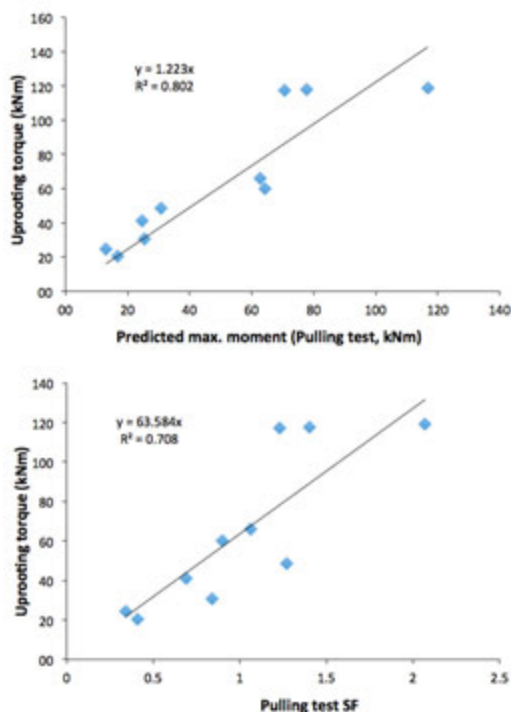


Figure 3.48.

The reliability of the pulling test: the relationship between the predicted and actual uprooting torque (top), and between the SF and uprooting torque (bottom)

In a recent study (Fathi 2020), researchers measured the Safety Factor of some diseased ash trees in Austria, both by the pulling test and the dynamic method. After testing, the trees were actually toppled using the pulling test setup, and the actual uprooting torque measured. Figure 3.48. shows the relationship between the pulling test parameters and the uprooting

torque. The diagrams clearly show that the pulling test predicted the uprooting torque very accurately and there is also a close relationship between the static Safety Factor and the uprooting torque.

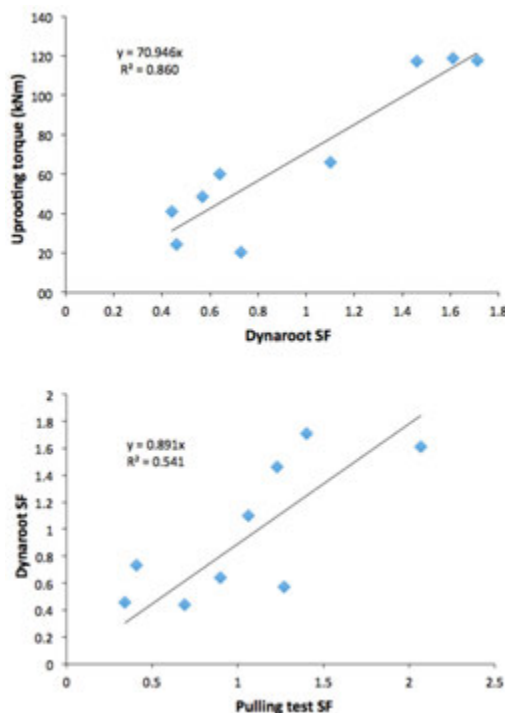


Figure 3.49.

The reliability of the dynamic test: the relationship the SF and uprooting torque (top) and the static and dynamic Safety Factor (bottom)

Figure 3.49. demonstrates the reliability of the dynamic test. Surprisingly the dynamic SF predicted the ultimate uprooting moment even better than the static value. This may just be a coincidence, because the dynamic pressure-inclination curve is actually a measure of the ultimate load that is required to uproot the tree in a dynamic loading situation, which is somewhat different from the static loading case. Unfortunately, there is no objective way to measure this; thus, we can only compare the

dynamically measured SF to the static uprooting torque. In any case, the good correlation is an encouraging sign concerning the reliability of the dynamic method.

Finally, the static and dynamic safety factors have a reasonably good correlation, but the relationship is not very tight. This is not surprising, since the two measurements work in different ways, and the differences between the two factors were as expected.



Figure 3.50.

Maple tree uprooted in a 63 km/h storm. Earlier, dynamic measurements indicated a $SF < 1$ using a reference wind velocity of 70 km/h

As mentioned before, it is almost impossible to compare the static and dynamic Safety Factor values to the actual uprooting wind loads, unless a “happy accident” occurs that proves the accuracy of the measurement in a real life situation. One such example is a weak maple tree in the Botanical Gardens of the University of Sopron,

Hungary. Dynamic measurements showed the uprooting Safety Factor value of this tree to be below 1 in a reference wind velocity of 70 km/h. A few weeks after testing the tree toppled in a storm with a 63 km/h peak wind velocity. (Fortunately no one was hurt.)

The dynamic measurement results of a single tree obviously do not prove the reliability of the method conclusively. However, this is a good indication that the method works, which is further supported by the presented static-dynamic comparison. Efforts to prove and improve the reliability of dynamic testing are ongoing.

4. FACTORS INFLUENCING TREE STABILITY TESTING

Whether we use static pulling or dynamic tree stability evaluation, there are several factors that may influence the results. We need to be aware that the results measured under certain conditions may be very different in other circumstances. We will list the most important factors that may influence stability.

A. FOLIAGE

The foliage of trees can affect the stability and trunk safety of trees very significantly. Leaves and branches offer up a surface for the wind to act upon. When this surface changes, the load on the crown changes and therefore the torque on the tree trunk and root collar, and ultimately the safety factor changes too.

There are two reasons that cause significant foliage change:

Seasonal changes: broadleaved species shed their leaves in the autumn, which decreases the crown surface area. This should theoretically decrease the wind load, and increase the safety

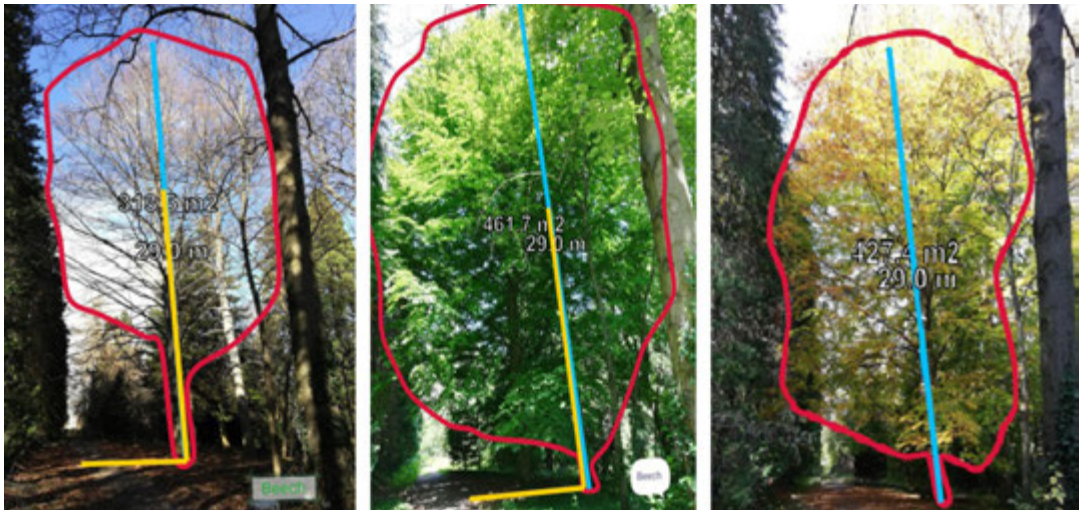


Figure 3.51.

Seasonal foliage changes (From left to right: winter, autumn and spring)

of the tree. However, in the absence of leaves, crown deformations are also smaller, the bare branches offer more resistance to the wind, and the drag factor becomes higher.

Recent studies (Göcke et al. 2018, Fathi 2020) found that dynamic Safety Factors often decrease, rather than increase in the winter, in spite of the smaller crown area.

Pruning: removing part of the crown is a frequent arboricultural practice. Forestry professionals use it to improve lumber quality, while in urban areas it is used for aesthetic purposes, or for improving the safety of the tree. Pruning removes all parts of the crown, including the branches and twigs. As opposed to seasonal foliage loss, pruning always decreases wind loads, and improves the safety of trees.

B. PRECIPITATION

Rainy weather – especially when prolonged – affects both the tree and the soil. Rain-covered foliage will have a somewhat increased inertia,

but the effect is much more pronounced in the soil. In theory, rainwater penetrates the ground, and loosens the soil, which will therefore allow more movement, and trees become less resistant to uprooting. However, this very much depends on the root structure of trees.

Fathi (2020) found that the stability of conifers tends to improve with increased moisture content. Many of these have a taproot system, with the main root reaching deep into the ground. The compaction of the lower soil layers by the added weight of the topsoil may stabilize deep-reaching roots. Other trees (like sequoia) have a dense, matted root system, which incorporates large amounts of soil. The added weight of this soil helps anchoring the tree and, again, improves stability (Fathi et al. 2020).

Snow tends to decrease tree stability. Snow will not penetrate and loosen the soil. Instead, it will accumulate on the branches (and, in the case of conifers, needles) of the tree. Sometimes the accumulation can be quite significant, and the weight of the snow will considerably increase the inertia forces, when the tree moves in the wind, and will therefore lead to increased dynamic

loads. The weight of the snow will also push the tree into the ground and help anchor it, which will alleviate the increased loading to a certain extent. Nevertheless, snow loads tend to decrease tree stability. (Sleet will also have a similar effect.)

C. FROZEN GROUND

In temperate and cold climates, temperatures may dip below freezing for prolonged periods in the winter months. This freezes the moisture in the ground, and restricts the movement of the roots. Moisture will also partially freeze in the trunk, which improves the strength. Stability measurements in prolonged cold periods may result in unrealistically high SF values (regardless of the method used for the measurement.) It is best not to use the pulling test or the dynamic tree stability assessment in such circumstances.

D. SEASONAL CHANGES

Many of the issues described under foliage change, frozen ground and precipitation (snow) are also related to seasonal changes, and we need to consider them during the evaluation of the safety factor results. One additional issue is the dormant period during winter, when the trees' biological activity is minimal.

This affects the root system, which tends to swell and be more firmly anchored in the soil in the spring and summer, due to the increased sap flow, and becomes somewhat looser in the autumn and winter. This affects the stability of all trees adversely, albeit not nearly as strongly as the foliage change or the frozen ground (Bieker et al 2010).

E. MEASUREMENT DIRECTION

As discussed earlier, each geographical area has a prevalent wind direction. Trees tend to develop their trunks and root systems so as to provide best resistance in this direction. This is usually also the direction in which we evaluate tree stability and trunk strength, because the strongest winds are also likely to blow from this point on the compass.

This is usually not a problem with static testing, where we control testing direction. The only issue is that we need to find an anchorage point roughly in this direction, which is sometimes tricky in an urban environment.

In dynamic testing, we have no control over testing direction, and have to accept whatever direction the wind blows during testing. Fortunately, this is most likely the same as the prevalent wind direction, while crosswinds and opposing winds are relatively rare.

Recent investigations (Fathi 2020) indicate that wind direction is probably not as influential as other factors, like soil moisture content or foliage. Nevertheless, we should always strive to test trees in the prevalent direction, if possible.



Figure 4.1.

Tree standing between two telecommunication shafts. Source: own work.



Figure 4.2.

Linden tree during its removal, the main roots can be observed. Source: Antal Buza

IV.

Root detection methods – instrumental, non-destructive possibilities

Information about root systems can be essential, especially in urban areas, construction sites or during utility reconstruction, etc. to avoid damaging roots. Root detection methods may find the main, bigger roots (above 20 mm in diameter) in the top layers of the ground (usually not deeper than 2 m).

For mapping the roots, without any or very little harm, the available instruments include ground probes (relatively simple and cheap), acoustic methods (which have the advantage to find the roots of the tested tree, not just roots in the ground), ground penetration radar and multi-electrode resistivity imaging (which ones can see deeper than the others). Excavation is possible as well, air-excavators can be relatively less damaging, these are useful when it comes to start digging in area of the roots. Of course, excavation is needed for research and development as well, as the roots found by mapping methods can be compared the excavated ones. So, root detecting instruments can be validated and can become more reliable.

The methods and their implementations vary on a wide range, their operational principles and some examples are presented in this chapter. While the limitations, advantages and disadvantages are collected as well.

Please note that root mapping has very limited correlation to stability or safety. (Of course, lack of bigger roots indicates stability problems.) The techniques presented here aim to avoid damaging, cutting the main roots during digging into the soil.

The safety of the root system or risk of uprooting is included in the topics of biomechanics and instrumental assessment. While for trunk base-ment or root collar examinations tomographies and resistance drilling are available.

Some the presented techniques are relatively not well-spread and used by only a few experts, while research and development are continuous. But as the demand for more and more precise tree examinations grows, the usage of these method will increase as well, as we can already observe it in a few countries, especially when the examined tree has a unique, specific value.

1. GROUND PROBE

The ground probe is presented in the “Simple tools in tree assessment” chapter as well, so here it will be just a very short review of the usage. The ground probe is a long metal rod with a rounded end (to not to hurt the roots) and a handle on the top.

The rod can be pushed into the ground by hand (or by foot). It will go through the soil, but of course, it will stop as it hits any rocks or roots. The sound and the feeling of the hit differs according to the different materials. Roots can be found, and their ways can be marked on the ground.

This tool a relatively simple and cheap one. Of course, it can not find roots deeper than its length (usually less than a 1.5 m). If the ground

is covered, for example there is a sidewalk or road, the probe can not get into the soil and find the roots.



Figure 4.3.
Soil probe. Source: Jerzy Stolarczyk

2. ACOUSTIC METHODS

As it was mentioned before as well, the great advantage of these techniques is that they can locate to bigger roots of the examined tree. Roots from other trees, pipes or other buried materials do only little disturbance to these techniques.

Another advantage can be that these instruments are usually in very close relationship to acoustic tomography. The instruments/software can be available as extensions for tomography. The reason for it is that the same acoustic sensors can be used to “hear” the signals which travelled in the roots (and soil) as for the ones in the trunk. As tomography for trunk is relatively well-known and well-spread, acoustic root detection has the possibility to become available.

The main idea of acoustic root mapping is based on the fact that sound waves travel faster in the roots than in the soil. The difference is remarkable, the velocity of the acoustic signal in soil is around 250-400 m/s and 2000-4000 m/s in roots depending on soil and root type and moisture content (Bucur 1995; Divos et al. 2009).

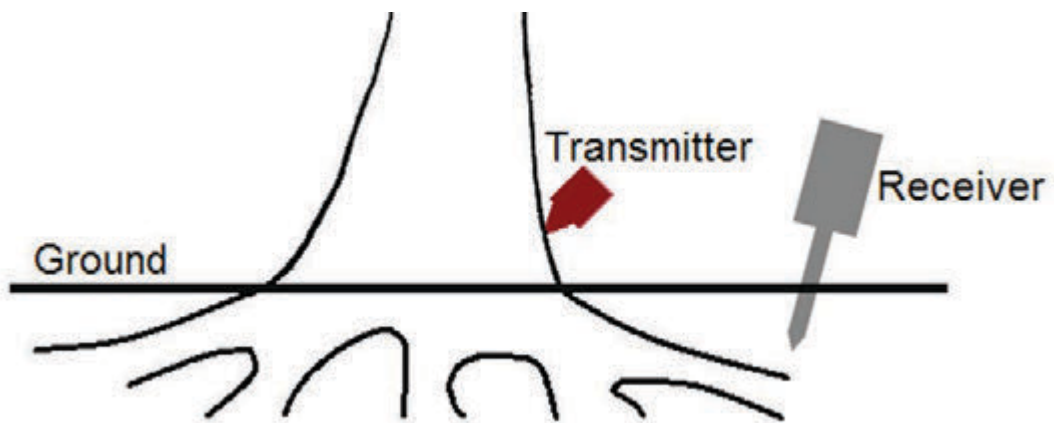


Figure 4.4.
Acoustic root detection with transmitter placed on the trunk near to ground and a receiver which can be stuck into the ground. In this case the transmitter generates an acoustic signal which travels through the wood material. If the receiver is near to a root the signal changes significantly. Source: own work

There are two approach of acoustic root mapping, one generates signals by hitting the ground and detects the arrival of it on the root collar (Arborix™, Rinntech), while the other send signals from the root collar into the ground and detects them with a soil probe (Root Detector, Fakopp).

The first method makes an assumption, if roots would grow in the radial direction from the trunk. This simplification is visible in Figure 4.6., as the roots are visualized as spikes in radial direction. When the detection is in the ground there is no such an assumption.

In both cases time (and distance) is measured, the time of flight (of the signal) drops down when a root is nearby. Velocity is calculated, higher velocities appear if the root is closer. When signals generated on the root collar, it travels fast in the roots, while it also penetrates into the soil. If there is no root nearby the receiver, the sound reaches the receiver relatively slowly. As the receiver gets closer and closer to a root, the time decreases.

The transmitter should be placed on the trunk of the tree as close to the ground as it is possible,

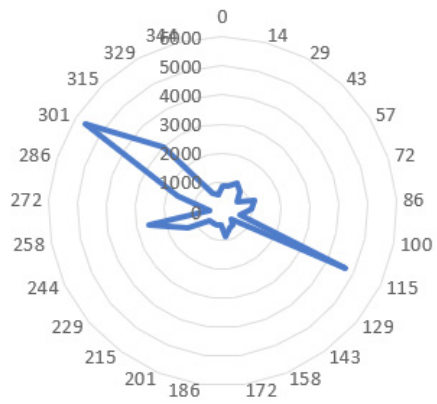


*Figure 4.5.
The velocity of acoustic signals visualized around the trunk. The increase of the velocity refers to the presence of roots*

and it should be hit with metal hammer (to generate the signals).

The receiver itself is a soil probe with a 30 cm long metal spike which has a good coupling for the soil. The travel time changes significantly if a root is nearby (around 10 cm) (Divos et al. 2009; Buza and Goncz 2015).



Time can be detected, or the data can be sent to a computer program.

Only the bigger roots (diameter > 4 cm) can be found in this way and this acoustic technique can separate roots from each other if there is at least a 20 cm gap between them.

A case study in subchapter 5) presents the usage of the technique.

When the sensors are on the root collar, similar results can be achieved. According to the developer, the Arborix™ system can:

- Checking uprooting safety
- Determine volume and weight of the root plate
- Locate roots

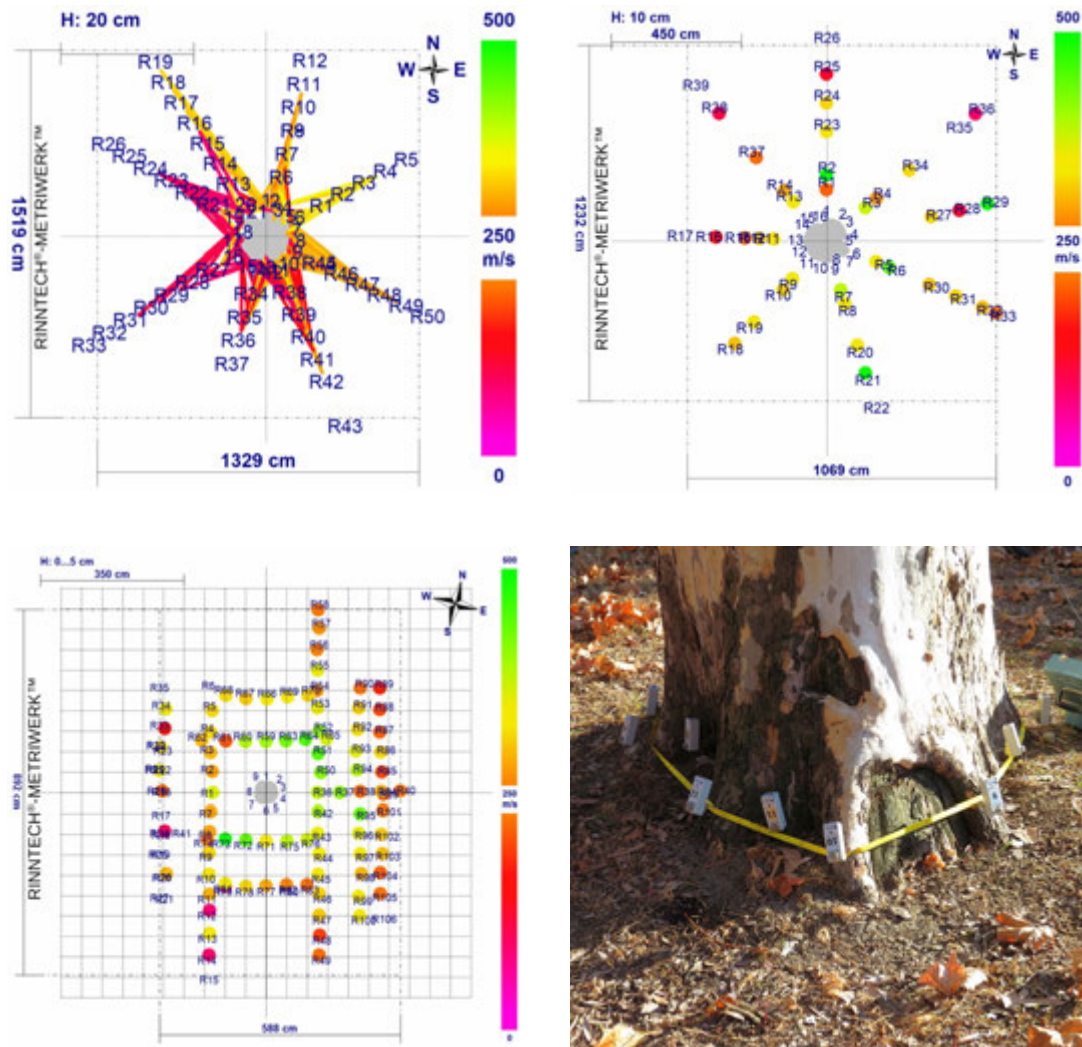


Figure 4.6.

Result representations with Arborix™ (up left and right, bottom left). Source: Frank Rinn, with permission, <http://www.rinntech.de/>. Sensors on the root collar (bottom right). Source: own work

3. GROUND PENETRATION RADAR

Ground penetration radar can find objects in the ground. The tricky part of the method is to decide if the object is a root or not.

The operational principal for this technique – in brief – is that there are some materials which are “transparent” for radar waves while others reflect or absorb them. If the proper frequency is set, the soil, the ground can just let the waves go, while roots, pipes, other buried materials reflect them.

The “echoes” can be detected and the location of the underground object (including depth) can be estimated.

The ground penetration radar (GPR) method originates from geophysics, as it can find different things under the ground. The idea of looking for roots goes back to decades and successful

usages were presented in several countries all around the world. (Hruska et al 1999; Cermak et al 2000; Guo et al. 2013; Wu et al. 2014)

Up to 83% of bigger roots could be found while false positives can be filtered or kept limited.

The arrangement of a standard GRP system is described by Gou and colleagues as follows. “A standard GPR system consists of three basic components: the control unit (including pulse generator, computer, and associated software), the antennas (including paired transmitting and receiving antennas), and the display unit.” (Guo et al. 2013)

The GPR’s transmitter’s signal penetrates into the soil and becomes reflected from the objects. The measured reflection has a hyperbolic shape which has travel time and amplitude data, which contain information about size, material, and depth (Fig. x).

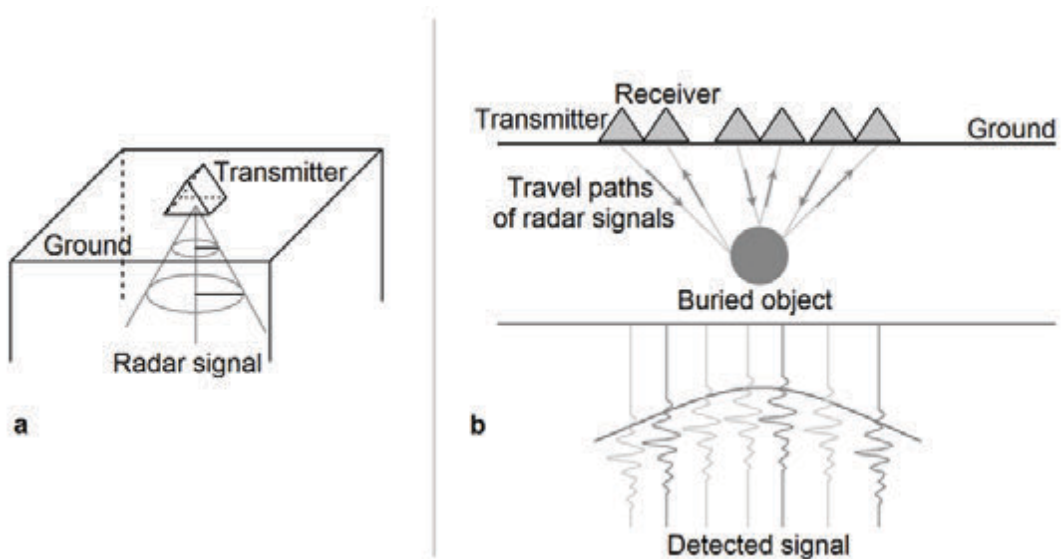


Figure 4.7.

- A radar signal penetrates into the ground as an expanding cone. The cone formation allows the radar to detect object sideways too.
- Upper: ground penetration radar (GPR) unit is moving on the surface while the buried object reflects the signal. Lower: reflected signals make a hyperbolic signal referring to the position of the buried object. Source: own work

The signal frequency is usually between 400 MHz and 2 000 MHz. This is important for the resolution and the penetration depth of the measurement which also depends on the soil type (the highest frequency belongs to a resolution about 0.25 cm and can find objects in the top 35-70 cm while the lowest ones' resolution is about 4 cm and might reach objects even at 250 cm depth) (Guo et al. 2013).

According to research papers, individual roots and a whole root system can also be found by GPR and this technique can also be good for the biomass evaluation for woody species, even under asphalt or rocks (Ferrara et al. 2014, Zhu et al. 2011; Hirano et al. 2012; Borden et al. 2014; Zhu et al, 201, 4Cermak et al. 2000). There is also a research on Beijing Normal University

about the automation of the system, their setup could find the 87.32% of the roots and construct a root system which fits to the reference one in 82.75%. (Wu et al. 2014)

The implementation of the measurement does not require physical effort as the radar antennas are usually mounted onto wheels and the GPR machine just should be pushed on the marked lines like a shopping cart. The measurement looks like a slow walking.

Beside the great possibilities offered by the technique, the GPR system still has some limitations.

- Soil conditions. The water content of the soil degrades the collected data. The ideal soil is dry and sandy (Hirano et al. 2008).
- Surface geometry. The surface should be flat (or close to it).



Figure 4.8.

Ground penetration radar in use (for demonstration). The operator should walk slowly pushing the radar. Source: own work

- The water content of the roots. The gradient between the water content of the soil and the root is important. Dried roots (volumetric water content under 20%) could not be found by GPR. (Dannoura et al. 2008; Hirano et al. 2009; Guo et al. 2013)
- Root diameter and position. The depth, direction, angle of the roots all influences the detectable signal as well as the distance or the crossing of the neighbor roots (Butnor et al. 2001; Stokes et al. 2002; Barton and Montagu 2004; Hirano et al. 2009; Guo et al. 2013).
- Nearby roots. If two nearby roots are too close, the GPR cannot discriminate them. For example, GRP (900 MHz) could find roots from 1.9 cm diameter, but it detected two roots to be dividual if their distance were 10-20 cm. (If there are many small roots in an area, they might be recognized as one bigger root). (Hirano et al. 2009).
- Other buried objects. Some objects (like stones, cables, water-filled pipes) can be distinguished from root; some others (like dead roots, empty PVC tubes, old pipes, etc.) cannot (Hruska et al. 1999; Stokes et al. 2002; Butnor et al. 2005; Cox et al. 2005; Zenone et al. 2008; Leucci 2010 Guo et al. 2013).



Figure 4.9.
The screen of a GPR instrument. The measure itself does not require special skills – while interpreting the data usually requires both special software and experience. Source: own work

The GPR method can find the coarse roots by the mentioned limitations in a non-destructive way. As it used to be highlighted by the developers the remarkable possibilities of the technique are the repeatability of the measurement, the in vivo monitoring, and the ability of long term studying of the root system architecture formation and development. (This statement is usually true for any kind of non-destructive testing methods.)

Not only the repeatability of the measurement is remarkable, but if the instrument is calibrated well and the proper software is used, this technique is able to find root under roads or sidewalks.

In some cases, it might be worth to consider asking for the help of one of the experts' for locating the roots.

4. ELECTRICAL RESISTIVITY TOMOGRAPHY

The electrical resistivity tomography (ERT) or multi-electrode resistivity imaging is another technique which gives us information about the soil and different materials in it.

It may sound similar to ground penetration radar, but both the operational principle and the implementation of a measurement are different. This may be most experimental among the presented methods, it is still important to know about the methods which may become well-spread in the future.

The ERT measures the electrical resistivity in a cylindrical surface of the ground. The electrical resistivity (similarly to radar reflections) depends on the different properties of the

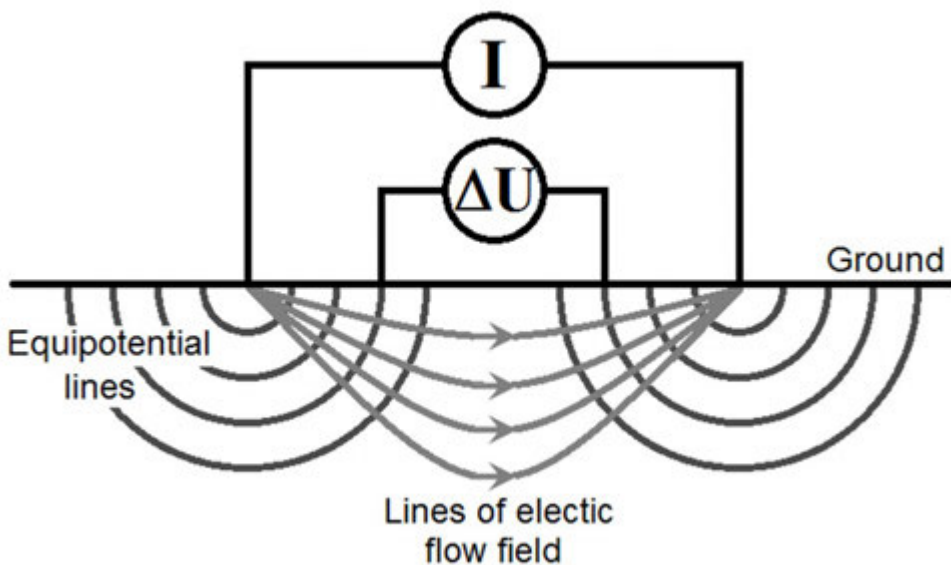


Figure 4.10.

Two electrodes conduct current into the soil ("I" is the source). The current causes a specific electric field which can be described by the lines of electric flow field and the equipotential lines. The generated voltage is measured ("ΔU") with two other electrodes. One specific position of both the electrodes gives information about one cylindrical slice of the soil. If the conditions of the soil change, or there is a buried object or disturbance the measured values change. As the electrodes are moved different slices can be measured and a 2D picture of the soil can be evaluated. Source: own work

different materials (Amato et al. 2008; Zenone et al. 2008).

The ERT needs at least 4 electrodes, 2 for conducting current into the soil and 2 for measuring the voltage, the electric potential. If the conducting or the measuring electrodes are moved to other position the measured cylindrical line changes (Figure 4.10.). By using several electrodes in a line or in other arrangement a soil layer or more layers can be evaluated (Hagrey 2006; Morelli et al. 2007).

The main roots can be found in the layers and it is possible to make a 3D model of the root and – after calibration – evaluation of the biomass, and the volume of the roots too. The moisture dynamics can also be studied by soil electrical resistivity methods (Morelli et al. 2007; Amato et al. 2008; Rossi et al. 2011, Srayeddin and Doussan

2009; Garre et al. 2011; Robinson et al. 2012).

In order to get more detailed information ERT can be combined well with GPR (Hagrey 2006; Morelli et al. 2007; Zenone et al. 2008; Zhu et al. 2011).

(Note that there is another technique used for trunk evaluation which is sometimes also referred as electrical or electric resistivity tomography. In the training material the technique for trunk is called impedance tomography.)



5. CASE STUDIES

To illustrate the possibilities and limitations of root detection, especially acoustic root mapping, two case studies are presented in this chapter. In both cases, the acoustic method described in chapter 2) was used. The sound was generated on the root collar and the signal was detected in the ground by a probe.

The first case is a root mapping followed by excavation, while the in the second case the assumed root plate was evaluated, and a trial of safety calculations were done.

5.1. ROOT MAPPING COMPARED TO EXCAVATION

A birch tree in the botanical garden of the University of Sopron was selected, and an acoustic root mapping with 8 soil sensors were performed in 2008. (One sensor is enough for the measurement; 8 sensors can speed it up.) The measurement was performed on a circles around the trunk, the time data is collected and with measuring the height of the soils sensors spike above ground it was possible to collect the data on the depth of the roots too.

A circular visualization of sound velocity was made.

And the roots were excavated. The results from the measurement could be projected onto the excavated roots.

The results fitted well to the root system as it can be seen in Figure 4.13.

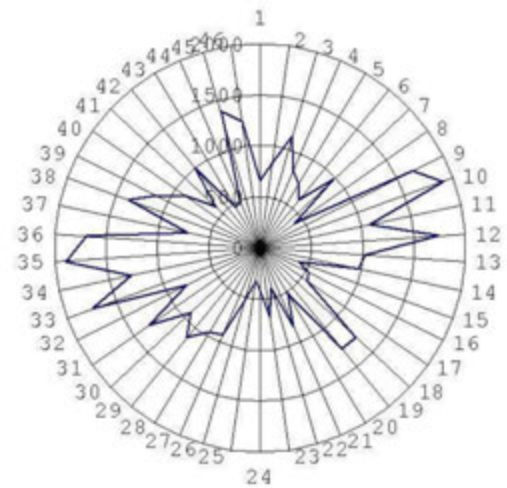


Figure 4.12.

The visualization of the velocities



Figure 4.11.

The soil sensors

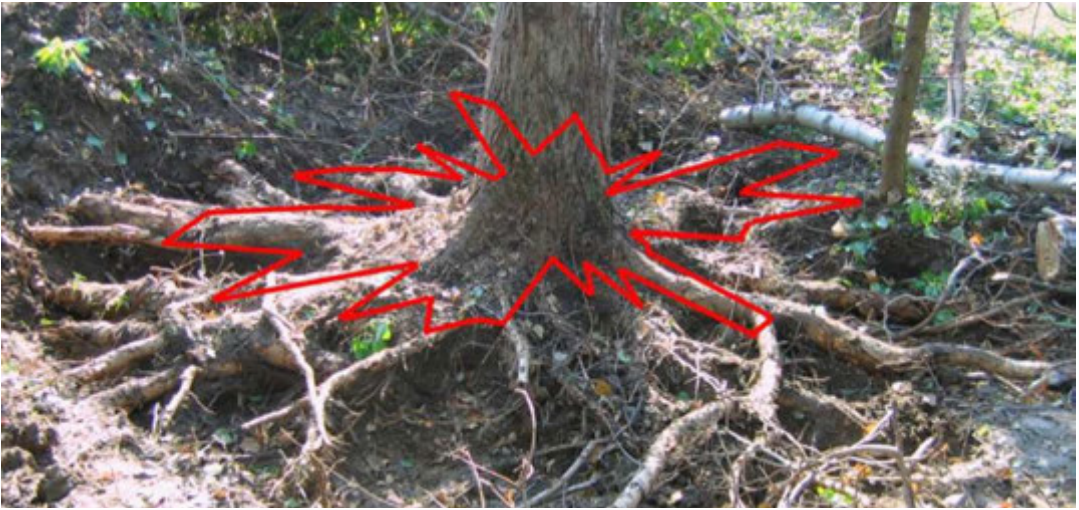


Figure 4.13

The visualization of the velocities layered onto a photo of the excavated roots

5.2.

ROOT MAPPING LINKED TO STABILITY?

The question if the root map can be related to the stability comes up again and again, but the mechanical. Load bearing capacity of the root system depends on other factors, not only the location of the main roots. Although a research was done to test the theory if a survey of the main root can be used to predict the stability of the root system.

For this measurement two Norway spruces (*Picea abies*) were selected in a botanical garden. They stand close to each other, so their living conditions can be considered to be the same. Only remarkable difference is that one of them was attacked by Honey fungus (*Armillaria mellea*).

As the first step of the research, root systems were mapped by acoustic method. The locations of the roots were determined along circles at 0.5 m, 1 m and 1.5 m from the middle of the tree. The soil probe was pushed into the ground in 15 cm steps.

We used a soil probe with 40 cm spike which is able to detect roots not deeper than 0.5 m but for spruce trees it was considered to be enough. (The transmitter was placed on the root collar, the nail of it pointed towards the ground in a 45° angle, and the transmitter was hit at least 3 times at each position of the soil probe.)

To become able to compare the results to already validated measurement, pulling tests were interpreted on both trees.

The aim of the project was to find relation between the root system and stability, but only the location of the roots is not a data which could be compared to safety factors coming from pulling tests. To solve this incompatibility a root plate area was evaluated based on the locations of the roots. (see in Figure 4.15.).

The areas in which roots can “hold” themselves were estimated. Soil parameters were estimated as well and the moment necessary for uprooting the tree was calculated. In this way a safety factor was able to be calculated as well.

The safety estimations from root mapping were far from the ones from pulling test (less than the half of them), but they show the proper trend, so it may be useful for predictions one day. The data are shown in table 4.1.

An interesting finding of the measurement was that no main roots were growing in the direction of the other tree.

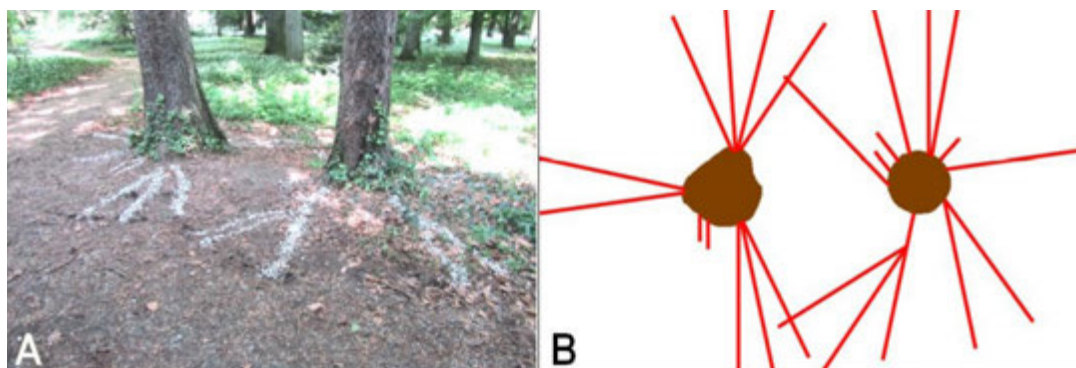


Figure 4.14.

Root mapping. A photo of the roots found (A) and the model made by a computer (B)

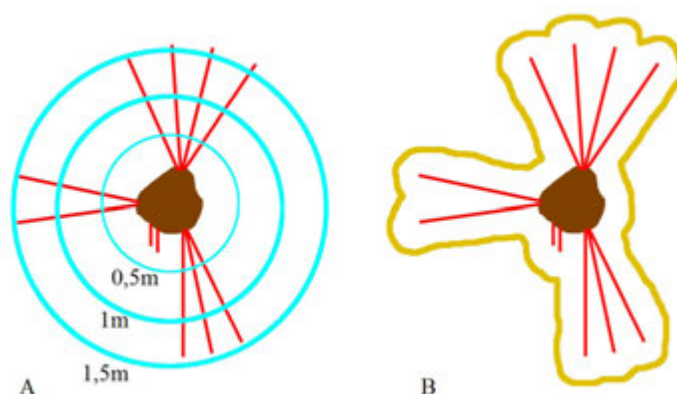


Figure 4.15.

The root map (A) and the surface reached by the roots (B) of tree No. 2.

	SF_pulling	SF_rootmapping	Ratio of safeties
Tree 1	5.07	1.94	2.61
Tree 2	3.02	1.27	2.38
Ration (Tree 1 / Tree 2)	1.68	1.53	

Table 4.1.

The safety factors from pulling test ($SF_{pulling}$) and root mapping ($SF_{rootmapping}$) and their ratios. It is interesting that the ratios of the two trees' safety factors are close to each other regardless of the used technique.



V.

Remote Instrumental Tree Assessment

INTRODUCTION

The term Remote Instrumental Tree Assessment refers to all methods of collecting data about trees that do not require direct access of the arborist to the examined tree. As a rule, these are also methods that allow a scalable approach – ie large-scale data collection on large populations. The great advantage of the approach is the fact that all input data are stored (archived), which can be subsequently analyzed with different (optional) level of detail within the

postprocessing. The limits of this procedure currently include:

- the need for professional technological equipment
- significant volumes of transmitted data
- significant problems with accuracy in case of neglect / failure of any of the technological elements.

SERVICE	PRINCIPLE	EXAMPLE OF USE
Positional analysis using GNSS	• satellite based information about the location • free service with limited accuracy	• basic location of my position • download of maps for area of interest • simple location of tree in question
Positional analysis using GNSS with IMU	• precise satellite based information about the location • need of sophisticated connection of more HW components	• exact location of objects (trees) in question • possible creation of accurate (calibrated) photographs
Picture analysis (horizontal pictures)	• large number of methods for quantitative/qualitative data analysis • necessary use of sophisticated SW and HW • possible combination with AI, LiDAR and other methods	• tree species determination • measurement of trees • selected qualitative data (vitality, horizontal leaf area index, etc.)
LiDAR	• detailed information on the shape of structures in either horizontal (aerial) or vertical (ground) use • hi-res LiDAR point clouds can be used for exact measurements of stem structures	• digital terrain model • accurate production of 3D models of trunks or whole trees
Drones	• sensor carriers for their application at heights	• survey of the condition of trees without the need to ascend to the crown • area survey of the condition of tree stands in high resolution detail

POSITIONAL ANALYSIS

GLOBAL NAVIGATION SATELLITE SYSTEMS

(GNSS) have been used extensively in recent years to locate trees. In the Europe there are available (or will be in coming years), following systems

- GPS (I, II and III),
- GLONAS,
- Galileo,
- Bei Dou-3.

Principle of the service is enabling autonomous spatial positioning with the help of satellites. Client devices use small electronic radio receivers, which, based on the signals sent from the satellites, allow their position to be calculated with an accuracy of meters. Accuracy in special or scientific applications can be down to several centimeters, using various calibration procedures.

In simple terms, satellite positioning systems can be described as a satellite radio rangefinder system:

- A radio system uses radio waves to measure a certain parameter. A “radio rangefinder” system uses radio waves to measure distance as follows: A transmitter is placed at a point with a known position that transmits timestamped radio waves. At the point whose position is measured, is placed a receiver that compares the timestamps with its “clock”. This makes possible to measure the delay. Since the radio waves move at a known speed, it is sufficient to multiply the measured delay by this speed to calculate the required distance. To determine the position, the distance must be measured from multiple points in the same way as in the first case. The resulting position of the receiver can then be calculated, for example, by trilateration or multilateration.

- By the satellite system the known positions are satellites orbiting the Earth. Therefore, their transmission must include not only time stamps, but also the path parameters of the satellite, from which the position can be calculated when sending the message.

The problems with GNSS are as follows :

- GNSS signals are very directional and can be blocked by buildings.
- Receivers have different start time (warm and cold start), which move in the order of ten e for seconds to one é min y . This start-up time is required for the receiver to obtain more satellite signals needed for position calculation.
- GNSS-only position updates are limited to once per second. This is good for tracking large, slow-moving objects. Startup time is too long and update frequency is insufficient for many applications, which use the output values. (For example: car tracking applications which rely on exact positioning.)
- GNSS accuracy is measured in meters, which is too rough to use in most embedded applications.

Inertial measurements (IMU) are used in combination with GNSS to eliminate the shortcomings of the method and to increase required accuracy. IMUs provide more accurate localization and faster updates. IMUs provide relative position data from a known starting point, while GNSS receivers provide absolute position information. So these two methods complement each other. IMUs contain one or more of the following types of motion sensors:

- Gyroscopic sensors measure changes in position angle, usually expressed in degrees per second. The integrated angular velocity can be used to monitor the change in orientation. Gyroscopic sensors are available with one, two or three axes. Gyroscopes monitor



Figure 5.1.
Area of error of a GNSS system shown on an aerial map

relative motion independently of gravity. Because of this, a position error called “drift” may occur.

- Accelerometric sensors measure linear acceleration, including acceleration caused by device motion and gravitational acceleration. Acceleration is measured in units of G, which are multiples of the gravitational force of the Earth. Accelerometers are available with one, two or three axes that define the X, Y and Z coordinate system. The accelerometer data can be used to measure the static orientation of the device by calculating the measured device angle and gravitational compensation.
- Magnetic transducers measure the intensity of the magnetic field, usually in microTeslas (μT) or Gauss ($100 \mu\text{T} = 1 \text{ Gauss}$) units. The most common magnetic sensor used

for mobile electronics is the Hall effect tri-axial magnetometer. The magnitude of the Earth's magnetic field ranges from 25 to 65 μT depending on the geographical position and the angle of inclination. Thanks to the detection of the angle of the magnetic field and the angle to gravity, we obtain data that can be used to determine position with high accuracy. To get the right position, you need to know the current latitude and longitude.

- Pressure sensors measure differential or absolute pressure in hectopascal (hPa) or milliBar (mbar) units. The standard atmospheric pressure at sea level is defined as 1013.25 hPa. Changes in altitude cause corresponding changes in ambient air pressure and can be used to monitor vertical movement.

PICTURE ANALYSIS

A number of parameters – both quantitative and qualitative – can be obtained from high-quality photographs of trees. For these purposes, terrestrial photographs taken either “freehand” or on a carrier with a precisely known position in relation to the scanned tree are used (see GNSS above). The precondition for possible analysis of dimensions from photographs are known parameters of the camera (characteristics of the scanning chip and lens). This is achieved by calibration. Cameras are calibrated taking a photo of calibration field under specified light conditions with consequent calculations of the positions of pixels in the sensing field. The following data can be obtained from the analysis of photographs :

- Dendrometric parameters (trunk and crown dimensions, tree height),
- Shape characteristics of the trunk (biomechanics, volume analysis),
- Horizontal leaf area index (level of defoliation),
- Analysis of changes in trunk anchorage (for comparative calibrated measurements over time).

SPECTRAL ANALYSIS

In infrared photography , the image sensor used is sensitive to infrared light. Part of the spectrum used is referred to as near-infrared to distinguish it from the far-infrared region, which is the domain of thermal imaging. The wavelengths used for photography range from

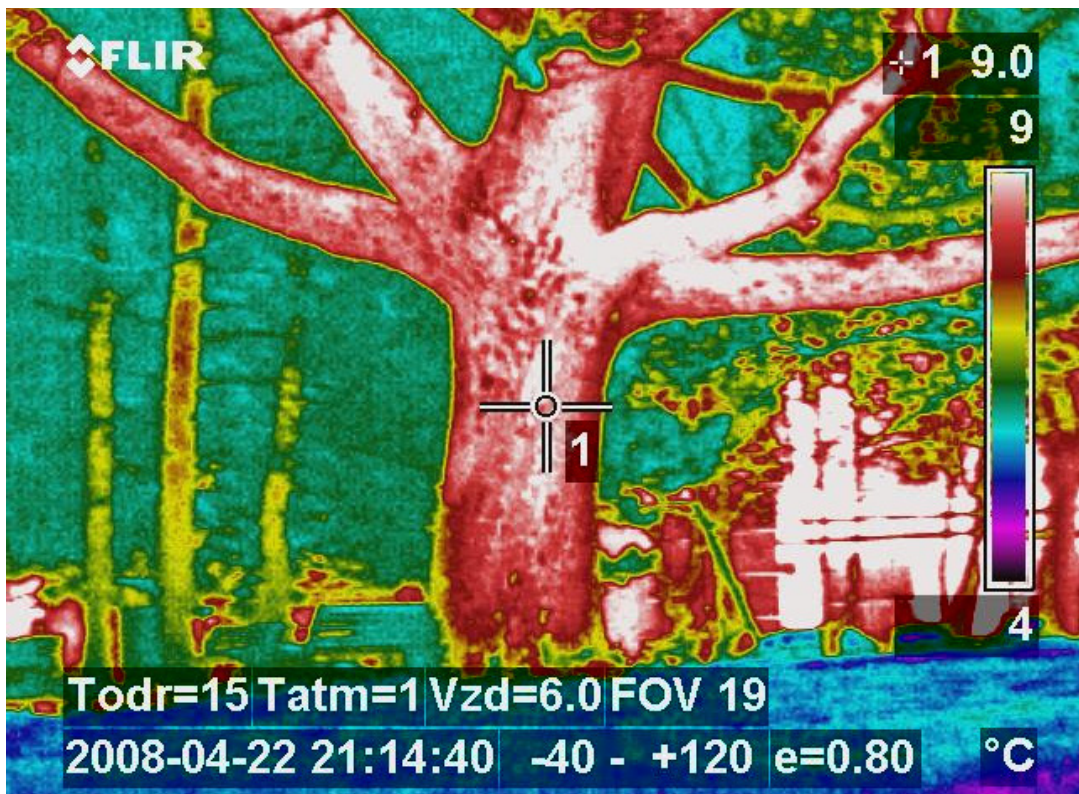


Figure 5.2.

The infrared photo of a tree trunk and main branches

about 700 nm to about 900 nm. The sensor is usually sensitive to visible light, so an infrared filter is used; This allows infrared (IR) light to pass into the camera, but blocks all or most of the visible light spectrum (making the filter look black or dark red).

Chlorophyll strongly absorbs radiation in the red and blue wavelengths, but reflects radiation in the green band of the spectrum. We perceive the leaves as the greenest in summer, when the chlorophyll content reaches a maximum. In autumn, when there is less chlorophyll in the leaves, there is less absorption and higher reflection in the red band of the spectrum. Therefore, we perceive the leaves as yellow or red (yellow is a combination of green and red). The internal structure of a healthy leaf acts as an excellent diffuse reflector of near infrared radiation. By measuring values in the near-infrared range, healthy vegetation can be distinguished from damaged or diseased vegetation.

In the past, attempts have been made with IR imaging of the stem to reveal a certain level of extent of internal defects (cavities). However, comparative tests did not prove this use of spectral photography to be valid and usable in practice.

NEURAL NETWORKS AND ARTIFICIAL INTELLIGENCE

In the near future, it is possible to count on the processing of photographs using neural networks. An artificial neural network is one of the computational models used in artificial intelligence. It is a structure designed for distributed parallel data processing. It consists of artificial (or also formal) neurons, preceded by a biological neuron. Neurons are interconnected and transmit signals to each other and transform them using certain transmission functions. The neuron has any number of inputs, but only one output.

The use of neural networks enables automated search for the required parameters during high-capacity data collection. They are currently used to determine tree taxa from the photographs, and work is being done on the analysis of other qualitative parameters.

LiDAR

LiDAR stands for Detection Light and Ranging. The ToF (Time of Flight) scanner uses light to determine the distance between two objects. It measures the time it takes for a light source to reach an object and reflect. Recently, this technology has been used to create 3D maps of the environment or objects.

With 3D scans of trees can be performed a variety of analyzes from simple (exact measurement of parameters in individual sections of stem or the entire crown) to complex (computation of load capacity of the individual profiles taking account of irregular cross section or residual strain of open wall cavity). The system of construction of 3D models of trees and their parts with connection to visual and instrumental evaluation of tree condition is called Advanced Biomechanical Analysis (www.adbian.com).

LiDARs can be used either “free hand” or carried on a device with accurate position detection. This device can be a drone, a measuring car or a mobile collection set (bike etc.).

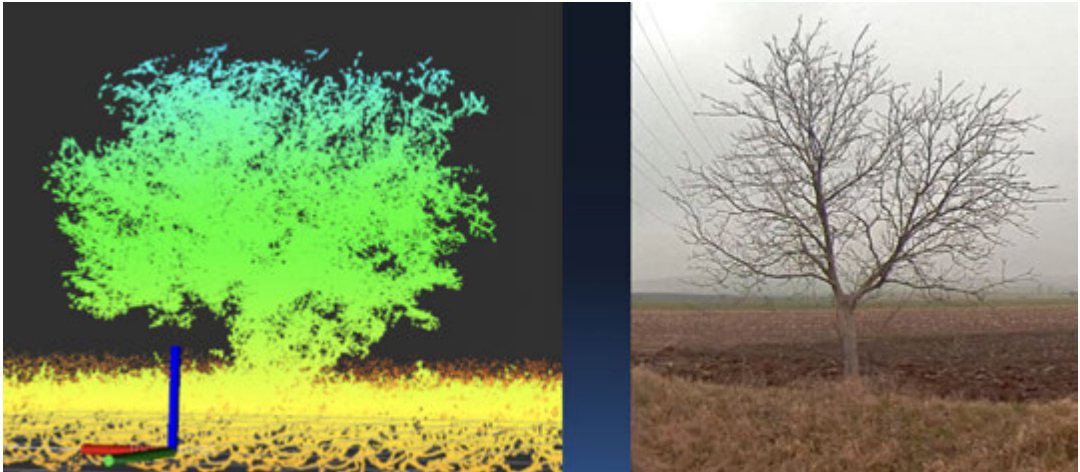


Figure 5.3.
Point cloud of a tree from LIDAR (left) and a photo of it (right)

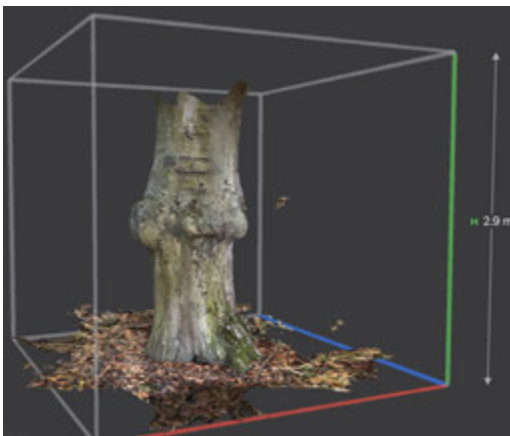


Figure 5.4.
3D model of a tree trunk based on
handheld LIDAR measurement

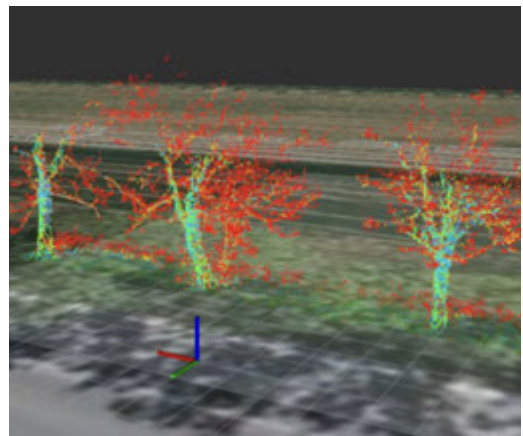


Figure 5.5.
The LiDAR scan of an alley from
a car at speed of 60 km/h

DRONES

An **unmanned aircraft** (sometimes called a UAV from the English Unmanned Aerial Vehicle or also a drone) is a small aircraft that can be operated remotely or is capable of flying independently using pre-programmed flight plans or more complex dynamic autonomous systems.

Drones can be carriers of a number of devices described above, which can be placed into the treetops and thus convey information about the qualitative / quantitative parameters of the monitored individuals. When examining larger populations of trees (stands), they can provide

easy access without the need to provide terrestrial access. This is a significant advantage especially in complicated terrain (rugged or sloping terrain, entry restrictions, etc.). At the same time, however, the use of drones has a number of limitations.

If a person flies with any drone or quadcopter, he/she becomes a participant in air traffic and must follow certain rules. Flying must be operated at a safe distance from people. Air traffic must also be avoided. This means that it is not allowed to fly near airports. The recommended distance is 5500 meters. It is also necessary to avoid air traffic outside the airport, so that it is not possible to fly higher than 300 meters above the ground. It is also not possible to fly in a restricted airspace or no-fly zone. When flying drones, it is also essential that the drone pilot always has the machine in sight, which de facto precludes the use of drones that have a tracking function of the user.

If the user operates a drone for commercial purposes, he must register with the Civil Aviation Authority and obtain the appropriate license there. Associated with this is the requirement to take out liability insurance to cover any damages.



VI.

Dendrochronology

Do you know if 147 B.C. was a dry year? Dendrochronologists from Denmark, Georgia state, England, Ireland, California, or Germany can answer this question as they have their so-called “master chronology” for the past cc. 2 300, 7 000 or even 12 000 years.

Dendrochronology is the science of tree ring dating, resulting with the ability to date a ring into a specific calendar year. The main users of it are from different fields of history and climatology, as the rings’ formation depends on the environmental conditions as well. Let’s see the details.

1. HISTORY AND PRINCIPLES

The idea that environmental conditions affect the growth of tree ring so it could be used to study the past climate goes back to the 18th century. While the idea of dating tree remains is just a little younger, appearing around 1830, but these ideas were more likely theoretical.

The wide-spread usage of dendrochronology started with A. E. Douglass, an American astronomer, who tried to prove the effect of solar activity on climate. He checked tree rings if he could find the 11-year period in them which could be related to the solar flares’ cycles. He was so successful in this area; he established the Laboratory of Tree-Ring Research at the University of Arizona in 1937 and became the father of dendrochronology. (The word itself

contains “dendro” for tree, “chrono” for time and “logy” for studying something.)

The growth of the rings depends on the specie, the environment (soil, riverside or not,...), the weather (sunny hours, humidity, precipitation, winds, temperature...), if any pests were present, and the age of the tree. Trees living on the edge of their ideal habitat are more sensitive to climatic changes.

Considering dendrochronology sometimes one area has a 500 km radius, so samples of trees even growing a 1 000 km far from each other can be handled together while sometimes a quite small region has its own climate and only the samples from that specific place can be handled together.

Usually one ring is formed during one year, for example oaks trees are very reliable, other trees like alder and pines grow 0-2 rings/year while some species like birch and willow are not used for dendrochronology at all.

The rings can be different in width, color and their chemical composition can differ from year to year.

Experts agree on that a 30-year long sample’s pattern is unique regarding both the age and the area from which it originates.

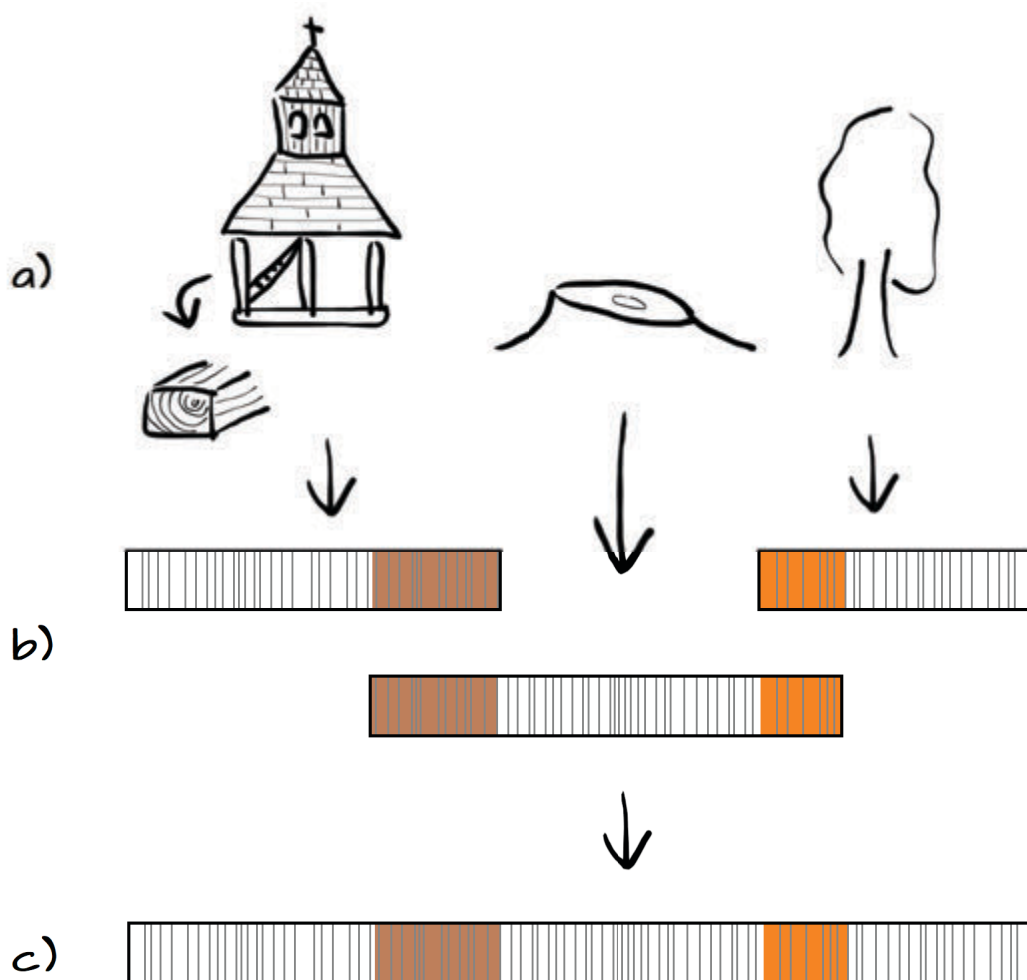


Figure 6.1.

The steps of making a master chronology a) examples of sources for wood samples, a beam of an old belfry, tree stump and tree b) the individual wood samples with their ring patterns. The overlaps are colored. c) the master chronology (the previous overlaps are colored). Source: own work.

2. OVERLAPPING AND MASTER CHRONOLOGY

Let's have a sample from a 100 years old tree which stands in a park. Its sample shows the growth ring pattern from 1920 to 2020. If we have a sample from a tree stump (same area, same specie) which was alive from 1780 to 1960,

the pattern between 1920 and 1960 should be similar. Like the pieces of a puzzle, when we have the match, the whole picture will get bigger as well. In this example the total ring pattern could be extended back to 1780.

The part of the samples which contains the same pattern, the “matches” are the overlaps, this is the overlapping or cross-dating, when two samples have the same pattern in a part. (See Figure 6.1.)

We also may find a proper piece of wood, from a wooden house or roof, which includes for example the ring pattern from 1780 to 1815 but has an older part as well, so the ring pattern can be extended again.

The extended patterns are called as master chronologies. (See Figure 6.1.)

3. SAMPLING AND USAGE

Wood samples can be collected with both non-destructive and destructive ways, sometimes even a macro photo of the wood, beam,... is enough, in other cases researchers can cut a thin layer from the wood, and when the a sample from a tree is needed, increment borer is used as well.

Recently the collected samples' 40% can be used for dendrochronology, as for example even if a year was a dry one, a tree standing on a riverside may not grow a thinner ring, and the pattern does not match to the chronologies.

Even when the match is correct, the dating still can be difficult. If the last ring is there, the year of the cut, or even the season can be determined. If the last ring is not included in the wooden sample, if at least a few rings of the sapwood is included, an estimation may be given about the year of the cut.

For example, Transylvanian oak trees have 15 ± 2 rings wide sapwood, so if a wood sample is found with 5 ring of sapwood, the year of the cut was about 10 years later than the last visible and dated ring. If not the last ring either a ring from the sapwood is found, exact dating is not possible. Statements like “it is sure that the tree was cut after ... date” can be made. Exact dating of wooden structures, building and artifacts can be difficult so as the wood might be replaced later, or a beam from a wrecking could be used. Sometimes when a pattern does not match to the master chronology of an area, it still can be found in another region. Logs, beams, ship timbers, panels for paintings, etc. were transported and traded during the history, dendrochronology can bring proves for transportation routes. In some other cases, some samples can not be matched to the master chronology, but it is already proven that they are from the same area. In this case that can be decided if the samples are from the same year(s) or not.



Figure 6.2.
Historical wooden structure of a belfry

So-called floating chronologies can be made from several samples which ones have overlaps to each other but can not be linked to any samples from the present, so the exact date of the rings is unknown. These can be used to decide if a sample is older or younger than another and of course further investigation may link these chronologies to the present and turn them into master chronologies as well.

Analyzation of the rings' width, color, cell/cell wall structure or chemical ingredients can give us information on the climate of the given year. Different tree species can be sensitive for different conditions, but the most common "ring slimming" effect is the lack of precipitation.

Dendrochronology, and isotope dendrochronology (usually oxygen isotopes are measured to find a missing ring) are important in climatology. As the past climate can be modelled, the climate models can be tested, to see if they could predict the later climate from the previous data. As dendrochronological dating is so precise, it is used to calibrate and check radiocarbon dating as well.

Checking recently living trees is not the main focus of dendrochronology but there were researches which compared trees living at the top of hills and in the calmer valleys next to them. As weather is measured for many decades, researchers knew which year was dry, so they could check if these years effected more the trees living at the tops. The found differences shows that the situation of these areas, from where the water could flow away and get dry sooner, affected the ring growth. The top positions are closer to the edge of the ideal habitat, so the trees are more sensitive to the environmental changes.

Dendrochronology is a great tool, but just like all the other instrumental tests, it's usability is limited. The main limiting factors are the need of samples from the same specie and area, and the minimal length (30-year) of the sample.

There are many ongoing dendrochronological researches as this field can show us both a slice of our past and future.



Figure 6.3.
Tree rings on a wooden floor

HOW TO USE DENDROCHRONOLOGY KNOWLEDGE AND TOOLS IN TREE ASSESSMENT?

- estimate the age of cut tree (if there are restrictions/limitation of falling trees of special age – for lawyers etc.), other special tasks
- help to decide if a tree stand on the edge of its ideal habitat
- precise resistograph drilling may be used for ring analysis as well (see reference for Rinntech)
- increment borer's samples can also be investigated



REFERENCES

- Bejo, L., F. Divos, and S. Fathi 2017. Dynamic root stability assessment – basics and practical examples. Proc. 20th Int. NDTE Wood Symp. Sept. 12-15, 2017, Madison, WI pp. 262-269
- Bieker, D., R. Keh, G. Weber, S. Rust 2010. Non-destructive monitoring of early stages of white rot by *Trametes versicolor* in *Fraxinus excelsior*. Annals of Forest Science 67:210
- Botár, I., Grynaeus, A. & Tóth, B. (2008). A “new” dating method for historical wood structure. Transsylvania Nostra. II/8
- Dávid, S. & Kern, Zoltán. (2007). Keleti- bakonyi és gerecsei tölgyek dendrokronológiai és dendroökológiai vizsgálata / Dendrochronological and dendroecological research of oak from Eastern Bakony Mts and Gerecse Mts, Hungary. In book: Archaeology and Ethnography of Forest and Wood / Az erdő és a fa régészete és néprajza (pp.89-102)
- Divos, F., L. Bejo, and L. Puskas 2015. Evaluation of the root system's stability based on actual wind intensity and inclination measurements. Proc. 19th Int. NDTE Wood Symp. Sept. 12-15, 2017, Rio de Janeiro, Brazil. pp. 514-519.
- Erk Brudi, Philip van Wassenae: Trees and Statics: Non-Destructive Failure Analysis, 2002, from “How trees stand up and fall down. Tree structure an mechanics conference proceedings”, p. 53-70.
- Fathi S., L. Bejo, F. Divos 2020. Investigating the Effect of Weather and Seasonal Factors on Root Stability Using Dynamic Measurements, Open Journal Forestry, 10:124-134
- Fathi, S. 2020. The reliability and applications of dynamic tree stability inspection. Doctoral Dissertation, University of Sopron, Hungary. 99 pp. (*In preparation*)
- Göcke, L., S. Rust, F. Ruhl. 2018. Assessing the Anchorage and Critical Wind Speed of Urban Trees using Root-Plate Inclination in High Winds. Arboriculture & Urban Forestry 44(1):1-11.
- David W. Green, Jerrold E. Winandy, and David E. Kretschmann. Wood handbook—Wood as an engineering material. – Mechanical Properties of Wood. Forest Products Laboratory. 1999. Gen. Tech. Rep. FPL–GTR–113. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 463 p.
- <http://www.pbs.org/time-team/experience-archaeology/dendrochronology/>
<http://www.rinntech.de/content/view/33/54/lang,english/index.html>
<https://dendro.cornell.edu/whatisdendro.php>
<https://en.wikipedia.org/wiki/Dendrochronology>
<https://lrr.arizona.edu/about/treerings>
<https://troweltales.com/2019/02/15/put-a-ring-on-it-a-brief-overview-of-dendrochronology/>
https://www.academia.edu/4908891/Dendrokronol%C3%B3giai_kutat%C3%A1sok_Erd%C3%A9lyben

<https://www.environmentalscience.org/dendrochronology-tree-rings-tell-us>
<https://www.thoughtco.com/dendrochronology-tree-rings-170704>
<https://www.thoughtco.com/dendrochronology-tree-rings-170704>
<https://www.youtube.com/watch?v=-Vfg4GieRTc>

James, K.R., J. Grabosky, G. Dahle, B.C. Kane 2014. Tree Biomechanics Literature Review: Dynamics Arboriculture & Urban Forestry 40(1)

James, K.R., N. Haritos, P.K. Addes. 2006. Mechanical stability of trees under dynamic loads. American Journal of Botany 93(10):1361–1369.

Jones, H.G., (1983) Plants and Microclimate: A Quantitative Approach to Environmental Plant Physiology. Cambridge University Press, Cambridge

Karl J. Niklas: Plant Biomechanics (An Engineering Approach to Plant Form and Function), 1992

Mattheck: Aktualisierte Feldanleitung für Baumkontrollen mit Visual Tree Assessment, 2007

Moore, J.R, D.A. Maguire 2004. Natural sway frequencies and damping ratios of trees: Concepts, review and synthesis of previous studies, Trees 18:195–203

Peltola, H., (1990) Model computations on the critical windspeed for windthrow and stem breakage of Scots pine. University of Joensuu Thesis for Licentiate Degree in Forest Sciences.

Sellier, D., and T. Fourcaud. 2009. Crown structure and wood properties: Influence on tree sway and response to high winds. American Journal of Botany 96:885–896.

Sinn, G. 1983. Standsicherheit von Parkbäumen Das Gartenamt, Heft 3, März S. 161–164.

Sinn, G. and L. Wessolly. 1989. A contribution to the proper assessment of the strength and stability of trees. Arboriculture Journal 13(1):45–65.

Strogatz, S.H. 2014. Nonlinear Dynamics and Chaos (Studies in Nonlinearity). 2nd ed., CRC Press, ISBN 13: 9780813349107

Wessolly and Erb: Tree Static and Tree Inspection, 2016

Wessolly, L. 1991. Verfahren zur Bestimmung der Stand- und Bruchsicherheit von Bäumen [Methods for determining the safety against uprooting and stem fracture]. Holz Roh- Werkst. 49:99–104.

Project: Partnership for the development of training standards for tree assessors in Central and Eastern Europe

PROJECT NUMBER – 2019-1-PL01-KA202-065670