Key result of sonic tree tomography

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Abstract: The use of sonic tomography for tree-risk assessment is increasing, but the results are often misunderstood and misinterpreted, mostly due to misleading demonstrations of the method. The colored picture of a cross-section ("tomogram") depicting a defect, such as decay within the stem of an urban tree that has undergone examination, is commonly considered the most valuable product for that type of risk assessment. However, the most important result of a sonic tomography is not the tomogram, but rather the information regarding relative loss in load-carrying capacity. Only this enables the tree-risk assessor to determine the probability of failure, required for a reliable evaluation of tree-risk.

Keywords: ***Sonic tomography, wood decay, load carrying capacity, breaking safety, pull-test, tree-risk***.

Introduction

Tree-risk is defined as the result of the probability of failure, and impacting a target, multiplied (or "combined") by the consequences of failure. Thus, tree-risk can only be estimated when the probability of failure (of a stem, branch, or root system) is known. This requires that the remaining load-carrying capacity of a decayed or defective stem or branch is adequate relative to the expected load (mostly by wind). For this reason, technical diagnostic methods were developed for assessing the internal condition of a stem or branch cross-section, starting in 1986. The first methods developed involved resistance drilling (Rinn 1988) and pull-tests (Sinn & Wessolly 1989).

In the 1990s, sonic- and impedance-tomography for trees was developed to overcome problems associated with the inappropriate use of the resistance drilling method, and limitations of pull-tests for breaking safety analysis. Thus, knowing the limitations and major problems of resistance drilling and pull-test helps to understand the key principles of sonic tree-tomography.

Soon after the presentations of the first mobile resistance recording drills (Rinn 1988, 1989), a number of similar 'drills' were offered by several different companies. Until more recently, more than 15 different kinds of resistance drills from at least 5 manufacturers were sold on the market (Rinn 2016), some of them successfully promoted by (supposedly) neutral scientists. Many of the drills were sold without:

- an explanation of what the profiles really mean in terms of wood condition
- providing adequate training necessary for inspecting trees properly
- providing the means to interpret the profiles correctly (Rinn 2012, 2015b), and
- a valid framework for evaluating the relative safety of defective mature urban tree (Rinn 2013).

Consequently, many trees were unnecessarily reduced in size, topped, or removed without reasonable justification, due either to improper use, such as drilling at the wrong spot, for example, between the buttresses, misinterpretations of drilling profiles, or because the drilling devices did not provide the precision and resolution required for tree-safety inspection.

Soon, resistance drilling was seen as a significant part of the "VTA" concept (Visual Tree Assessment; Mattheck et.al. 1993). And, together with VTA, resistance drilling came under criticism by an increasingly influential group of tree-experts. Localized measurement of shell-wall thickness using resistance drilling and application of VTA criteria (such as shell-wall thickness divided by radius) was declared "scientifically untenable" (Gruber 2008). As an alternative to VTA, pull-tests and the so-called "SIA" (static integrated assessment concept, Wessolly & Erb 1998) was promoted ostensively to evaluate tree-risk more correctly.

> *The tomography system discussed here provides information about the most dangerous wind-loading direction more easily and with less effort than doing a pull-test.*

Due to the criticism, the proper use and limitations of the resistance drilling method were no longer being presented at major conferences, or discussed in scientific journals. This is why many arborists today are unfamiliar with the details needed to do resistance drilling properly, and are unaware of the major differences among the various types of drilling devices available on the market, as well as the relative effectiveness of each.

The application of different resistance drills used at the same spot on a tree, for example, can result in significantly different profiles, leading to contradictory conclusions about the condition of the wood (Rinn 2016), crucial in making valid tree-risk recommendation. It is, though, quite simple to determine whether or not a particular drill produces accurate profiles. This is done by checking the correlation to wood density (as the key measure for wood condition, Rajala et.al. 2010). Although it's easy to measure the accuracy of this correlation, this information has not been published for most resistance drills on the market. As a result, it's not clear what the profiles produced by these drills reveal in terms of wood condition (Rinn 2015b, 2016). Therefore, these profiles cannot be interpreted correctly, and tree-risk can't be evaluated reliably because wood condition cannot be judged correctly. In addition, it's also important to understand that a single resistance drilling is limited because it only provides useful information for that spot – but this limitation is valid for practically all technical diagnostic methods.

The measurement of strain as part of a pull-test can only describe the stiffness as a mechanical property for that spot. The limitations of localized measurements for tree-risk evaluation becomes more obvious when we realize that, for example, the modulus of elasticity of wood can vary by a factor of 5 or more within relatively short distances on the surface of a tree trunk or branch (Evans and Ilic 2001; Evans 2006). These changes are largely related to the fact that the cellulose fiber angle of the newly formed wood changes with age of the tree (Lichtenegger et.al. 2000). In addition, results of a pull test are valid only for the direction of the pull. This became clear to many German arborists after a mature urban tree in a German city toppled. The tree had been pull-tested a few weeks before the failure. It had been pulled perpendicular to the direction of lean and deemed a low risk. This underscores that the inclination and strain measurement is only valid for the spot where the sensor is placed and the direction the tree is pulled.

In addition, wood reacts very differently under tension and compression, depending on local wood condition (white rot, soft rot or brown rot). In the early stages, brown or soft rot can reduce strength under tension by up to 90 percent, while density and compression strength are only reduced by about 10 percent (Wilcox 1978). If such decay is present on the side of the stem cross section that is loaded under compression, the pull test is not able to detect any significant reduction of the load-carrying capacity (similar to sonic tomography). However, if the same tree is pulled in the opposite direction, the result is likely to be much different, because the strength under tension is greatly reduced. Thus, for evaluating breaking-safety of defective mature urban trees, pull tests usually make sense only when using many sensors at different (potentially weak) spots of the trunk, and pulling in at least 4 directions. But, this would make pull-tests for breaking safety analysis of the stem extremely time-consuming and expensive.

This demonstrates one of the advantages of sonic tomography: it determines relative loss in load-carrying capacity for all loading directions within one measurement. Consequently, experts understanding the limitations of pull-tests for breaking safety analysis, use this pull testing method primarily for assessing uprooting safety.

In response to the problems and limitations of resistance drilling and pull-tests, other methods of assessing tree risk including stress wave timing were investigated in the early 1990s. Ultimately, a sonic sensor-system was developed and patented internationally (Rinn 1999) in order to overcome the problems of drilling and pulling by providing a colored picture of the whole cross-section of a tree being assessed for risk, to help evaluate loss in load-carrying capacity for all loading directions.

Unfortunately, unsubstantiated claims about the capabilities of sonic tomography were made by some purportedly neutral experts and scientists. And this lead to some frustration among practitioners using the method. What arborists need to understand is that sonic tomography generally cannot reveal wood condition! Sometimes the tomogram correlates fairly well with wood condition in the cross-section, but often it doesn't. The tomogram may look better than the actual wood condition or worse (Rinn 2015a). This is usually not the fault of the device (if applied

Figure 1. (Left) Typical lower cross-section of a forest spruce (*Picea abies*) with a central heart rot in a nearly circular stem cross section.

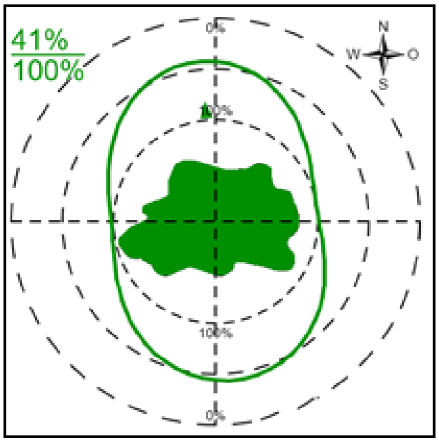
Figure 2. (Right) Mature urban trees usually show non-circular cross-sections and off-center defects, largely because the decay often starts at damaged lateral roots, growing into the stem base from the side.

properly). More importantly, it confirms that sonic tomography primarily reveals the load-carrying parts of the cross-section (Rinn 2014). And this is very fortunate, because this is the most important information needed for evaluating tree-safety.

The questions I get at conferences and workshops show that this basic aspect of sonic tomography needs to be explained in more detail.

Breaking safety

Figure 3. (Below) This sketch shows the lower stem cross-section of a mature urban tree. The oval solid green line around it represents the relative section modulus, representing the load-carrying capacity (assuming homogeneous material strength) for all loading directions: the further the green curve bents out, the weaker the cross section by loading into this direction. This tree stands to the North of a building on a site where the wind predominantly comes from the West and Southwest directions. Because of the adaptive growth, the stem cross-section is strongest for the major loading direction (where the green oval touches the 100% (= inner dashed-line) in the Northeast (= in the direction of the prevailing wind). For wind coming from the South and Southeast, this cross-section only loads approximately 40% - meaning: if the building south of this tree is removed, wind from the south could be dangerous because the cross section is significantly weaker when loaded in this direction.



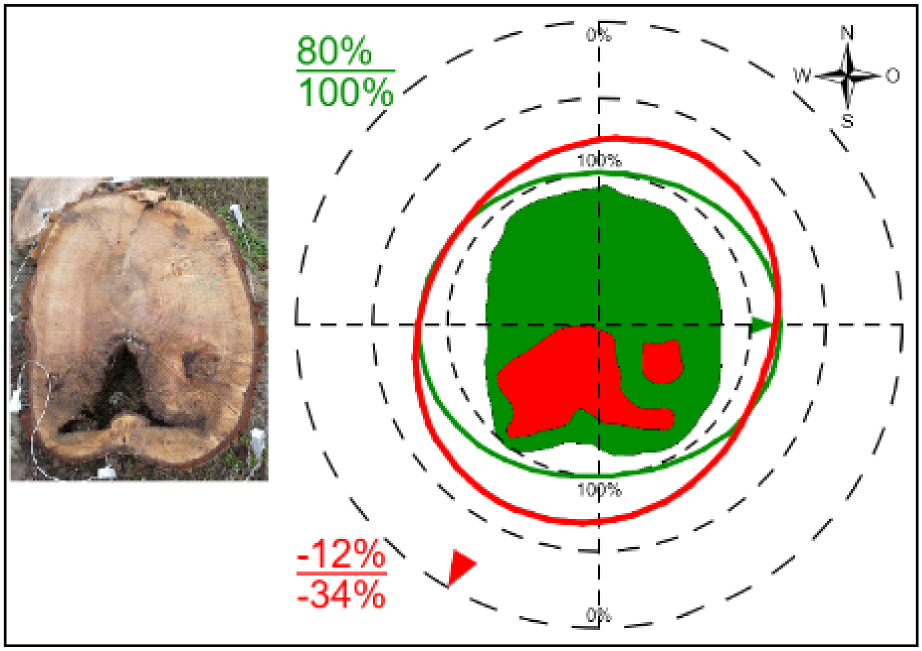


Figure 4. (Above) This tree stem cross-section shows an off-center defect, resulting in a relative loss in load-carrying capacity as represented by the red curve, and varies ranging from approximately 12 to 34%. That means, loading from Northeast is more than twice as dangerous as compared to wind loading from Southeast or Northwest. If the tree had been loaded in a pull-test to Southeast or Northwest direction, it would have been considered safe (only 12% loss in load carrying capacity). The result would have been very different if pulled (loaded) to the Southwest, because the loss in load-carrying capacity there is nearly 3 times more. Because such internal defects are usually not visible from the outside, the weakest loading direction is not known and thus may be missed in a pull-test when only loaded in one or even two directions. This is why a proper sonic tomography with a system providing this information on relative loss in load carrying capacity is highly advantageous.

The safety (factor) of a structure is basically the ratio of the load-carrying capacity divided by the load. For safety related evaluations, usually worse-case scenarios are applied, meaning that the load-carrying capacity at the 'weakest' point or loading direction has to be determined and compared with the maximum expectable load.

When determining the load-carrying capacity of a cross-section, some aspects are most important:

- The load carrying capacity of a stem or branch cross-section depends more on the size and circumference-shape than on the strength of the material (Rinn 2011).
- The location of a defect within the cross-section is more important in terms of a loss in load carrying capacity than the size of it (Rinn 2013).
- In comparison to forest trees (**Fig. 1**), stem cross-sections of mature urban trees are often not circular (**Fig. 2**). Consequently, the load carrying capacity of such cross-sections is not symmetric but varies depending on the loading direction (**Fig. 3**). When defects are located off-center in non-concentric cross-sections, it is usually impossible to estimate the weakest loading direction and the remaining load-carrying capacity by gut feeling alone (**Fig. 4**). So, the use of technical devices is required. And this is why technical diagnostic methods have been developed.

Technical results

Following Nielsen (1990), results of static load tests depend on many external (such as soil depth, soil texture, soil water content, etc.,) and internal factors (i.e. material uniformity) so that results are not very precise as long as they are given in absolute numbers. But, it is possible to compare the result of a bending test of a defective cross section with that of an intact cross-section of the same tree, assuming similar material properties. This results in a relative risk assessment but is valid only for the measured spot and the direction of loading applied in the pull-test.

Based on the 2-dimensional sonic tomography picture (tomogram), the software of the sonic tomography device described here calculates the relative loss in load-carrying capacity as compared with the fully intact cross-section (assuming similar material properties). So far this is the same as what can be done in a pull-test.

Based on calculations by L. Wessolly (Stuttgart, Germany), Lesnino, compared remaining load-carrying capacity of decayed cross-sections as estimated by pull-tests and sonic tomography in 2009 (**Fig. 5**). He found a surprisingly high correlation when compiling the results of 6 measured trees. Later, J. Wolf (Bremen University, Germany), confirmed this correlation, however, using just a few trees.

What this means is that the relative loss in cross-sectional load-carrying capacity, determined by the tomograph software, is similar to the results of a pull test – but, the tomograph provides the same result for all loading directions with one measurement. This is significant when you realize that the results can be quite non-symmetric, meaning that one wind-loading direction can be significantly more dangerous for the tree compared to another (**Fig. 4**).

When wind load has to be reduced to compensate for a defect, the 'weakest' direction has to be checked first. The tomography system discussed here (ARBOTOM®) automatically provides information about the most dangerous wind-loading direction more easily and with less effort than doing several pull-tests.

Thus, pull-tests should be used mainly for analyzing uprooting safety and only in special cases for breaking safety analysis, for example, weak unions or grafted trees, but then the sensors would have to be able to bridge a distance of more than 50cm (20 inches).

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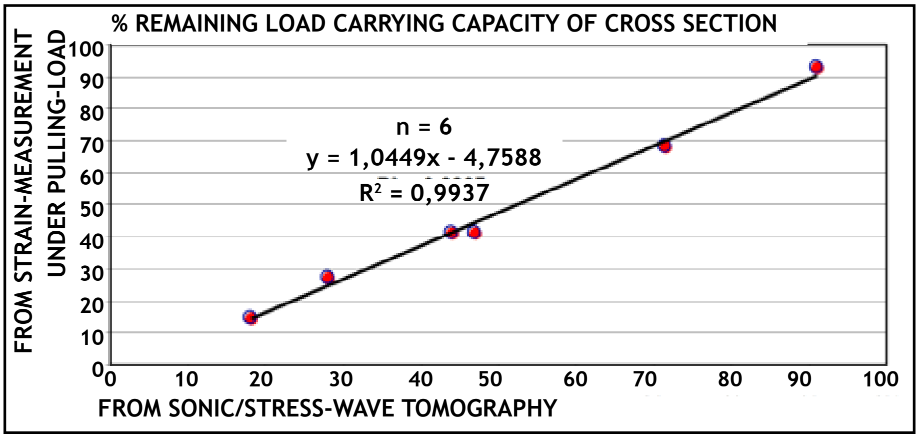
Figure 5. Using calculations by L. Wessolly, G. Lesnino compared remaining load carrying capacity of defected cross-sections as estimated by pull-tests and sonic tomography (Lesnino, 2009) and found a surprisingly high correlation when compiling the results of 6 measured trees.



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