# Principles and challenges of static load tests ('pull-testing') for estimating uprooting safety

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## Introduction

In the 1980s, German landscape architect Günter Sinn asked the University of Stuttgart, Germany, to investigate the practicality of wind load simulation by static-load testing of urban trees to evaluate their structural stability and relative safety (Sinn & Wessolly 1989). Unfortunately, the grant proposal was not funded and in consequence, Wessolly quit the University and started working on his own (Wessolly 1991). In 1998, Wessolly and Erb published a book describing a comprehensive method for measuring uprooting and breaking safety of trees (by static load tests), often called "Static Integrated Assessment" (SIA).

Currently, several hundred tree experts around the world use pull tests when applying SIA to evaluate uprooting safety. However, probably only a handful of arborists really know how this method works, largely because the math behind the method is rather complex, and has not been widely published or confirmed by non-biased research institutions.

Taking into account that there is no peer-reviewed publication confirming the principles and hypothesis for SIA-pull-testing analysis, or substantiating data (of trees pulled down for correlating estimated and actual failure loads), it is more than just surprising that this method has been incorporated into national and even international standards, such as by the German FLL (**www.fll.de**) and ISA (**www.isa-arbor.com**). Because many arborists just follow the recommendations in these standards, pull-tests are increasingly being done worldwide, despite the fact that it is not well understood. As a result, I'm frequently asked by arborists and tree-safety experts at tree-risk assessment workshops in Europe, America, and Asia how pull-testing really works and how uprooting safety is calculated. So, I'll try to explain the basic principles behind this method in the discussion below.

Many experts apply the inclination (uprooting) analysis in combination with a strain measurement at the stem for an evaluation of breaking safety. Because this is a very different kind of analysis, this topic shall be explained in another article.

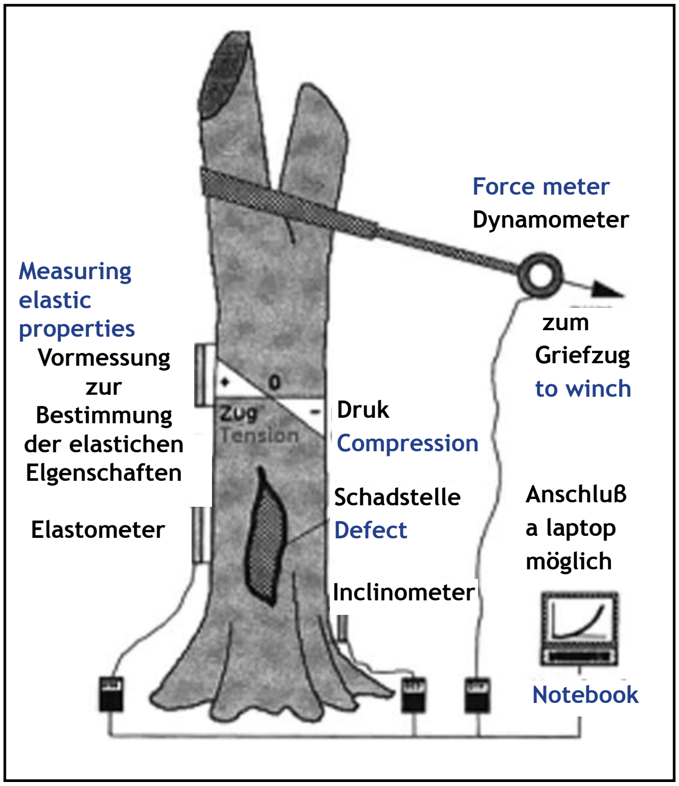
## Method

The practical application of pull-testing is relatively simple (**Fig. 1**): one end of a rope is fixed to a point as high as possible on the main stem of the test tree. The other end is attached to a winch fixed to a neighboring tree, heavy truck or immovable object at a distance greater than the height of the tree. A load scale is placed between the winch hook and the attachment loop or sling at the end of the rope to continuously record the pulling force.

A picture of the whole tree is taken before pulling to estimate the wind load as the major reference value for the pull-test. We usually install at least three inclination sensors at the base of the stem (for preferably continuous recording) of the inclination of the stem and the root plate while pulling. Usually, one sensor is placed in the pulling direction, one at the opposite side, and one at the 90° position. Our inclination sensors provide a resolution of 1/1000° in two (orthogonal) directions in order to monitor all relevant inclinations.

A mobile computer simultaneously records the force and inclination data and displays the results in a graph for further analysis and evaluation.

Figure 1. Sketch from Wessolly (1991) describing the pull-test setup at the tree. For uprooting safety, usually the inclination ("Inclinometer") is measured and compared with the pulling force ("Dynamometer").



### Basic assumption

Based on pull-tests on real trees (**Fig. 2**), Wessolly suggested (1991): the force required to pull a tree to an inclination at the stem base of 0.25° equals 40% of the force required to pull the tree to failure (**Fig. 3**). The uprooting safety is then derived by dividing this estimated "tipping load" by the wind load, estimated on the base of an estimation of wind speed and surface roughness:

Safety = Tipping load / Wind load

$S = M_{kl} / M_{wl}$

So far, this method is quite simple. However, when applied to actual trees, a number of issues can result. Some of which are discussed below.

For many trees, it's not practical to apply the force required to get an inclination of 0.25° at the stem base for various reasons: the upper stem may be to too small in diameter, requiring the pull rope to be placed below the point that would provide a sufficient lever-arm length relative to the stem base, the anchor point may also be too weak to resist pulling, or the winch may not be strong enough (**Fig. 4**). Consequently, Wessolly suggested pulling with less force and then extrapolating the obtained values to the point where an inclination of 0.25° would most likely be reached. He referred to this extrapolation as the "generalized tipping-curve" (Wessolly 1991). Unfortunately, according to Wessolly, this curve is not linear (**Fig. 2**) and the "theoretically correct" mathematical formula is not simple. "Theoretically", because there is no publication yet from the method's developers regarding what the mathematical description of the curve looks like. In 2015, Buza and Goncz published a mathematical description of a generalized tipping curve for estimating the tipping load, however, the approach was not confirmed by supporting data or other publications.

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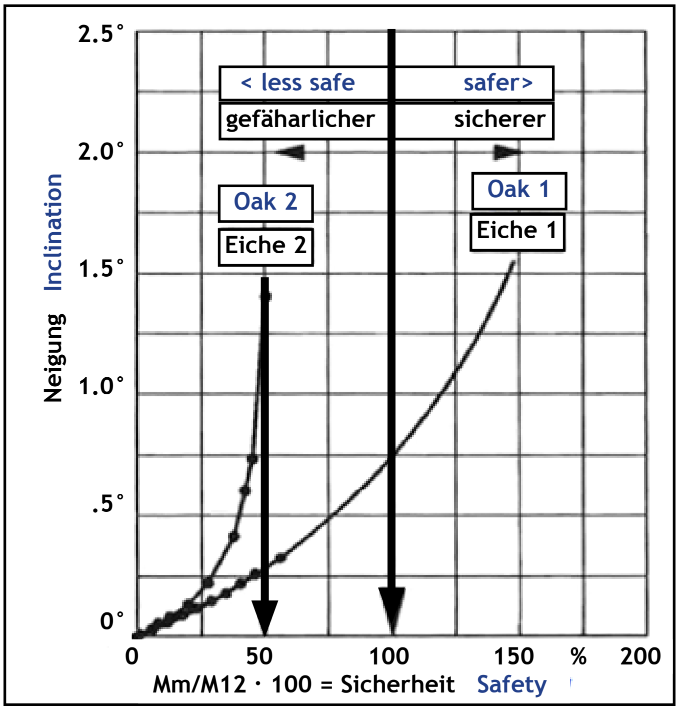
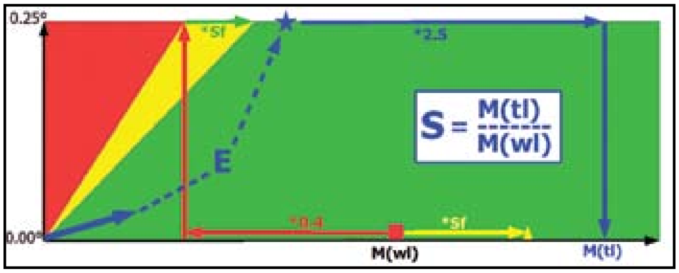
**Figure 2. (Left) The original graph of Wessolly (1991) showing the so-called tipping curve of an unsafe oak (*Quercus*) on the left and of a safe oak on the right. "Mm" means applied load and "M12" represents the estimated wind load at (windspeed) Beaufort 12.**

**Figure 3. (Right) The main hypothetical assumption is that a 'normal' tree inclines 0.25° when being statically loaded with approximately 40% of the load required for uprooting. Pull-tests evaluations commonly are based on this assumption and are shown here in one graph: the windload M(wl) is estimated by using a picture of the tree. Following the SIA concept, the tree shall not incline more than 0.25° (red area) at 40% of the windload for safety reasons. Many experts require an additional safety-factor: Sf=1.5, leading to the yellow area. The blue arrow starting at 0° and zero force, represents the real measured values of inclination (ordinate) at the stem base as a function of the applied load (abscissa). This blue arrow should be in the green area. Commonly, maximum pulling load is significantly smaller than required for achieving an inclination of 0.25°. Consequently, the measured inclination is extrapolated until this point. Thus, the blue line usually ends before reaching 0.25° and is extrapolated based on a mathematical model. (dotted line) This extrapolation ("E") is based on the so called "tipping curve" - a non-linear curve without any simple mathematical analytical description.**





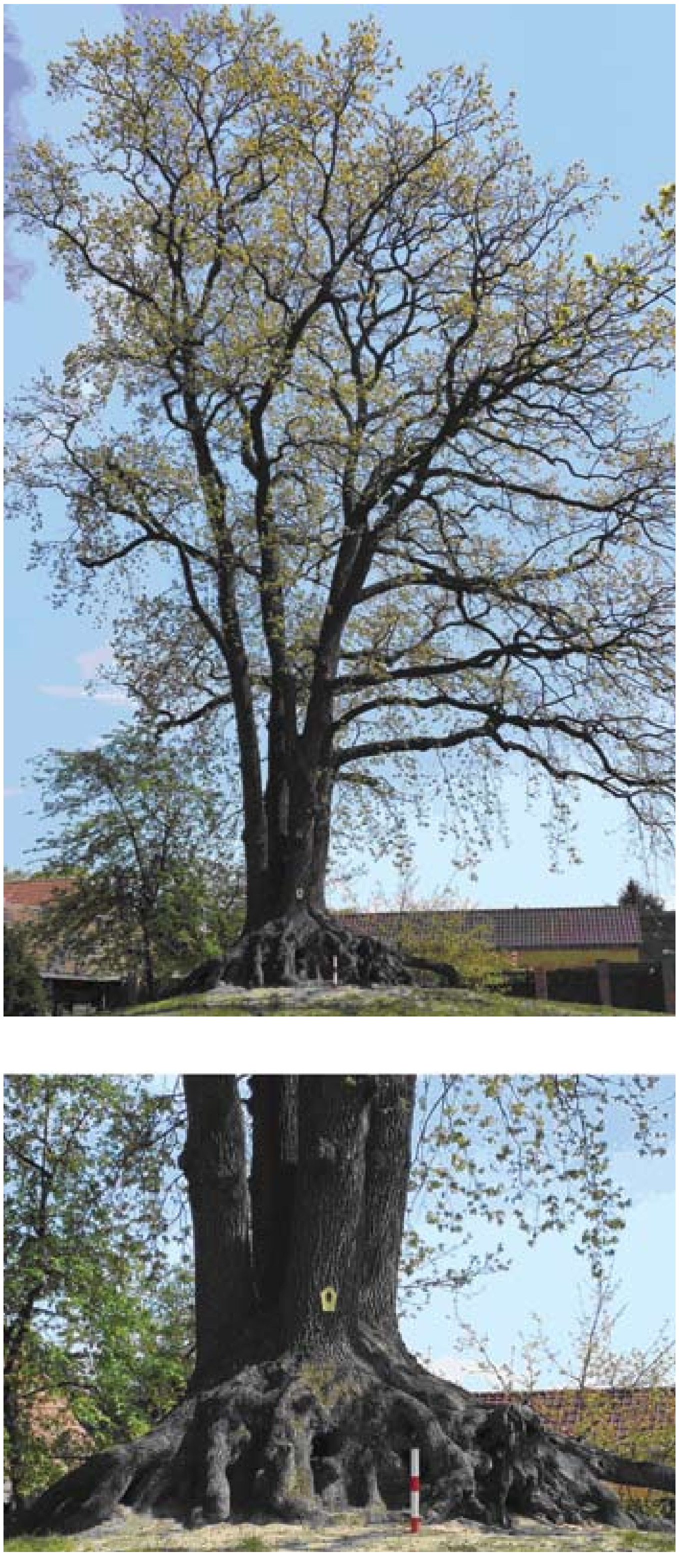


**Figure 4. Example for a mature tree with multiple competing branches where doing a pull test is not possible because the branches at the correct height are too small in diameter. Many of our large, mature trees have a similar crown structure restricting the use of pull-testing. Consequently, uprooting safety has to be determined using other means, such as sonic root plate analysis (Rinn 2016b).**

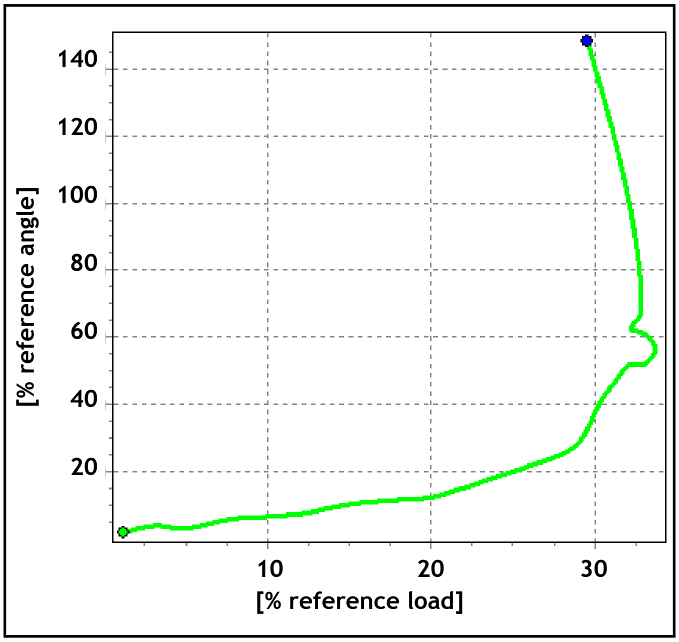


**Figure 5. In this inclination measurement, the force required to bring the mature beech tree (*Fagus sylvatica*) to failure was not far from the hypothesis (Fig. 3) with a deviation in the range of ±20%. In other experiments, the estimation error was bigger, in some smaller. Consequently, our results from pulling trees to failure do not yet confirm Wessolly's hypothesis.**

The results of our own static load tests, when we pulled trees to the point failure, indicate that Wessolly's hypothesis was a good guess, however, the data we obtained did not allow us to really confirm the concept (**Fig. 5**). The estimation errors differed strongly and didn't allow us to determine a clear correlation (**Fig. 6**) between estimated and real tipping loads. But, such a correlation is a mandatory requirement for any method estimating the likelihood of a failure as part of a risk-assessment. Without confirmation of the method by a clear correlation (preferably measured by independent experts/institutions), no method should be used for safety related risk assessments.

One reason for the measured variations in pulling-test estimations may be that, for example, the impact of soil moisture has not been taken into account in the standard mathematical approach. In addition, the obvious differences in inclination between sensors at different positions at the tree root flare show that the stem base of trees obviously does not incline like a rigid uniform plate, but deforms under load (**Fig. 7**). The more sensors we use, the larger the differences we encounter, clearly demonstrating the lack of confirming data and understanding of the method.

Finally, when we pulled trees to failure, the tipping load did not closely equal 2.5 times the load required to pull the tree to an inclination of 0.25°, indicating that there may be significant estimation errors due to the many (partially unknown) variables in the system. In addition, the final re-

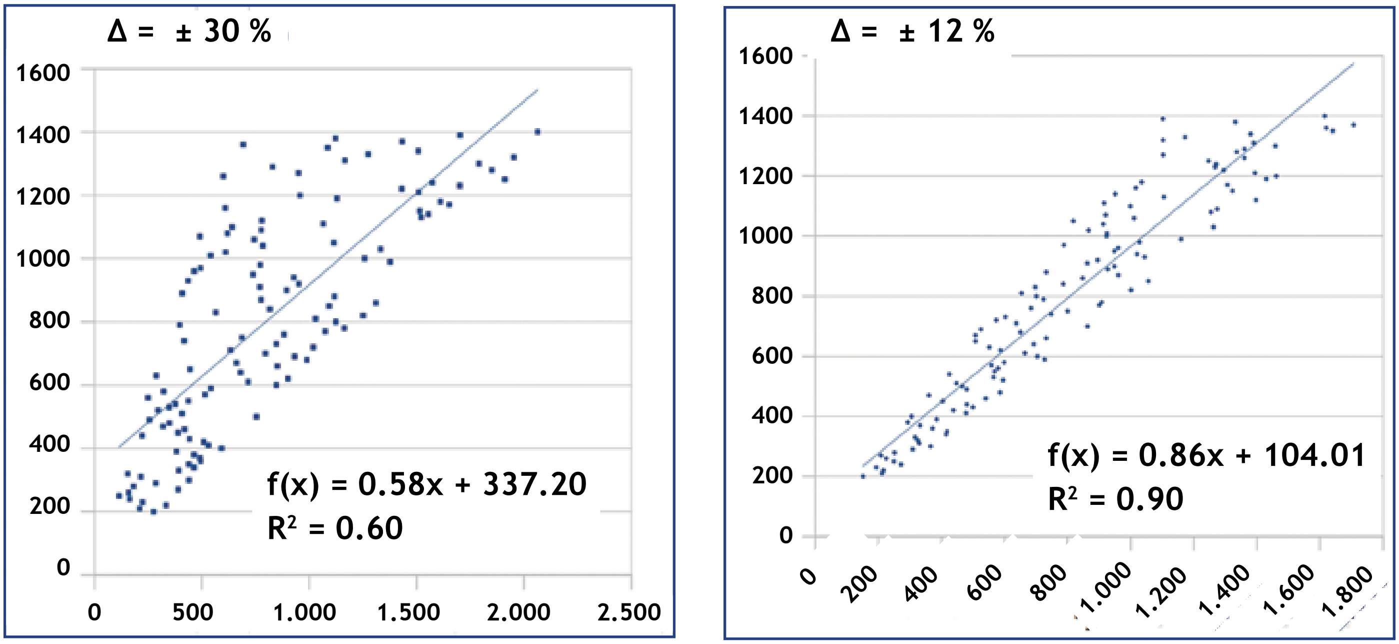
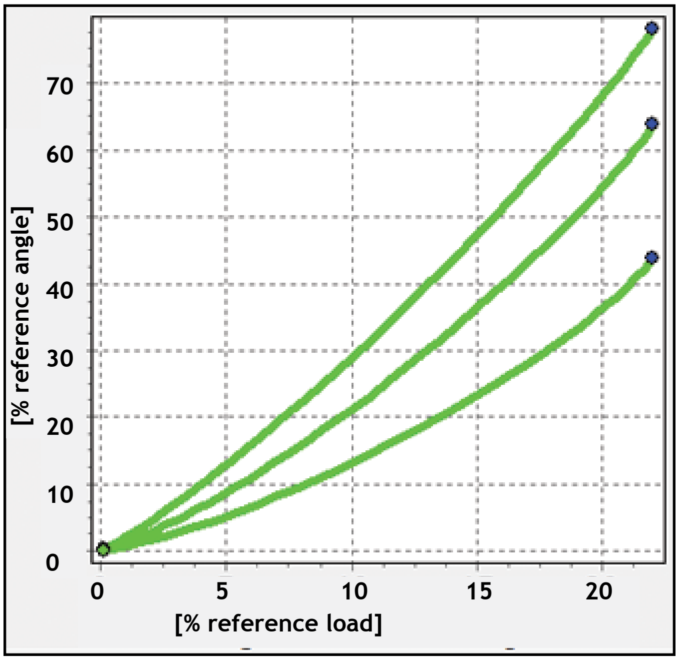


**Figure 6. Two typical examples showing the linear correlation between an estimated (X = abscissa) and the real value (Y = ordinate). The coefficient of determination ($r^2$) is commonly used to describe the quality of such a correlation, however, many people struggle with what it means. When $r^2=0.9$, this typically corresponds to an estimation error of 10 to 14%. In the example shown above, this data set delivers $r^2=0.9$ and an error of ±12% when estimating Y based on X. The other data set (left) shows $r^2=0.6$ and an estimation error of ±30%. This means that when estimating the value Y based on a measurement and/or calculation of X, the results is correspondingly imprecise and unreliable.**

sult of the pull-test (the "uprooting-safety"), does not only contain the tipping load as an estimated variable (with a corresponding error span), but depends on the wind load. This value can't be determined directly, and consequently it is estimated based on several rough assumptions (Rinn 2014a). The total error span of the uprooting safety as the final result of the pulling test is then the sum of the error spans of the two variables, estimated wind load and estimated tipping moment (Rinn 2014b). And this final error span needs to be determined by comparison between estimated results and real measurements. As long as this job is not done neutrally and not published in peer-review

**Figure 7. Three sensors were placed at the base of a beech tree (*Fagus sylvatica*). One in the pulling direction, one opposite and one at a 90° angle. The resulting tilting curves differed significantly and would have led to three correspondingly different final estimations of uprooting safety.**



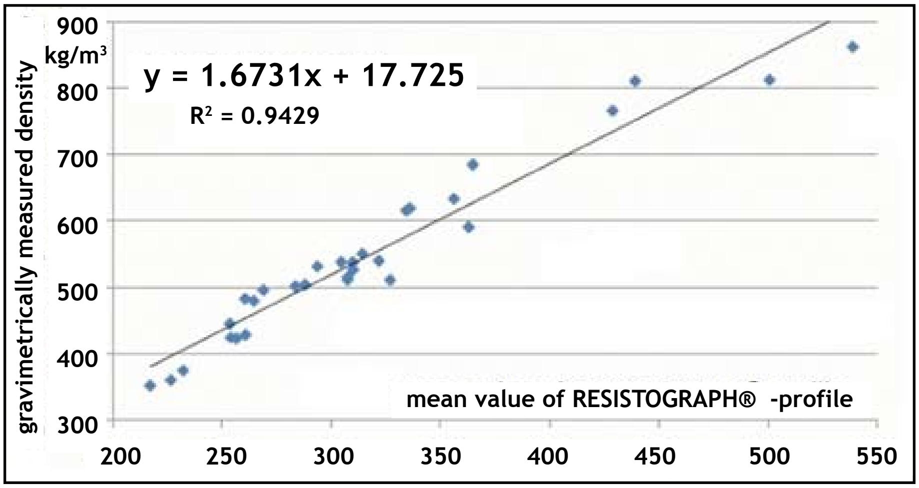


**Figure 8. Example graph showing a clear linear correlation between a measured and a real value. Profiles of real RESISTOGRAPH® devices highly correlate to wood density as shown by $r^2>0.94$, recently confirmed by Brashaw et al. (2013). That means, even slight density variations by incipient decay can be identified in such resistance drilling profiles and, even more important, gradients from intact to decayed parts are revealed correspondingly correct, enabling the user to estimate the speed of further radial spread of decay (Rinn 2016a). For other kinds of resistance drills, $r^2$ was found to range from 0.5 to 0.6, approximately, leading to correspondingly less precise profiles. This correlation is critical because wood condition can only be evaluated reliably when $r^2>0.8$. In addition, early stages of decay can already reduce wood strength by 90% when only having lowered density by 10% (Wilcox 1978). This can only be detected by resistance drilling when the profiles correlate to wood density with $r^2>0.8$ or even more. Thus, the correlation coefficient between the drilling profile and real wood density is the key measure to evaluate suitability of a resistance drill. Drills with $r^2<0.7$ or even $r^2<0.6$ do not really allow to detect decay reliably.**

journals, standardization organizations should not recommend corresponding methods.

## Summary and conclusions

Our measurements indicate that Wessolly's hypothesis probably was a good guess. But, according to the differences between the measured inclination curves for the same tree and the significant spread of the estimated tipping loads from the real failure loads obtained while pulling trees down, it's obvious that this method needs further research by neutral and independent research institutions, and subsequent publication of the test results in peer-review journals. Fortunately, the test setup is quite simple: a relatively large number of trees need to be pulled to failure to be able to correlate the estimated tipping load (based on Wessolly's hypothesis mentioned above) with the actual force applied to cause uprooting. Because young trees commonly don't need to be tested in terms of uprooting safety, the only way to potentially confirm Wessolly's hypothesis is to pull mature trees with significant root and stem base defects to failure. Because soil moisture is a critical factor in uprooting, it has to be measured for the same trees under both wet and dry soil conditions.

The estimated 'tipping load' can then be shown in correlation to the actual failure-load after having pulled the tree to point of failure. Comparison of these values allows the reviewer to evaluate the reliability of the pull-test method for estimating uprooting safety based on the coefficient of determination (**Fig. 6**) of the correlation. Two examples of such a correlation from the area of technical tree-safety diagnostics illustrate how this can verify a method (**Figs. 8 & 9**).

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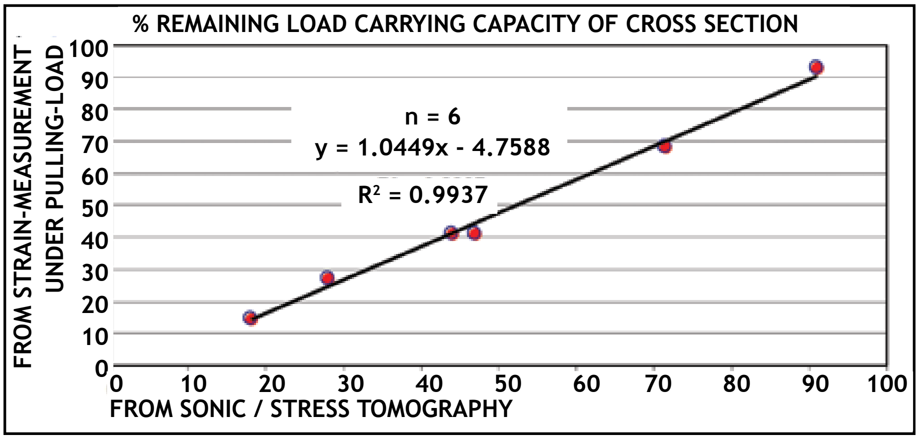

**Figure 9. Based on calculations of Wessolly, Lesnino (2009) found a surprisingly high correlation between the relative loss in load-carrying capacity based on sonic tomography and pull-tests. Because this correlation was much closer than expected, further studies were carried out by an independent institution (Bremen University, Germany), leading to $r^2>0.9$, still indicating that this kind of sonic tomography is able to predict relative losses in cross-sectional load carrying capacity.**

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