Comparative Analysis of Tools and Methods for the Evaluation of Tree Stability

Results of a field test in Germany

By Bodo Siegert

In a field-test project, sixteen trees were examined and evaluated through the use of tree stability evaluation methods and common tools. After assessment of each tree's stability and a determination of the likelihood of failure, each tree was pulled until it fell over. Data on the trees' actual static conditions were collected. By evaluating the measured data, conclusions were drawn regarding the accuracy of assessment and predictions using the various tools and methods.

In recent years, the number of tools and methods available for the examination of tree safety has steadily grown. Due to rapid technological progress, experts in tree safety face both the problem of selecting adequate tools for individual analysis as well as the challenge of assessing, if the chosen methods are still state-of-the-art. Among the experts there are considerable differences in opinion regarding the selection of proper tools to measure trees' stability. In Germany, this discussion, called "the dispute over methods," has persisted for years.

Objectives of the Project

In 2008, the German association of certified arborists (Fachverband gepruefter Baumpfleger) established a research group to evaluate commonly available measurement tools [Arbeitskreis Untersuchungsgeraete (AKU)]. In a two-year practical project, the AKU conducted a comparative analysis of common tools and methods used for the evaluation of tree stability and safety against failure. In addition to members of the German association of certified arborists, both independent scientists and equipment manufacturers were invited to join the project and to evaluate their tools.

The project's objectives were:

A) to evaluate the suitability of single tools and methods to answer specific questions on the condition of trees (with a special focus on tensile tests),

B) to find out if different measurement techniques can yield comparable results and conclusions regarding a tree's structural health, and

C) to determine if the combined use of different methods and tools provides a more complete picture of a tree's status than the use of a single tool/method.

Trees Examined and Proceedings

The 16 trees examined in this project were mature urban trees already planned to be felled due to major defects (e.g., fungal decay, cracks, hollows in the trunk or base).

For each tree, two days of field work were scheduled. On the first day of analysis, the project team examined the trees thoroughly using various evaluation tools and methods, resulting in a prediction of the tree's stability and likelihood of failure. On the second day of analysis, the trees underwent a tensile test, in which the tree was pulled until it fell or fractured. Afterward, measurement data were collected, samples of the analyzed stem disks were collected, the root plate of each tree was excavated, and the wood samples were photographically documented.

Results

Drill Resistance Measurement

Drill resistance measurement involves recording the penetration resistance of a drilling needle through wood to generate a profile of wood decay and cavities. The resulting graphs are often referred to as measurement curves. Devices used are listed in Table 1.

In order to obtain a three-dimensional image of the trunk damage of a tree, up to 12 drillings per level were completed. Typically, several levels were identified for testing. The profile readings were converted into a "statement on the overall stability."

At the examination, several devices of one single model were used whenever possible to evaluate uniformity of performance. At the test of drill resistance tools, up to three devices of RESISTOGRAPH® 4453/4452-P/S and up to four devices of IML-RESI 1410 were used. The scatter of results turned out to be insignificant.

When conducting visual evaluations of the measurement profiles generated by the different examination devices, it became apparent that the less expensive devices showed a much less precise and less obvious profile than the higher-quality electronic models by RINNTECH and IML. The mechanical devices (IML-RESI F-series and IML-RESI M-series) proved to have lower resolution and sometimes displayed non-interpretable readings, implying that minor variations in wood thickness were not always displayed in a reliable form. However, these are not new findings, as this had been previously determined from earlier examinations. Of the electronic devices used, the RINNTECH device had a higher resolution than the IML device (Figure 1; Figure 2).

The field test showed that the direct analysis of tree drill resistance tree profiles requires a solid understanding of the anatomy of wood, species-specific knowledge, and extensive experience in the handling of measurement technology. In comparing machines, drill resistance measurement curve profiles varied. Depending on machine type, changes in the measurement curve can be caused by a variety of factors—in addition to wood anatomy—including the mechanical properties of the machine and the drilling process, such as spring-resonances within the machine or the drifting of the drilling needle during sampling. Massive rotting, however, was clearly recognized by all machines, and related wall thicknesses were determined in a quite decisive manner. In most cases, peaks caused by considerable wood degradation were also clearly interpreted.

However, the origin of a couple of profile drops was not interpretable in early stages of certain fungal infections (e.g., *Ustulina deusta*). In these cases, other measurement methods were deployed to get additional information. In the analysis, sonic tomography and electric tomography turned out to be adequate tools to clearly identify the beginning of wood degradation.

Sonic Tomography

Sonic tomographs detect defects (e.g., hollows or wood rot) in a non-invasive way by generating a two-dimensional map of the sound velocity transmitted across a tree's section, mirroring the integrity of the inspected wood.

Measurements were carried out at three levels. In order to minimize examination costs, 12 measurement points were defined per level, except in the case of trunks with many folds, when more measurement points were added. The same measurement points were used for all devices.

To evaluate uniform performance, up to five ARBOTOM® devices and up to three PICUS devices were deployed. The overall performance turned out to be similar. A more critical inspection of the results might discern that a divergence in results was caused by different settings of tools and related software.

Table 1. Drill resistance devices used in the analysis.

Type	Devices used	Number of trees
RESISTOGRAPH® 4453/4452-P/S (RINNTECH)	Up to 3 devices	16
IML-RESI 1410 (IML)	Up to 4 devices	16
IML-RESI E-series (IML)	1 device	2
IML-RESI F-series (IML)	1 device	2
IML-RESI M-series (IML)	1 device	1

Table 2. Sonic tomographs used in the analysis.

Type	Devices used	Number of trees
ARBOTOM® (RINNTECH)	Up to 5 devices	16
PICUS (ARGUS ELECTRONIC)	Up to 3 devices	16
FAKOPP 2D (FAKOPP)	2 devices	2

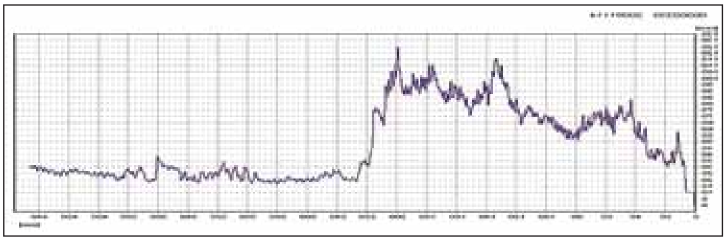


Figure 1. RESISTOGRAPH® 4453-P (RINNTECH) profile. This is a mirror-inverted display to ease comparability with the IML-RESI profile in Figure 2.

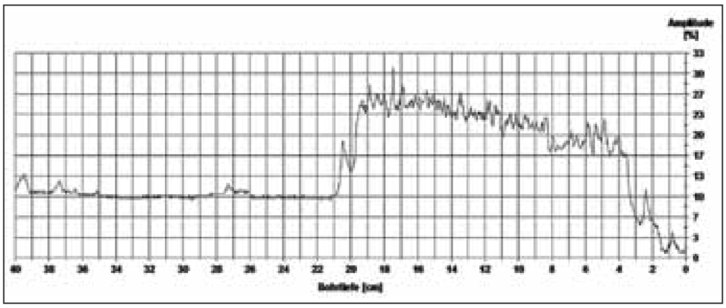


Figure 2. IML-RESI 1410 (IML) profile.

At similar measurement points, examination of the sonic tomographs produced by different measuring devices revealed very similar results (Figure 3a; Figure 3b; Figure 3c) (All examinations refer to the same tree. In Figure 3c, the examinor's position differs, however, the tomograph reveals similar results as with Figure 3a and Figure 3b). However, the colors displayed on the tomographs varied considerably among the models. The FAKOPP 2D and PICUS models use pre-set colors. For example, PICUS displays areas with high "sonic speed" in dark brown whereas low sonic values are shown in sky blue. Other colors of violet and green represent various levels of rotting zones based on sonic speed measurements in the respective areas. ARBOTOM uses a broader range of colors to visualize sound transmission times. While default settings can be accepted, ARBOTOM also allows for manual scaling. This enables an improved visual representation of actual conditions.

The test showed that sonic tomography can be used to detect wood structural changes, but is not able to determine the factors that cause them (crack, hollow, or moisture). In order to deduce the definite reason for the changes, other measurement methods were deployed. For this, the data generated by drill resistance measurement and electric tomography were used to produce a wood density reference to verify the tomogram measurement. Consequently, clear statements on the trees' structural integrity could be made.

Electrical Impedance Tomography

This tool analyzes a tree by sending electrical voltage through the investigated trunk zones, providing a two-dimensional map reflecting the corresponding status of electrical impedance, allowing the user to draw conclusions about the tree's structural integrity.

Both the PICUS TREETRONIC instructions and scientific literature indicate that the tool's application close to ground level is limited due to existing ground humidity influencing measurement results. However, when examining tree conditions, the area of the trunk near to the ground is of particular interest. Therefore, measurements at the ground level were taken for all examined trees in this practical test (Figure 4). The tool measures the relative differences in humidity for one level, dependent on the distance between the sensors or the distance to the ground.

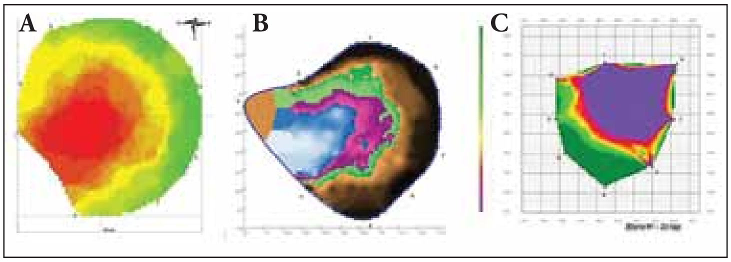


Figure 3. Device results: a) ARBOTOM, b) PICUS, c) FAKOPP 2D.

Table 3. Electrical impedance tomographs used in the analysis.

Type	Devices used	Number of trees
PICUS TREETRONIC (ARGUS ELECTRONIC)	1	10

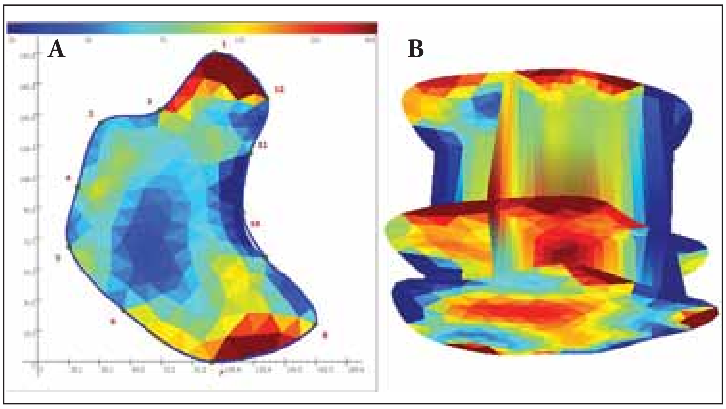


Figure 4. Device results: a) PICUS TREETRONIC, b) PICUS TREETRONIC 3D tomogram.

Table 4. Static load test sensors used in the analysis.

Type	Devices used	Number of trees
WESSOLLY	1 set of sensors	1
SINN	1 set of sensors	1
DYNATIM (RINNTECH)	1 set of sensors	16
DYNATREE (SIEGERT)	1 set of sensors	16

While an electric tomograph usually cannot be used as the sole basis of tree-static assessments, it turned out to be an adequate verification tool of unclear findings given by sonic tomography devices. In combination, these two methods provided findings that enhanced the trees' overall evaluation.

Static Load Tests

In a tensile test, a tree is exposed to a simulated wind load. The data measured by strain sensors and inclination angle sensors, combined with empirically measured comparative standards, provide information on the trunk's load-bearing capacity and the tree's anchorage force in the ground, resulting in an evaluation of the tree's static condition. There are several software applications available to ease the complexity of this calculation process. These calculation programs have individual characteristics, but they all use the same calculation principle and share the same basic mathematical formulas. (This applies to major tree static load test software programs available in Germany.) Both methods for how to conduct a tensile test on a tree and the mathematical formulas to evaluate measurement data were originally developed by WESSOLLY ("Wessolly's method") (Wessolly and Erb 1998).

For the performance of the static load tests, measurement values were manually recorded at the devices by WESSOLLY, SINN, and SIEGERT. For the DYNATIM system by RINNTECH, data were transmitted electronically to a measuring transformer. When installed properly at the measurement points (Figure 5; Figure 6; Figure 7), all sensors supplied identical measurement values.

For the evaluation of sensor values collected by WESSOLLY and SINN, these manufacturers used their own calculation programs. The values measured by RINNTECH and SIEGERT devices were evaluated using the TSE calculation program by SIEGERT. (TSE: Tree Stability Evaluation, calculation software for tensile tests, based on Wesolly's method.) All calculation programs provided similar results.

In Figure 8, results of forecasts from the static load test and the actual failure are displayed. Row #1 contains the forecasted tensile load, Row #2 shows the actual force of failure, and Row #3 specifies the deviation of both values (%). In the worst case, the deviation of actual failure from that forecast is 37 percent, and in the best case, 4 percent. Although these results may suggest an inaccuracy in the method, these are in fact currently the most exact statements available regarding the failure behavior of trees.

Figure 5. DYNATREE (SIEGERT).

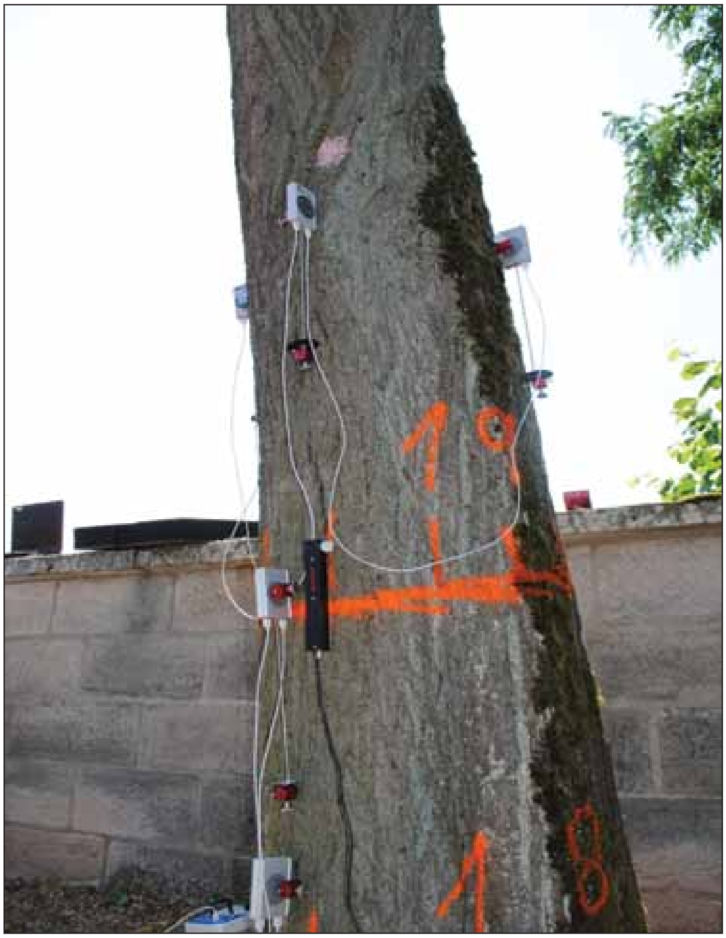


Figure 6. DYNATIM (RINNTECH) and WESSOLLY sensors.

Figure 7. SINN sensors, DYNATIM (RINNTECH), and DYNATREE (SIEGERT).

The overall analysis put a special focus on the evaluation of the static load test method. The suitability of the WESSOLLY formulas to answer questions on fracture resistance and tree stability was evaluated.

For the calculation of fracture resistance, measurement data from the tensile tests are projected and compared with statistical data on the properties of green woods (Wessolly and Erb 1998). Therefore, conclusions can be drawn regarding the maximum tree tensibility (Yield Point) (Wessolly and Erb 1998). As a result, a value that reflects the fracture resistance of the examined tree at gale force winds can be obtained.

In the analysis, 16 trees were examined. Thirteen of them were torn down in the tensile test, whereby 12 failed due to uprooting and one tree reacted to the load introduction with a forecasted trunk fracture. Consequently, the planned analysis of fracture resistance could not be carried out. Also, the confirmation of statistical data on the properties of green wood, published in Wessolly's

▶

	Pulling-test Tree ID	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
	TSE solution, factor stem break	2,8	3,0	1,6	4,6	2,2	0,6	1,0	0,8	2,0	x	3,3	2,0	3,0	3,4	0,8	0,9
	TSE solution, factor uprooting	1,4	2,0	1,0	3,4	2,0	0,8	1,6	1,4	1,6	x	0,6	2,0	0,6	2,2	1,6	0,9
1	fail force calculate in t	9,0	4,4	1,5	2,2	13	1,0	2,3	0,8	2,2	x	1,2	7,0	0,4	1,9	2,2	0,9
2	fail force real in ton	9,7	6,0	1,8	2,8	x	1,3	2,6	1,1	2,0	x	1,2	x	0,3	2,1	1,8	1,1
	fail force visibility in	9,8	5,0	1,8	2,5	x	1,2	2,6	1,0	1,8	x	1,1	x	0,3	2,0	1,7	0,8
	visibility fail effect	earth crack	earth crack	stemfoot rupture	stemfoot rupture	no, Tree was ok	stem rupture	stemfoot rupture	earth crack	earth crack	x	earth crack	branch rupture	stem-foot rupture	earth crack	stem-foot rupture	break of root
	type of fail	tilt over	tilt over	tilt over/ breaking	tilt over/ breaking	no, Tree was ok	tilt over/ breaking	tilt over/ breaking	tilt over	tilt over	x	tilt over	branch breaking	tilt over	tilt over	tilt over/ breaking	break of root
3	discrepancy %	8	36	20	27	x	27	13	37	9	x	4	x	16	9	18	12 in average

Figure 8. Comparison of forecasted and actual tree fail force, based on TSE calculation program results.

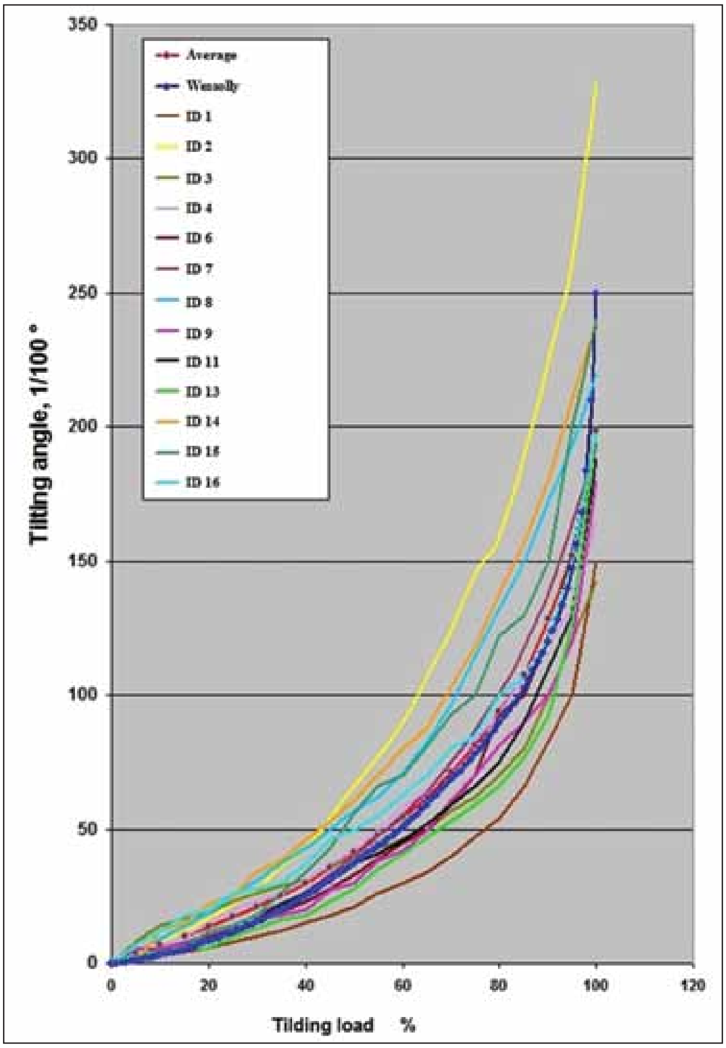


Figure 9. Individual titling curves of trees 1–4, 6–9, 11, and 13–16 in comparison to Wessolly tilting curve (dark blue).

"Stuttgart reference table" (Wessolly and Erb 1998), could not be conducted. It was merely noticed that the data collected in the analysis never fell below the reference table's data.

To evaluate tree stability with a tensile test, the minimum inclination of the root plate and the resulting inclination of the trunk base are recorded and compared to empirically-determined limit values regarding the natural tilting behavior of trees (the "generalized tilting curve," according to Wessolly and Erb (1998). Thus, the reaction of the tree to the simulated wind load within its "normal behavior" is examined, and as a result, a factor that maps the tree's stability can be determined (Wessolly and Erb 1998).

At the practical test project, the most important result of the tree tensile tests was the confirmation of the generalized tilting curve for 12 of the 13 trees that were torn down. Thus, it was determined that the average tilting curve of the examined trees corresponds quite well to the generalized tilting curve according to Wessolly, and is reasonably consistent with the forecasted stability.

In the analysis, this method provided concrete measurement values, allowing for a comprehensible, transparent calculation result. The static load test method came to conclusive results regarding the failure behavior of the trees, allowing well-founded statements on the trees' stability.

However, the analysis also pointed to the limits of the static load test. This method could describe the stability of certain areas exposed to a load. It could not be used to illustrate a spatial situation (e.g., determine the form of an internal damage). Moreover, the tensile test did not point to structural changes caused by moisture and cracks. To answer these questions, other measurement methods need to be deployed (e.g., drill resistance measurement and sonic tomography).

Applications to Estimate Fracture Resistance

The SIA (Static Integrated Assessment) method developed by Wessolly is a calculation process to evaluate the static condition of a freestanding tree with a special focus on its fracture resistance. Several software applications are based on this calculation method.

Apart from the SIA Online calculation program by the SIM group (http://sia.simgruppe.de/sia.php), the analysis software of the PICUS sonic tomograph is based on the SIA method. The TSE calculation program for static load tests also uses the SIA method by calculating a theoretical fracture safety value and comparing it to actual measurement results.

The analysis showed that all applications based on the SIA method provided reasonable values for the estimation of the fracture resistance. As expected, there were no major differences between SIA Online and the PICUS analysis software. The TSE program showed higher accuracy, as the user can enter a concrete measurement value at a certain calculation step. In contrast, SIA Online and PICUS analysis software use standard figures for the same step.

The SIA methods evaluated in the analysis provide a mere theoretical value to estimate fracture resistance. It is an ambiguous indicator for a tree's status, but a basis for further tree evaluation measurements.

Summary

Analyzing the results of single categories of devices at the same tree, differences in measurement values were obtained for drill resistance tools and sonic tomography. Thus, only rough

Table 5. Applications to estimate fracture resistance used in the analysis.

Type	Number of trees
SIA Online (WESSOLLY)	1
PICUS (ARGUS ELECTRONIC)	1
TSE (SIEGERT)	1

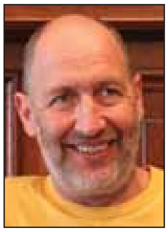
statements on the trees' status could be deduced by these methods. As drill resistance devices, sonic tomographs, and electric tomographs measure changes in wood structure only above the ground level, they could not provide statements on the trees' stability against uprooting. The planned analysis to evaluate fracture resistance with static load tests could not be carried out since 12 out of 13 trees examined reacted to the static load test with uprooting, not fracture. Looking at the strengths of the single categories of tools and methods, drill resistance devices seemed to be a good tool for a basic tree evaluation as certain factors and symptoms could be assessed well. When specific defect locations needed to be identified, sonic tomography was the method of choice. Static load test were essential for the evaluation of trees' stability against uprooting, as they are the only common method to evaluate this.

As each group of measurement tools analyzed specific wood properties, comparable conclusions of the trees' status could not be obtained. While changes of measurement values were determined, the possible cause for the wood degradation could not be deduced. Specific measurement values were obtained through the static load test. The other examined measurement processes required interpretation of results, and often depended on estimated values. This affected the accuracy of the forecast considerably, and required the user to have a high level of expert knowledge in order to understand the potential and limitations of the applied method.

It has been generally determined that the measurement devices and processes used in the field test do supply highly precise information for answering individual aspects of tree condition questions. However, the comparison also showed that the use of a single tool entails risks, as a single detection method may incorrectly indicate a defect, for example due to a non-decay related wood moisture or other conditions. In this case, a second method may clarify the result. Limits of tools and methods evaluated may be overcome by the suggested deployment of complementary devices and methods. As comprehensive tree evaluation requires both the evaluation of fracture resistance as well as evaluation of stability, the integrative deployment of complimentary tools and methods provides a complete picture of the tree's real status. Thus, accurate assessments of tree stability requires experts with not only years of practical experience in the handling of old trees, but solid knowledge of the anatomy and mechanics of wood and tree conditions as well as training in the integrative use of measurement devices.

Literature Cited

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



Bodo Siegert is a court-certified expert in tree care and tree statics in Nuremberg, Germany (www.sv-siegert.de). He is heading the research group on examination equipment at the German association of certified arborists and is actively involved in the FLL committee, the national board that develops technical tree care rules and regulations ensuring the corresponding quality assurance. Siegert's latest project is the Independent Tree Expert Group (www.iteg-network.com), a new association for tree statics experts pursuing an integrated, holistic approach in tree safety tests.

The author appreciates the editor's permission to revise the article for publication and appreciates the critical readings by R.B. Allison and P. Brewer whose helpful comments and questions definitely improved the article.

This article is a revised and expanded version of the original which appeared in AFZ-Der Wald in March 2012.