Nondestructive Testing in the Urban Forest

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Trees within an urban community provide measurable aesthetic, social, ecological and economic benefits. When growing normally and stably, they contribute to making a city more livable and comfortable for its inhabitants. However, as large physical structures in close proximity to people and property, their failure can cause harm. The science of tree stability analysis uses both biological and engineering principles in determining a tree's structural soundness and predicting the probability of failure. Nondestructive testing methods of locating and quantifying wood decay and defect are used to measure the physical condition of trees within the urban forest to promote public safety. These methods are of special value to the urban forest managers and arborists responsible for the general safety of city residents, roadway transportation, and utility corridors. This chapter will discuss the commonly used methods of visual inspection, acoustic testing, and microdrill resistance with two case studies presented to illustrate how they are used in combination plus how to best interpret data collected in evaluating the nature and threat of discovered defects.

Tree Decay and Visual Inspection

Tree decay is an essential process that links tree growth to soil fertility, wildlife habitat, and many other critical functions in all forests. However, decay in roots, trunk, and limbs can be a major problem for tree managers. Concealed internal decay presents a special problem in managing urban trees for public safety. Knowledge and special tools to measure the presence of internal decay are needed by tree managers responsible for safety in parks and recreational areas, populated residential and commercial neighborhoods, and along utility and transportation corridors. Trees can reach great height, mass, and age. Wood decay and defect can cause structural failure damaging property, endangering lives, and affecting the efficiency of transportation and energy distribution. Urban forest managers need to understand how decay fungi interact with the tree and how and why visible external characteristics of the tree can reveal internal decay conditions.

Decay fungi enter standing trees through wounds or breaks in the bark. Wounds can result from a variety of incidents including storms, pruning, or root cutting. Once the decay fungus breaches the bark, it enters the sapwood and can eventually affect the heartwood.

A variety of fungi species affect woody plants and they can progress over time in succession, one species preparing the way for the invasion of another. They live in a tree's structure, and its reaction to the presence of the fungal parasite influences how the fungus advances within the tree. Decay fungi are parasites. Unable to produce their own carbohydrates for energy, they digest the carbohydrates within the tree's structure. The drawings in Figure 7.1, provided courtesy of the United States Forest Service, illustrate how decay fungi interact with trees (Shigo 1979).

Trees "wall off" or compartmentalize wounded areas to resist the spread of decay, confining it to the wood present at the time of wounding. The concept of compartmentalization was developed by Dr. Alex Shigo as part of his research for the U.S. Forest Service on the biology of tree decay (Shigo 1979, 1984). Following his retirement from the Forest Service in 1985, he continued to write and teach about tree biology until his death in 2006.

Compartmentalization produces chemical and anatomical boundaries that vary in effectiveness to resist the spread of decay. The ceiling and floor and the interior wall are usually less effective than the exterior wall formed by new growth of xylem tissue. Thus decay tends to move in columns and back to the interior. Understanding how decay advances within a tree allows the tree manager to visualize the shape of internal decay, estimate its point of origin, and predict the direction of movement.

The tree manager can use visual inspection of a tree for observing external indicators of internal decay and defect. Seams on the bark, for example, can indicate internal cracks and decay. Other external indicators of decay include open cavities. Fungal fruiting bodies are a sign of the presence of wood decay fungi. They present the opportunity to identify the species of fungus and thereby know its significance and probable course of advancement within the tree. Examples of useful wood decay identification books include *Wood Decay Fungi* by Christopher Luley (Luley 2005) and *Manual of Wood Decay in Trees* by Karlheinz Weber and Claus Mattheck (Weber and Mattheck 2003).

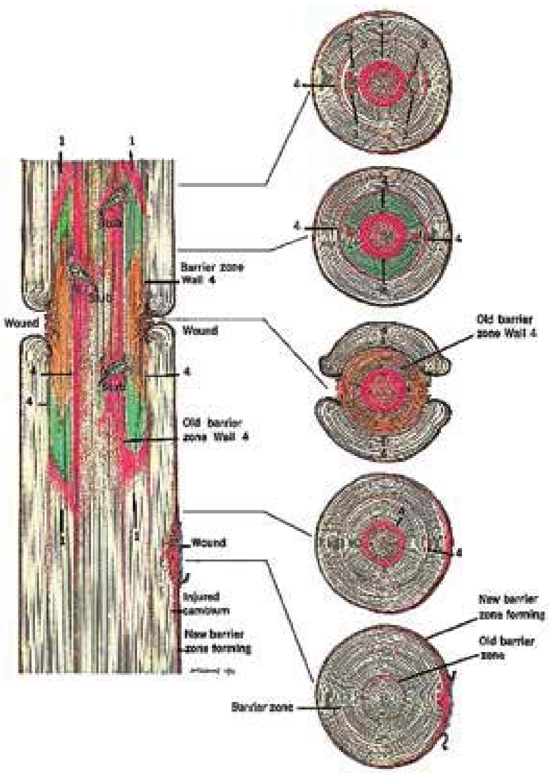

Figure 7.1—Wounds start the processes that could lead to discolored and decayed wood. The classical concept and the expanded concept both recognize wounds as the starting point for the processes. Trunk wounds can be caused by a variety of agents: insects, birds, small and large animals, wind, ice, snow, temperature extremes, chemicals, and people and some of their activities (Shigo 1979).

The visual inspection of a tree's "body language" is another way to estimate the presence of internal decay. For example a tree with an unusually expanded base sometimes called "bottle butt" could indicate the presence of extensive lower trunk decay. Trees are self-optimizing organisms highly reactive to the environmental stress around them. They are under constant mechanical stresses from holding their own weight, from leans or horizontal branching or dynamic loads from wind or ice. From Newtonian physics it is understood that a horizontal force against the tree will produce an equal and opposite resultant force tending to uproot the tree unless there is a reciprocal force to maintain stability. Wind loads in the crown are distributed down the trunk to the anchoring root system as mechanical stresses. The reciprocal force is the weight and friction of the soil against the root system resisting the shear force. Without it, tree trunks would be like the masts of sailing ships pushed along by wind forces.

Internal decay in branches or trunks reduces the area for those mechanical stresses to pass on the way to the root system. Living parts of trees can respond to those areas of concentrated mechanical stresses by laying down additional wood. This process is called thigmomorphogenesis. It explains the bottle shape or bulges that are sometimes evident on trunks with internal decay. Evidence of this self-optimizing growth reaction to environmental mechanical stress is observed in cross sections of horizontal branches or leaning trunks that have produced wider annual rings on one side compensating for the extra gravitation loading. In angiosperms, the extra wood growth occurs on the tension side of the lean acting as a guy line holding back the trunk or limb. In gymnosperms, the extra wood growth occurs on the compression side acting as prop to hold up the trunk or limb. Examples of book references discussing this body language of trees and the visible anatomical indicators of decay are *The Body Language of Trees* by Claus Mattheck (1996) and *Evaluating Tree Defects* by Ed Hayes (2001).

Figure 7.2—Traditional tools for inspecting trees—Increment borer and sounding mallet.

In addition to these visual methods of internal decay detection, tree managers have used other traditional tools including increment borers and sounding mallets (Fig.7.2). Increment borers allow the visual examination of a core sample taken from the trunk using inexpensive, simple tools. But they have the disadvantage of leaving a significant wound at each location sampled. Small-diameter drill bits on a battery powered hand drill can also be used to "feel" for changes in resistance and look for wound-initiated discoloration in the shavings, but no core sample is produced and results are not graphically recorded.

Sounding mallets allow a trained ear to listen for the telltale drum sounds of internal cavities. They are limited in determining the extent or location and do not produce a record of the sound wave characteristics.

Electronic tools are available to vastly improve upon these traditional forestry methods. The increment borer and sounding mallet have evolved into sophisticated electronic tools of micro-drill resistance and acoustic measurements.

Table 7.1—Radial stress wave velocity and time-of-flight measured in healthy trees (Mattheck and Bethge 1993)

	Radial stress wave velocity		Time-of-flight per unit length	
Species	m/s	ft/s	µs/m	µs/ft
Hardwoods				
Ash	1162–1379	3810–4520	725–861	221–262
Birch	967–1150	3170–3770	870–1034	265–315
Black locust	934–1463	3060–4800	684–1071	208–326
Black poplar	869–1057	2850–3470	946–1151	299–351
Horse chestnut	837–1557	2860–5110	642–1145	196–349
Lime	940–1183	3080–3880	845–1064	258–324
Maple	1006–1600	3300–5250	625–994	191–303
Oak	1382–1610	4530–5280	621–724	189–221
Pine poplar	967–1144	3170–3750	874–1034	266–315
Plane	950–1033	3120–3390	968–1053	295–321
Red beech	1206–1412	3960–4630	708–829	216–253
Silver poplar	821–1108	2690–3640	903–1218	275–371
Sweet chestnut	1215–1375	3990–4510	727–823	222–251
Willow	912–1333	2990–4370	750–1096	229–334
Softwoods				
Douglas-fir	905–1323	2970–4340	756–1105	230–337
Fir	910–166	2990–3830	858–1099	261–335
Larch	1023–1338	3360–4390	747–978	228–298
Pine	1066–1146	3500–3760	873–938	266–286
Spruce	931–1085	3050–3560	922–1074	281–327

Acoustic Measuring Devices

Single-Path Stress Wave Timing

Simple stress wave measuring devices are used to record the time it takes for an impact-induced stress wave to travel through the wood sample. When used for tree inspection, this nondestructive testing procedure is often called single-path stress wave timing measurement. A stress wave is created with a strike to the tree. An accelerometer mounted at the strike point senses the impact and sends a start signal to the measuring device to start a timer. A second accelerometer attached to the opposite side of the tree senses the leading edge of the stress wave and sends a stop signal to the timer. The time between the start signal and stop signal is the time-of-flight (TOF) of the wave propagating through the tree trunk. The TOF data are usually measured in microseconds. Transmission time per unit length, such as microseconds per meter and velocity, such as meters per second, are calculated using the known distance between the sensors and the TOF.

The first instruments using acoustics to determine forest product quality were developed by Metriguard, Inc., of Pullman, Washington, in the early 1960s to evaluate particleboards (Pellerin and Ross 2002). In the 1990s, foresters began using longitudinal stress wave testing on both cut logs and standing timber for log selection and grading based on material strength. The first report of the use of stress wave testing to determine internal degradation of living trees was by Claus Mattheck and Klaus Bethge in 1993 (Mattheck and Bethge 1993).

Stress wave propagation in wood is related to the physical and mechanical properties of the wood. Stress waves travel faster in defect-free wood. Areas of cracks, cavities, or decay-induced low density will require longer times for the stress wave to arrive at the opposite timing sensor. By measuring TOF or wave transmission time through a tree stem in the radial direction, the internal condition of the tree can be determined.

The presence of deterioration from decay can greatly affect TOF in wood. TOF for decayed wood are much greater than that for non-decayed wood. For example, TOF for non-degraded Douglas-fir is approximately 800 µs/m (244 µs/ft), whereas severely degraded members exhibit values as high as 3,200 µs/m (975 µs/ft) or greater (Wang et al. 2004). A study conducted by Pellerin and others (1985) demonstrated that a 30% increase in stress wave TOF implies a 50% loss in strength. A 50% increase indicates severely decayed wood.

The speed of stress wave propagating perpendicular to grain is also affected by tree species. Mattheck and Bethge (1993) measured speed of sound in different species of healthy trees using a commercially available stress wave timing unit. The speed was determined by dividing the transit distance (tree diameter) by the TOF measured. Table 7.1 shows both radial stress wave velocity and TOF on a per length basis for 5 softwood species and 14 hardwood species.

Table 7.2—Reference stress wave velocity and time-of-flight in healthy trees (Divos and Szalai 2002)

	Radial stress wave velocity		Time-of-flight per unit length	
Species	m/s	ft/s	µs/m	µs/ft
Beech	1670	5479	599	183
Black fir	1480	4856	676	206
Larch	1490	4888	671	205
Linden	1690	5545	592	180
Maple	1690	5545	592	180
Oak	1620	5315	617	188
Poplar	1140	3740	877	267
Scotch fir	1470	4823	680	207
Silver fir	1360	4462	735	224
Spruce	1410	4626	709	216

Figure 7.3—A Fakopp Microsecond Timer (Fakopp Bt., Agfalva, Hungary) was used to inspect a large red oak tree at the University of Wisconsin–Madison campus through a single-path stress wave timing measurement.

Generally, stress waves travel faster in hardwood trees than in softwood trees. To account for species difference, Divos and Szalai (2002) provided some baseline reference velocities for different species for field tree inspection (Table 7.2). This reference velocity can be used to evaluate the actual measured wave velocity and assess the internal condition of the tree inspected.

Figure 7.3 shows the use of a stress wave timer. When measuring TOF across a tree trunk, an inspector should make sure that the start and stop sensor probes are aligned in a horizontal line across the diameter of the trunk. The spike of a sensor probe should penetrate the bark and reach the sapwood so that the probe is securely attached to the trunk. Use a small hammer that is provided along with the stress wave timing device to tap the start sensor probe and obtain several consistent TOF readings.

Acoustic Tomography

In recent years, tomography techniques that were developed for geophysical engineering and medical applications have been evaluated for their applicability in tree inspection. Investigations on urban trees showed great success using acoustic tomography to detect internal decay hidden from view within the trunks (Nicolotti et al. 2003, Gilbert and Smiley 2004, Wang and Allison 2008, Wang et al. 2009).

Acoustic tomography employs multiple sensors (usually 8 to 32) to measure stress wave transmission time at multiple directions. The distance between the sensors is measured with a caliper scale. An impact-induced stress wave is generated by striking each of the sensor recording points with the hammer. A computer records the time-of-flight of the stress wave to each of the other recording points. Knowing the distance and the TOF data, a velocity can be calculated by the computer. Computer projection software using stress wave data from these multi-path measurements creates an image of the distribution of relative acoustic wave velocity in the cross section.

Figure 7.4 shows the acoustic tomograms obtained from a black cherry tree at 50-, 100-, and 150-cm heights versus corresponding photographic images and 2D hardness maps of the cross sections (Wang et al. 2009). The tomogram in this example is displayed in four colors representing varying recorded velocities. Velocities from lower to higher values are displayed as blue, violet, green and brown. The acoustic shadows in the tomograms are in good agreement with the physical conditions revealed by visual examination and 2D hardness mapping of the cross-sections. This map of the acoustic characteristics of the sample cross section, with accurate interpretation, can determine the size and location of internal trunk decay and defect.

The acoustic tomogram is not a spatially precise map of the internal structure but only a representation of the wood's

(a) Cross-section No. 1-50

(b) Cross-section No. 1-100

(c) Cross-section No. 1-150

Figure 7.4—Acoustic tomograms of a black cherry tree compared with the photographic images and 2D hardness maps of the cross-sections at different elevations (Wang et al. 2009).

acoustic characteristics as determined by the perceived velocities of the stress waves moving between the sensors. The shape of a tomogram will vary depending upon the type of decay and defect within the trees. Areas of low velocity could be a result of a decay hollow, snake crack, or ring crack. When internal cracks are present in a tree trunk, acoustic tomography tends to overestimate the size of the defect. The acoustic shadows are usually in the form of wide band and its size is significantly greater than the true defect area as indicated in Figure 7.5.

Resistography

The Resistograph (RINNTECH, Heidelberg, Germany) is a portable electric drill with a long, thin metal drill bit. As the micro drill bit (1.5-mm diameter in shaft and 3-mm wide in tip) moves through the wood in a linear path, the penetration resistance along its path is measured and recorded. The denser the wood, the greater the resistance is. Hollows, cracks, and decayed wood with lower density are detected by the reduced resistance to the drill as it progresses through

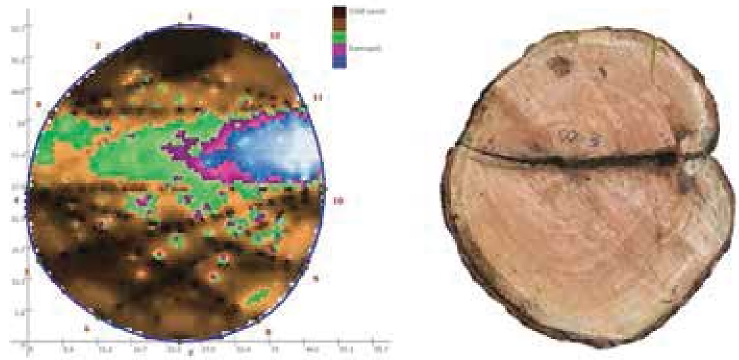

Figure 7.5—**Acoustic tomogram and the cross-section image of a black cherry tree with internal crack (Wang et al. 2009).**

the wood sample. The pattern of change in density measurements is recorded on scaled graph paper or in a digital representation display.

The Resistograph technique was developed in Germany in the 1980s as a portable tool for tree ring analysis. The first prototype of the resistance-based drilling machine was developed by Kamm and Voss in 1984 employing a spring-loaded recording mechanism (Rinn 2012). The resonance effects of the spring mechanism were later found to lead inaccurate readings and profiles. A study conducted at Hohenheim University (Stuttgart, Germany) and the Environmental Physics Institute Heidelberg University made a breakthrough in the resistance drilling concept and proved that electronic regulation and electronic recording of motor power consumption is able to achieve much more reliable and reproducible resistance profiles than the spring-loaded mechanism (Rinn 1988). Further experiments demonstrated that when the needle's tip was flat and twice the diameter of the shaft, the measured electrical power consumption (EPC) was proportional to the mechanical torque at the needle and it mainly depended on the local density at the point of contact of the drill bit (Rinn 1989, 1990). After thousands of tests, a shaft diameter of 1.5 mm and a 3-mm-wide tip was found to be a good compromise between minimizing damage and maximizing information in the profiles (Rinn 1989, 1990). With this breakthrough and new electronic improvements, the Resistograph tool can now simultaneously measure, display, and record the relative resistance profile through direct measurement of the EPC of a direct-current, needle-rotation motor while a drill bit is driven into the tree.

More research on urban tree decay detection has shown that Resistograph technique is effective in detecting and defining the extent of internal decay, including early stages of decay, if the drilling device is oriented so that its path goes through the decay zone (Wang et al. 2005). However, orienting the drill through the decay is difficult to guarantee. Considering the orientation limitation, Resistograph technique is best suited to confirm and determine the extent of decay in trees after suspect trees are identified by other inspection methods

Figure 7.6—**Dr. R. Bruce Allison used rope and saddle techniques to climb an American elm to position him along the trunk crack for Resistograph testing. The goal of the testing was to determine by sampling if there was extensive heartwood decay associated with the crack that could compromise the holding strength of the remaining trunk wound.**

such as visual assessment, stress wave timing, or acoustic tomography. Figure 7.6 shows the field use of the Resistograph tool for inspecting an American elm on Forest Products Laboratory property in Madison, Wisconsin.

Tree Decay Inspection Procedure

Based on previous studies and tree inspection practice, Wang and Allison (2008) have developed an effective tree decay inspection procedure that uses a combination of visual assessment, acoustic tools, and micro-drill. The steps of the procedure are the following:

1. Simple screening test using a combination of visual inspection and single-path acoustic wave testing
2. Multi-sensor acoustic tomography to identify the location and approximate magnitude of defects
3. Micro-drill resistance tool to confirm defects or differentiate between decayed wood and internal cracks

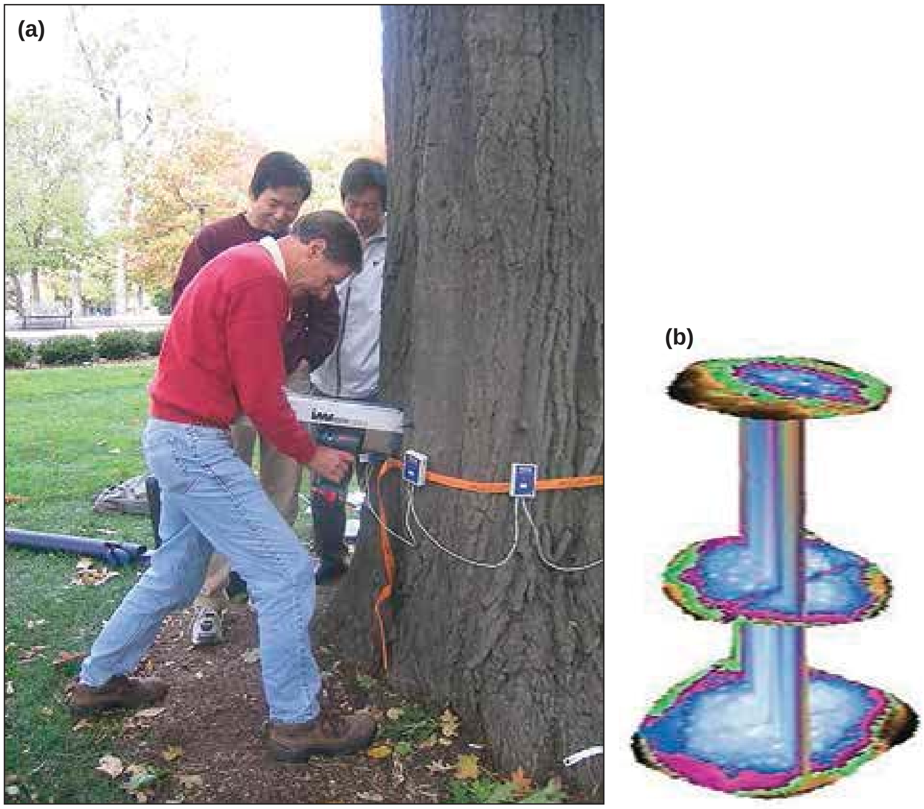

Figure 7.7—Case study in the Capitol Square, Madison, Wisconsin. (a) Decay detection in red oak trees using a combination of visual inspection, acoustic testing, and resistance microdrilling; (b) 3D acoustic tomogram generated by the computer software through combining three tomograms of three different elevations.

Two case studies, one in an urban park and the other in a forest camp ground, illustrate how this tree inspection procedure allows the tree manager to maximize the understanding of a tree's concealed, internal condition.

Case Study 1: Urban Park

A tree stability study was conducted on the 153 trees in the heavily used urban park surrounding the Capitol in Madison, Wisconsin (Allison 2005). The park managers were concerned about tree stability after some tree failures. The Forest Products Laboratory assisted in designing a nondestructive evaluation procedure for detecting internal decay. It started with a visual inspection of all directly and indirectly observable defects.

Next a simple, quick screening test using a single-path acoustic tool was conducted on all of the larger trees' lower trunks. The results were compared to the anticipated stress wave velocities in comparable tree species and were tabulated by Wang et al. (2004).

These tables offer a range of values only. There are no uniform reference standards. Stress wave velocities of solid wood can vary due to moisture levels and tree-growing conditions; therefore conducting a self-reference test on a part of the tree or comparable neighboring tree with known solid wood creates the preferred reference standard. In this study, if the sampled trunk cross section had a velocity reduction greater than 25% of the solid wood reference standard it was judged to have failed the screening test.

Multi-path acoustic tests were then conducted on those select trees with problems indicated by the visual and single-path acoustic tests (Fig. 7.7a). The multi-path acoustic tests generated tomograms requiring interpretation to identify the type, size and location of internal trunk defects. In the case of this 100-year old red oak (*Quercus rubra*) tests at cross section elevations of 10 cm, 100 cm, and 200 cm indicated decay and defect most severe at the root collar level. Tomography software is able to combine the three tomograms creating a 3D representation of the study area on the trunk (Fig. 7.7b). Resistograph test were then performed to verify the exact type and extent of the suspected defects and decay indicated on tomograms. The value of tomograms in those cases was that they identified the best location for the drilling, significantly reducing the number of drills required and enhancing the value of the data acquired. Resistograph testing indicated snake cracking and a large area of heartwood decay at the root collar area of the red oak.

Having carefully progressed using the procedure in gathering and interpreting the data, confidence was established to recommend the removal of this historic and very public tree. Measurements of the defect, knowledge of the way decay interacts with the wood, and understanding the physical requirements for mechanical tree stability led to the conclusion that this tree had a high probability of failure under loading. Tree risk assessment considered both the likelihood of tree failure and the severity of consequences to people, property, or disruption of activity (Dunster et al. 2013). In this frequently occupied public park, large tree failure could be catastrophic. A 300-page report was submitted to the park managers detailing the cases of internal decay and defect revealed using these combined nondestructive testing methods (Allison 2005). Select tree removal and pruning were conducted based on the report’s conclusions. Just weeks before the last two trees were to be removed, a violent storm with unusually high velocity winds passed through the capitol park causing these two remaining trees to fail. Of the remaining 143 trees in the park, the only trees to fail were these two that had been identified as high risk using the procedure. Seldom does nature cooperate so fully in validating a procedure for testing tree stability.

Case Study 2: Forest Campground

Another example of the successful use of combined visual, acoustic, and micro-drill decay detection procedure occurred at a recreational ropes course located at the U.S. Forest Service’s Camp Nesbit in Upper Michigan (Allison et al. 2008). The recreational course consists of steel cable and ropes attached to a cluster of twelve 60-ft-tall red pines (*Pinus resinosa*). Groups of school children regularly use the course, mounting the high suspended walkways and swinging from ropes. Undetected internal decay within any of the trees has the potential for disastrous consequences. A team of scientists from the U.S. Forest Service Forest Products Laboratory, Michigan Technological University, and the University of Minnesota Duluth were asked to nondestructively evaluate the trees for evidence of internal decay and instability.

First a visual inspection was conducted looking for cavities, cracks, seams, bulges, decay fruiting bodies, carpenter ants, or other evidence of decay activity. Then single-path stress wave tests were conducted on the lower trunks, and with the aid of an aerial lift, at select locations in the upper crown (Fig. 7.8). To establish a standard for stress wave velocities of solid wood in this particular stand, we conducted stress wave tests on red pines known to be without decay or defect. When velocities were at least 25% slower than this standard, the sampled tree failed the screening test.

At those locations where visual inspection and failed acoustic screening test indicated a problem, multi-path acoustic tests were conducted. Tomograms from those tests sites were interpreted to determine an estimate of the type, size, and location of internal decay and defects. Using the acoustic map of the sampled cross section to guide the entry point and direction of the micro-drill, additional crucial data were gathered while minimizing the number of drill holes.

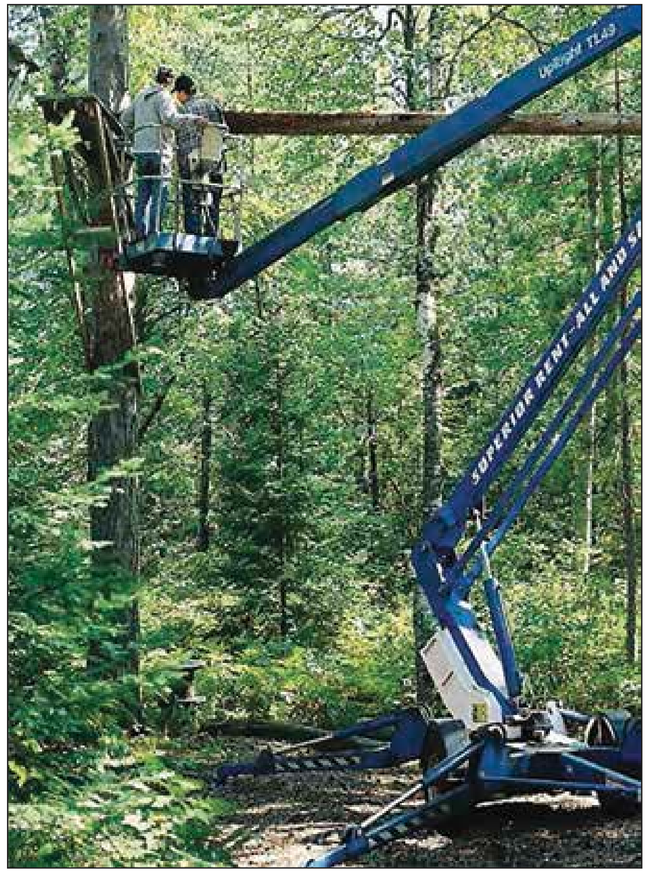

Figure 7.8—**Case study at the U.S. Forest Service Nesbit Lake Camp, Sidnaw, Michigan—Visual and nondestructive evaluation of red pines supporting a ropes course.**

The use of the less time-consuming visual and single-path acoustic tool as screening tests reduced the use of the multi-sensor tomography test. And by using the tomography to guide the number and direction of the micro-drill, fewer drill holes were needed and more meaningful information was gathered. Single-path stress wave testing in two directions takes less than 5 min, each micro-drill test about the same. Multi-sensor tomograms with set up and measurements requires around 30 min per cross section tested.

Only one of the 12 tested trees was determined to have significant internal decay and was removed from the course. It is important to keep in mind that the mere presence of decay, even extensive decay, is just part of the story in determining whether a tree should be removed. Decay is a critical factor in tree stability because a loss of wood strength occurs as the percentage of decayed stem increases. Researchers have arrived at various formulas to evaluate the strength loss associated with wood decay (Table 7.3). Although useful to consider the possibility of failure, they should not be used as a threshold for tree removal without first considering the actual strength loading factors on the particular tree.

Table 7.3—Common methods to evaluate "strength loss" associated with wood decay (Harris et al. 2004)

Source	Formula[a]	Threshold for action	Comments
Coder 1989	$\left(d^4/D^4\right)\times 100$	20–44% caution >50% hazard	Based on engineering formula for bending stress in a cylinder. Thresholds based on experience.
Wagener 1963	$\left(d^3/D^3\right)\times 100$	33%	Adjusted formula to account for discontinuities in trunks. Applied only to conifers without aggravating defects.
Smiley and Fraedrich 1992	$\dfrac{d^3 + r\left(D^3 - d^3\right)}{D^3}\times 100$	33%	Modification of Wagener to account for cavity openings. Surveyed 54 fallen and 31 standing trees. Using 33% strength loss as a threshold for action, 50% of fallen and 13% of standing trees would have been removed.
Matteck, Gerhardt, and Breloer 1992	t/R	<0.30	Based on buckling failure in cylinders. Measured *t*/*R* for fallen and standing trees. Using a *t*/*R* of 0.3 as a threshold for action, 95% of the fallen trees and 35% of the standing trees would have been removed. Based on data, no conclusions can be made on threshold for trees >50 cm (20 in.) in diameter.

[a]Abbreviations: *d*—diameter of decayed wood; *D*—diameter of trunk; *r*—size of cavity opening/circumference of trunk; *t*—width of sound wood; *R*—radius of trunk.

These case studies illustrate that a combination of nondestructive tests, following a procedure of visual inspection then screening with quick single path stress wave tests, then progressing to more complex multi-path acoustic testing as needed with the use of a few directed micro-drill tests to assist in interpretation, offers tree managers an efficient method to measure hidden internal decay and defects in standing trees. Other less frequently used NDT techniques include ground penetrating radar (GPR) (Miller and Doolittle 1990; Nicolotti et al. 2003; Butnor et al. 2009), static pull testing (Peltola et al. 2000; Kane and Clouston 2008), electrical impedance (Gocke et al. 2008), and, on an experimental bases, portable x-ray CT scanning (Allison 2011).

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