Typical Trends in Resistance Drilling Profiles of Trees

By Frank Rinn

Basics, potential uses, and limitations of the resistance-recording drilling method for tree inspection can best be understood by reviewing the development of its technical specifications, because they reflect the different properties of the instrument's currently available models. In addition to technical specifications, knowledge about wood anatomy and mechanical wood properties is required for proper application of the method and a reliable interpretation of the results.

Manual resistance drilling (without recording), as known from historic carpenter recordings from the 1920s and still used today, is not described here because this does not provide printed evidence and should, therefore, not be used in professional tree risk assessments.

Origin and Purpose of Resistance Drilling

Today it seems obvious that the penetration resistance of thin needles (drill bits) can correlate to wood condition. The evolution of this method, starting with the first ideas, subsequent tests of several different technical concepts, basic scientific research, development of the first working prototypes, and finally the current models, took quite a bit of time, money, research, and effort.

Based on the idea of Prof. Gersonde from the 1970s, working at German Federal Material Testing Institute (BAM, Berlin), German company Weserhütte AG tried to develop a machine for improving the penetration of preservatives by pushing thin needles into wooden utility poles in order to create channels for the chemicals. This method has since become established worldwide, and is known as "In-Sizing." It is especially useful for species like spruce (*Picea*), where wood preservatives do not penetrate well, even under pressure, because the bordered pits close while the cells are dying. The engineer in charge at Weserhütte, Thorwald Kipp, noticed that some needles were breaking, while others penetrated wood quite easily. He concluded that the recorded penetration resistance could tell something about wood condition and strength. However, at Weserhütte, which specialized in big machinery, it was virtually impossible to develop a wood-diagnostic method for this application.

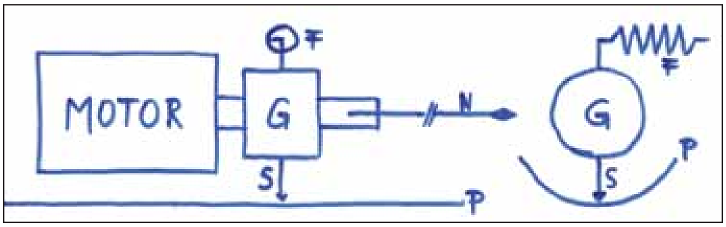

Figure 1. Sketch of a Kamm-Voss resistance drill from 1984: a scratch pin (S) was fixed at a spring- (F) loaded gearbox (G) between motor and needle (N), creating a 1:1 scaled resistance profile on a waxpaper strip (P) within the machine's casing. Because of resonance and threshold effects due to the spring-loaded recording mechanism, the device delivered systematically wrong and misleading profiles, Kamm and Voss abandoned this approach and switched to electric recording of motor power consumption.

Years later, two retired, leading engineers of Weserhütte (Kamm and Voss) developed a simple drill (Figure 1), and later received permission from the company's board to apply for a patent describing the idea of needle resistance drilling. Although this patent from 1985 was later declared invalid by the German Patent Supreme Court, it prompted a development that led to the first properly working resistance drilling machine developed in my physics master's thesis in 1986, and the first series of portable drills by Rinn and Fein (1987) (Figure 2), which were sold to selected experts worldwide.

The drill developed by Kamm and Voss in 1984 recorded the penetration resistance of a thin, pointed needle with the help of a spring-loaded gearbox and a connected scratch pin, creating a one-to-one scaled profile on pressure-sensitive wax paper while drilling into wood (Figure 1). But resonance effects of the recording spring mechanism (triggered, for example, by tree-ring density variations) led to inaccurate readings and profiles: the curves were either too high or too low (thus never correct), fluctuating much more than the wood condition changed along the drilling path. Resonance notably occurred if a spring was loaded in the frequency of how it would swing by nature, mostly leading to extreme amplitudes. Such misleading spring-resonance effects can be partially reduced by compensation springs for damping an over-exaggerated fluctuating curve. However, this damping introduces additional stimulus thresholds into the recording system, causing another systematic and inherent error: drill resistance values below certain stimulus thresholds are suppressed and not displayed; or plateaus appear in the profile: the curve stays on the same level, although the properties of the penetrated wood are changing.

In addition, profiles with such a spring-driven recording mechanism often dropped down to zero in areas of soft (but intact) earlywood, likely misinterpreted as insect damage or decay. As a consequence, profiles from intact but soft wood (as is common in the center of most conifers or in the sapwood of many other species) were often misinterpreted as being decayed. These mechanically recorded profiles were thus shown as systematically wrong because they were nonlinear and non-reproducible. Consequently, evaluation of wood condition based on such profiles was incorrect, unreliable, and could never have been a reliable basis of an expert report on wood condition of trees or timber. Kamm and Voss developed a new drill in 1985 with an electrical recording mechanism, starting with a loudspeaker and headphone connected to the drilling motor. They applied for a patent (Kamm and Voss 1985) and made inquiries with German electric tool companies that might be interested in buying the intellectual property rights.

The company of the former inventor of the first electric drilling machine (in the 1880s), Fein GmbH&Co KG (Stuttgart, Germany), was interested in buying the Kamm-Voss patent, but asked for the independent opinion of researchers from a German University, as to whether the needle resistance method could work at all. At that time, no one imagined that it might have been possible to drill a thin needle deep enough into wood because strong steel nails often failed, could not penetrate, and broke.

In a joint project of the tree-ring lab at Hohenheim University and the Environmental Physics Institute of Heidelberg University, the resistance drilling idea was tested at the beginning of the summer of 1986. Preliminary drillings with an electrically recording drill prototype in a physics master's thesis revealed an obvious correlation of the profiles to wood density. Because tree-ring density variations had been shown to cover more information on wood quality, past climate, and environmental changes than ring width (Schweingruber et. al. 1978), the aim of the scientific project was to measure the intra-annual density variations of tree rings for climate reconstruction (Rinn 1986–1988). For achieving this, the measurements clearly showed that electronic regulation and electronic recording of motor power are required for obtaining reproducible profiles and reliable results that can be clearly correlated to wood density, as opposed to the unreliable and systematically incorrect spring-loaded recordings used earlier.

Figure 2. First portable resistance drill series (1987), based on the results of a physics master thesis, built by the German company Fein, and sold to experts worldwide. Görlacher and Hättich (1990) proved a linear correlation of its profiles to wood density.

Technical Basics

The power consumption of both electrical motors—one responsible for feed and the other for rotation of the needle—was measured individually and recorded while the needle was moving forward and backward, producing four curves per measurement. Detailed comparative analysis showed that the variations of the power consumption of the feeding motor at constant speed, and of both motors while pulling the needle backwards, did not contain significant additional information (Rinn 1989a; Rinn 1989b). Consequently, resistance drills from then on usually measured and recorded the electrical power consumption of a direct-current, needle-rotation motor. This value is proportional to the mechanical torque at the needle, if the motor acts linearly. If the needle's tip is flat and twice the diameter of the shaft (Figure 3), the torque that has to be provided by the electrical motor for rotating the needle mainly depends on the density of the penetrated material at the current position of the needle's tip.

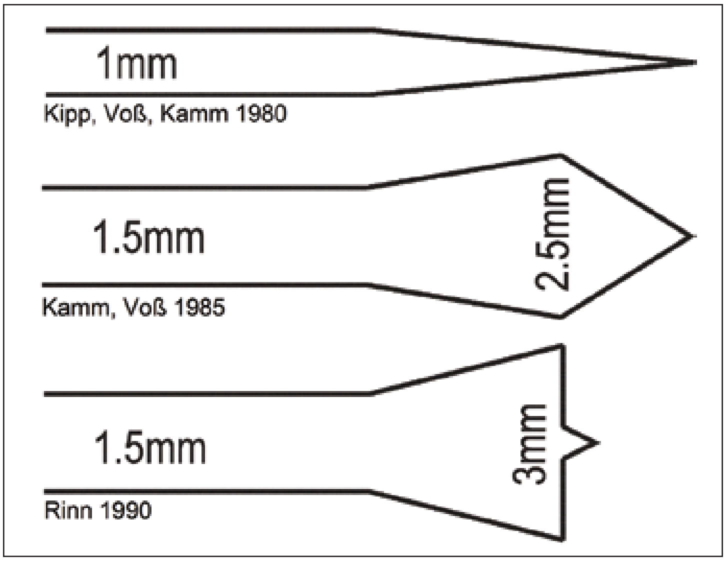

Figure 3. A needle shaft of 1.5 mm and a flat tip of 3 mm width were found to be a good compromise for achieving maximum resolution and stability at lowest damage to the sample.

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Because the goal was to determine radial density profiles at the highest possible resolution, drill resistance had to be measured at a smallest possible point of the drilling path at a time. Therefore, the front end of the needle had to be flat. A thin centering tip was added to guide it in a straight path (Rinn 1991). Because tree-ring borders are not straight lines, but rather, concentric or even undulating, the width of the needle's tip determines the radial resolution by tangential averaging, and therefore, should be as small as possible. A bigger needle would not allow the method to detect thin tree rings, because the bigger tip would rotate in earlywood and latewood of two, or even more rings at the same time, unable to differentiate between the density of individual earlywood and latewood zones.

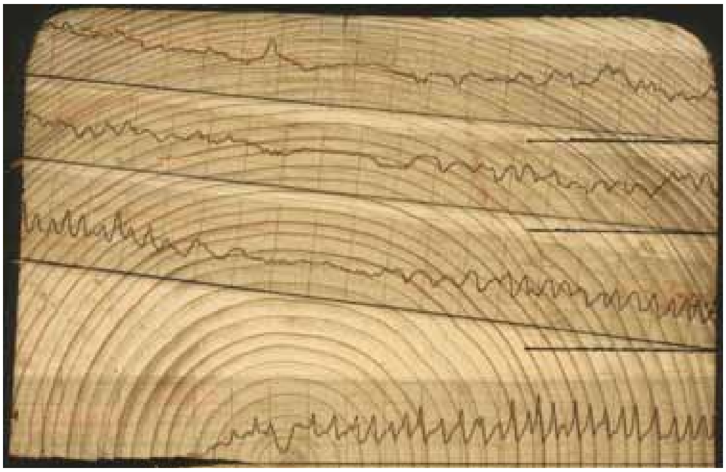

Figure 4. The angle between penetration direction and tree ring borders influences the detectability of tree rings, as shown here for spruce (*Picea*). In tangentially penetrated areas, the profiles cannot show differences between earlywood and latewood. Decay or insect damage can be identified by the drop of the profile below the earlywood level, as can be seen in the bottom profile when the needle penetrates the soft pith and subsequently the crack.

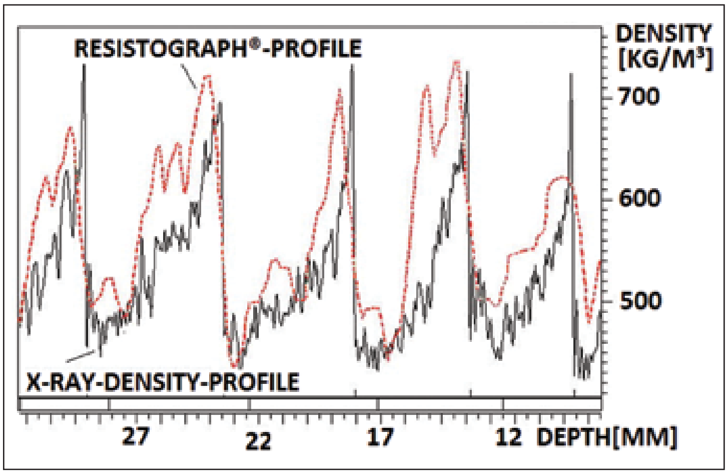

Figure 5. This superposition of a radial x-ray density profile (resolution 1/100 mm) of larch (*Larix*) with a resistance drilling profile shows that local wood density determines the resistance value. The slope of the resistance profile at the tree-ring border equals the resolution limit of tree-ring detectability (~1/10 mm) when penetrated perpendicularly (Rinn et.al. 1996).

In addition, the needle needed to be kept as thin as possible to minimize damage to the tree being tested. But, because of several reasons, it was required to increase the needle's diameter: thin needles (<1mm) were often deflected by rays, knots, or other wood anatomical features, and did not maintain a straight path. In addition, needles had to be thicker in order to penetrate high density trees. After thousands of tests, a shaft diameter of 1.5 mm and a 3 mm tip were found to be a good compromise between minimizing damage and maximizing accuracy and reliability in the profiles.

All subsequently shown profiles in this article were obtained by an electronically regulated and electronically recording resistance drill, using a flat-tipped 1.5/3 mm steel needle as described here. It is important to know this and to understand why only a few types of resistance-drilling devices available on the market can reveal curves of this kind that can be interpreted reliably in terms of local wood condition along the drilling path. It is only when the profiles are clearly correlated to wood density (preferably in a defined linear manner) that the curves allow experienced users to evaluate wood condition reliably. This was not the case for the early versions of devices using spring-driven recording mechanisms (which, by design, could not reveal precise and reproducible profiles due to resonance and damping, stimulus thresholds, and plateau effects).

Although the resistance-drilling method was originally developed for tree-ring analysis, its ability to detect decay and wood quality now drives the market. Several thousand drills have been sold worldwide since 1987 by at least five different manufacturers. These devices differ not only in size, weight, and price, but fundamentally in resolution, precision, reliability, and applicability. A clear correlation to wood density (as a mandatory pre-requisite for reliable profile interpretation) was demonstrated for electronically regulated and electronically recording device types only.

Detection of Decay Requires Tree Ring Structure Visibility

If the needle's geometry as well as machine design and regulation follow the guidelines described here, local wood density at the position of the needle's tip is the main factor influencing mechanical penetration resistance and thus the profile obtained. Consequently, due to density variations between earlywood and latewood, tree-ring structure and penetration angle determine the shape of the profiles. Therefore, it is necessary to understand basic wood anatomical properties in order to interpret resistance profiles correctly.

In addition to needle geometry and electronic regulation, the drilling angle determines the ability to detect tree rings. Maximum resolution of tree-ring structures is provided by radial drillings so that the needle penetrates the tree-ring borders radially inward (perpendicular to the stem and to tree-ring borders). The more this penetration angle deviates from 90°, the less clear tree rings appear in the profiles (Figure 4).

Wood Anatomy

Regarding wood material properties and the cutting mechanism at the needle's tip while penetrating wood, local shear strength may be even more closely related to the measured drill-resistance value. Comparison with high-resolution radial x-ray density profiles have shown that electronically regulated and electronically recorded resistance drills produce profiles highly correlated to local wood density (Figure 5), revealing tree-ring density variations down to a width of about 1/10 mm or even less, depending on machine version and needle geometry (Rinn et. al. 1996).

In temperate zones, where tree-rings are clearly differentiated by earlywood and latewood, the combination of the following wood anatomical properties determine the typical appearance of radial resistance drilling profiles, as long as they are measured and recorded electronically:

- Latewood is generally much denser than earlywood.
- Wide tree rings are commonly dominated by:
  - Earlywood in conifers.
  - Latewood in ring-porous species.
- Due to the age trend (Bräker 1981), the average ring width declines with tree age and usually remains at a relatively low level throughout maturity.
- The center parts of trees are dominated by broad rings.
- In the case of narrow conifer rings, the relative amount of latewood is higher, and density, as a result, is also higher. Consequently, slow-growing conifers are denser and stronger, comparatively.
- Width of earlywood in ring-porous trees mostly does not show strong variations in a cross section. Therefore, the relative amount of earlywood is higher in narrow rings of this kind of wood. The narrowest rings of oak (*Quercus*) or elm (*Ulmus*), for example, are composed primarily of very soft earlywood (Figure 6). Consequently, the wood of slow-growing ring-porous trees is low in density and strength because most strength properties are closely related to density. However, the fact that wood density and strength is relatively low in slow-growing ring-porous trees does not mean that these tree are less stable.
- Wider rings of ring-porous trees contain more latewood and are correspondingly higher in density. Consequently, the faster a ring-porous tree grows, the higher its density and the higher the strength of its wood, but monetary value of forest or plantation trees does not often depend on density. The most expensive veneer trees, for example, are often slow-growing oaks, providing low density but long, straight trunks without knots, and an extremely homogenous wood structure.
- The consequence of slow or fast growth, in terms of density, is opposite in conifers and ring-porous species.

There are many other consequences of the combination of these wood anatomical properties for tree inspection

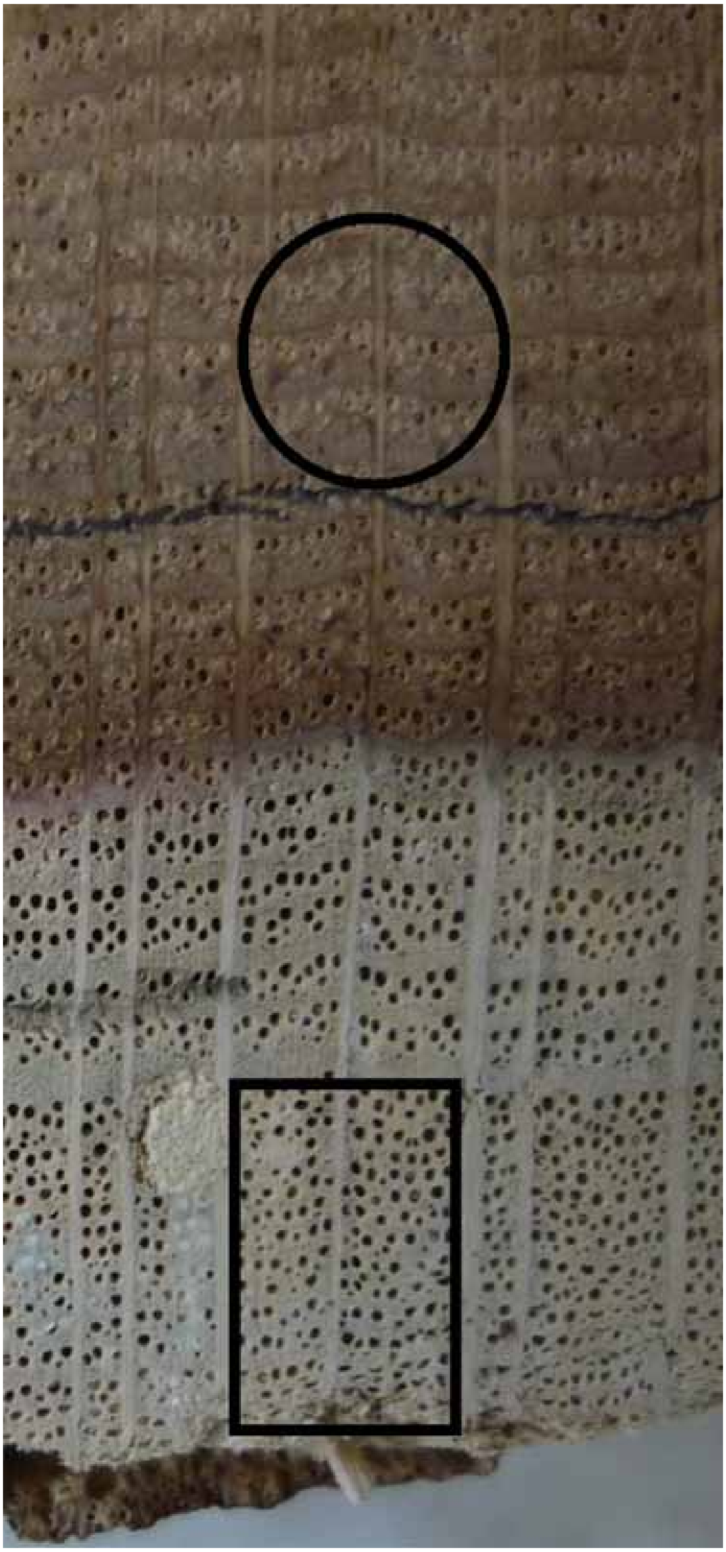

Figure 6. Typical example of declining oak tree-ring width with age. In the center of such stems, big latewood zones are visible (circle), leading to a high density. Closer to the bark, the narrowing rings may only consist of big earlywood vessels for water transport (rectangle). As a result, local wood density is very low, even lower than common in softwood species. Thus, the slower a ring-porous tree grows, the higher the relative amount of earlywood in the tree rings and the lower the density of the wood. However, this effect is not correlated to durability of the wood as this is mainly determined by the content of resin/tannins and other impregnating substances.

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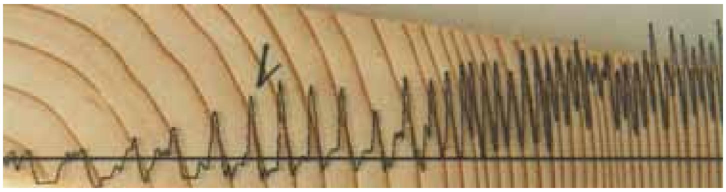

Figure 7. Broad conifer rings are usually dominated by soft earlywood. Due to age trend (Bräker et.al. 1981) in ring width, conifers (trees, beams, and poles) are mostly much softer in the center. The corresponding decline in drill resistance can only be distinguished from a decline by internal decay if the intra-annual density structures are revealed correctly. This requires a high-resolution profile, measured and recorded electronically; other profiles will lead to misinterpretation and wrong evaluation of trees and timber.

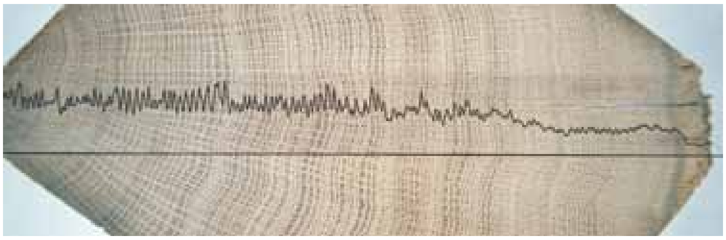

Figure 8. Broad, ring-porous tree rings are dominated by dense latewood. Due to age trend in ring width, ring-porous trees, branches, or beams are denser in the center, leading to an increasing drill resistance. Narrow oak (*Quercus*) rings are dominated by soft earlywood, leading to a drop in density and drill resistance profiles. High-resolution electronic drills are mandatory for distinguishing such zones of narrow but intact rings from areas of decay, where the profile drops down below earlywood level.

(with all kinds of devices): conifer stems, for example, are commonly soft in the center and stronger in the outer areas of the cross section (Figure 7), while the opposite applies to all ring-porous species (Figure 8). Most important for resistance drilling is that radial profiles derived from conifers have a tendency, by nature, to drop down in the center. This can only be reliably distinguished from a profile drop caused by internal decay, if the profile is highly correlated to wood density and the resolution is high enough to clearly differentiate between earlywood and latewood zones. If the profile drops down below the lowest earlywood resistance level, this indicates decay, a crack, or the pith as shown (Figure 4). This proves that only if the tree ring structure is clearly visible, can decay be identified and differentiated from soft but intact wood.

In ring-porous tree species, resistance drilling profiles are commonly quite low in wet and soft sapwood with narrow rings, primarily containing soft earlywood. The profiles typically rise up in the center of the cross sections because the inner tree rings are dominated by the high-density latewood. Again, a high resolution and high correlation to wood density is required to differentiate between intact but soft sapwood and decay.

Correctly measured resistance profiles (by electronic measuring and recording) derived from tropical species without distinct tree rings are similar to most diffuse-porous trees from moderate climate zones, but tend to rise up slightly in the center. There are three types of wood in general, but with exception of palms, that have to be distinguished in terms of typical drilling-resistance profile shapes:

1. Temperate conifers (drop down in the center)
2. Temperate, ring-porous wood (rise up in the center)
3. Diffuse-porous wood and wood of tropical trees without distinct tree rings (mostly, relatively constant over the cross section or slightly increasing in the center)

These typical radial density trends have to be taken into account while interpreting resistance drilling profiles (Figure 9). At the same time, the influence of the angle of the needle's path in relation to the tree-ring borders must also be considered. Tangential drillings may look completely different, even in intact wood (Figure 4).

If an individual drilling profile cannot be interpreted, a reference drilling farther up the stem may help, although the number of drillings should be limited in order to minimize damage to the tree.

Summary and Conclusions

Anatomical properties of the tree species determine local density of the wood. Because decay leads to a distinct drop in wood density, reflecting stage and type of deterioration, measurement of density profiles help users assess the internal condition, growth rate, and quality of wood. In contrast to spring-driven recording of drilling resistance,

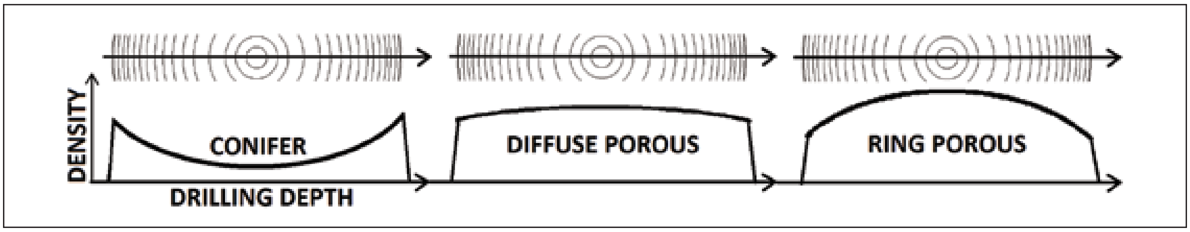

Figure 9. One of the major consequences of the wood anatomical properties of the three species groups (i.e., conifers, ring-porous, and diffuse-porous trees), in combination with the age trend (a the decreasing ring width with age), is a typical radial density trend that may be slightly different depending on height: these trends lead to typical mean profiles because drilling resistance mainly reflects wood density along the drilling path. This aspect has to be taken into account while interpreting every profile and it makes clear how important it is to know which species was drilled into and from direction in relation to the tree-ring borders. However, individual trees can have different mean profiles (e.g., if growth was suppressed). In case of doubt, a reference drilling at the same tree helps. These age-trend effects are visible in trees from temperate zones only, where a clear distinction between earlywood and latewood is formed.

profiles of electronically regulated and electronically recording machines have been shown to correlate to local wood density along the drilling path. This allows the user to interpret and evaluate the data revealed in the profiles. In addition, needle penetration angle in relation to tree-ring borders, needle tip geometry, and the ratio between revolutionary speed and feed rate influence the typical shape of the resulting resistance drilling profiles.

Thus, technical properties of resistance drills have to be taken into account before purchasing/renting and using a resistance drill. For expert reports, only machine versions that can be calibrated should be used, because only such machines deliver profiles that are reproducible and can be interpreted reliably because they are clearly correlated to wood density. In addition, proper interpretation and evaluation of resistance drilling profiles requires knowledge of typical species-specific density trends within the tree rings and along the drilling path (either radial or tangential). Wood anatomical properties differ strongly between the three wood-type groups (i.e., conifers, ring-porous, diffuse-porous trees) and determine the typical mean trend and local variances of resistance drilling profiles, as well as the mechanical behavior of the corresponding trees in general. Ring-porous trees typically have the highest density values in the center, and are typically much softer outside. Conifers, usually, are just the opposite. Diffuse-porous trees tend to be more homogenous in terms of density and strength values in a cross section (similar to many tropical trees). Material properties and density profiles of palms are different in many ways but show some similarities, in terms of radial trends, to conifers (Rinn 2013).

Additionally, because modulus of elasticity (MOE or E) determines the stiffness of any material and is highly correlated to density, the aspects described here regarding density distribution in a typical tree cross section are important for all kinds of measurements of the mechanical behavior of trees, including the use of sonic tomography and even static load tests.

Stress-wave-timing in sonic tomography measures time of flight (Rinn 1999) and determines an apparent sonic speed (v) in wood that is determined by density (D) and modulus of elasticity (E): $v^2 = E/D$. Static load tests (Sunley 1968) typically measure strain of wood and determine MOE for estimating load-carrying capacity.

The results of all of these assessments depend on density and thus, on the density distribution in the measured cross section. It is important to understand this not only for evaluating the tree but for understanding the results of other methods, too. The moisture content of wood influences both modulus of elasticity and density, and also plays an important role, but this shall be described in a future article.

Additional Reading

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Figures courtesy of the author.