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# Assessment of Preservative-Treated Wooden Poles Using Drilling-Resistance Measurements

**Evgenii Sharapov [1,2], Christian Brischke [3,*] and Holger Militz [3]**

1 Volga State University of Technology, Lenin sq. 3, 424000 Yoshkar-Ola, Mari El Republic, Russia; SharapovES@volgatech.net
2 Northern (Arctic) Federal University named after M.V. Lomonosov, Severnaya Dvina emb. 17, 163002 Arkhangelsk, Russia
3 University of Goettingen, Wood Biology and Wood Products, Buesgenweg 4, 37077 Goettingen, Germany; hmilitz@gwdg.de
* Correspondence: christian.brischke@uni-goettingen.de; Tel.: +49-(0)-551-392-29514

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**Abstract:** An IML-Resi PD-400 drilling tool with two types of spade drill bits (IML System GmbH, Wiesloch, Germany) was used to evaluate the internal conditions of 3 m wooden poles made from Scots pine (*Pinus sylvestris* L.). Drilling tests were performed on poles that were industrially vacuum-pressure-impregnated with a copper-based preservative (Korasit KS-M) and untreated reference poles. Both types of poles were subject to 10.5 years of in-ground exposure. Wood moisture content (MC) was measured using a resistance-type moisture meter. MC varied between 15% and 60% in the radial and axial directions in both treated and untreated poles. A higher MC was detected in the underground, top, and outer (sapwood) parts of the poles. Typical drilling-resistance (DR) profiles of poles with internal defects were analyzed. Preservative treatment had a significant influence on wood durability in the underground part of the poles. Based on DR measurements, we found that untreated wood that was in contact with soil was severely degraded by insects and wood-destroying fungi. Conversely, treated wood generally showed no reduction in DR or feeding resistance (FR). DR profiling is a potential method for the in-situ or in vitro assessment and quality monitoring of preservative treatments and wood durability. The technological benefits of using drill bits with one major cutting edge, instead of standard drill bits with center-spiked tips and two major cutting edges, were not evident. A new graphical method was applied to present DR data and their spatial distribution in the poles. Future studies should focus on the impact of preservative treatments, thermal modification, and chemical modification on the DR and FR of wood. This may further elucidate the predictive value of DR and FR for wood properties.

**Keywords:** decay; drilling-resistance measurements; internal defects; nondestructive wood testing; preservative treatment; wooden poles

## 1. Introduction

Roundwood is still globally used in utility poles, piles, and structural elements in wooden constructions. Wood is a natural and organic material, and is therefore susceptible to biological degradation and destruction due to internal stresses. Thus, one of the main problems associated with the safe use of wooden poles is the evaluation of internal defects that may lead to structural failures. Different techniques for the evaluation of the internal condition of wooden poles have been developed. These include drilling-resistance (DR) measurements. From the first prototype of DR measurement (penetration resistance) [1] to basic tool design [2] and advanced drilling tools, the in-situ assessment of timber- and utility-pole structures has always been the main application of this method.

DR measurements are a nondestructive way of indirectly evaluating wood properties [3–5]. DR is based on the use of thin-boring drill bits (e.g., 3 mm diameter) to drill into wood while continuously monitoring energy consumption. Energy consumption is correlated with the physical, mechanical, and technological properties of wood. The main advantages of the DR method are that the drilling tool is portable, measurements are made in situ, it is quick and minimally invasive, and it has high sensitivity for fungal decay and other wood defects [6–9]. Furthermore, DR can be used to predict the density and other elastomechanical properties of wood [3,10–24].

The structural condition of wooden bridges was assessed by Brashaw et al. using a DR device (IML RESI F300-S, IML System GmbH, Wiesloch, Germany) [25]. The authors reported on the potential for DR measurements to detect internal decay, and the need to combine different test methods, including visual inspection and acoustic methods. Kappel and Mattheck [26] reported that DR is a good tool to detect internal defects in timber structures, such as cracks and decay. They recommended transversal drillings in a radial direction in the wood. In cases where longitudinal drilling in early wood or in cracked areas of wood cannot be avoided, additional transversal drilling is helpful to better determine the extent of wood damage.

The efficiency of DR measurements in determining the damage and residual cross-section of decayed wood in timber structures has been presented by different authors [27,28]. Imposa et al. [29] evaluated the extent of decay in ancient wooden trusses and concluded that DR measurements allowed for the quantification of material loss and microvoids in wood.

More detailed analysis of the suitability of DR measurements for the in-situ assessment of structural timber was presented by Nowak et al. [30]. They concluded that DR allows for the detection of internal defects in wooden structures, but that it is influenced by many factors such as moisture content (MC), drill-bit sharpness, and drilling direction relative to grain direction. An IML-RESI F-300 drilling tool was used by Gezer et al. to inspect wooden utility poles [31]. DR measurements were made at breast height and underground with a 45° angle between the direction of penetration and the pole axis; approximately 90% of wood deterioration occurred underground. However, the authors pointed out that, although internal defects in poles could be accurately detected, information from DR measurements was limited to the site of drill-bit penetration.

A comparative assessment of utility poles using three inspection techniques was presented by Reinprecht and Šupina [32]. DR in poles made from Norway spruce (*Picea abies*) and preserved with creosote was measured in radial directions using an IML-Resi F-400 drilling tool. Strong linear correlation ($R^2$ = 0.96) was found between mean DR measurements obtained from two orthogonal drillings in a radial direction in the same plane.

To enhance the durability and prolong the service life of wooden poles, wood is often treated with preservatives such as pentachlorophenol (63%), creosote (16%), and copper chrome arsenate (16%), as reported for the United States [32]. The mechanical properties of treated wood can be affected by the impregnation method, type of preservative, and uniformity of the treatment [33]. Precipitation and soil moisture led to the wetting of poles. Wood MC greater than 20% increases the chance of decay, and MC above 25%–30% indicates a high likelihood of extensive decay [34,35]. Furthermore, wood MC can have significant impact on DR measurements [36–39].

The aim of this study was to determine the influence of preservative treatment and wood MC on the condition of wooden poles above and below ground using DR measurements.

## 2. Materials and Methods

### 2.1. Specimen Preparation

Ten logs of Scots pine (*Pinus sylvestris* L.) with a length of 9 m were crosscut into 3 equal sections. Half of the 3-m sections (poles) were industrially vacuum-pressure-impregnated (3 kPa, 180 min, and 0.8 MPa, 180 min) in an autoclave with Korasit KS-M (Kurt Obermeier GmbH and Co. KG, Bad Berleburg, Germany). Korasit KS-M is a waterborne copper-based preservative. Impregnation was conducted at industrial impregnation plant Carl Scholl GmbH (Cologne, Germany). The mean preservative retention of the examined poles was 25.5 kg/m$^3$. Treated and untreated wooden poles were vertically buried in the ground at a depth of approximately 0.5 m at a field test site in Goettingen, Germany (51.6° N, 9.9° E). In total, 6 samples of treated ($n$ = 3) and untreated ($n$ = 3) poles were removed from the soil in January 2019 after 10.5 years of in-ground exposure. They were then evaluated.

### 2.2. Drilling-Resistance Measurements

An IML-RESI PD-400 tool and 2 types of spade drill bits were used (IML System GmbH, Wiesloch, Germany) for DR measurements. Both types of drill bits were almost 400 mm long, and had a thin shaft of 1.5 mm diameter and a 3-mm triangular cutting part with a hard chrome coating. The first type of drill bit (Type 1) consisted of 2 flattened and symmetrical major cutting edges that were perpendicular to the rotating axis (axis of the cylindrical drill-bit shaft). The center-spiked tip of drill bit Type 1, which was designed to stabilize linear penetration of the drill bit during the drilling process, was about 400 µm in height from the level of the major cutting edges. The second type of drill bit (Type 2) did not have a tip and only had 1 major cutting edge (Figure 1).

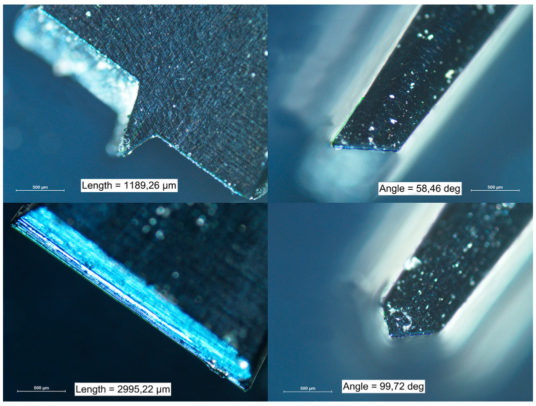



**Figure 1.** Drill-bit types and their main geometrical parameters. Note: length, length of major cutting edges, angle, angle sharpness for major cutting edges.

DR measurements were taken radially, in 1 plane, and in a north–south direction (Figure 2). Drilling was first done in the ground-level parts (level 0 in Figure 3), followed by the above-ground parts in 300-mm intervals (levels 1–7 in Figure 3), and then the underground parts in 100-mm intervals (levels −1 to −4 in Figure 3).

**Figure 2.** Drilling-resistance measurements in a preservative-treated pole.

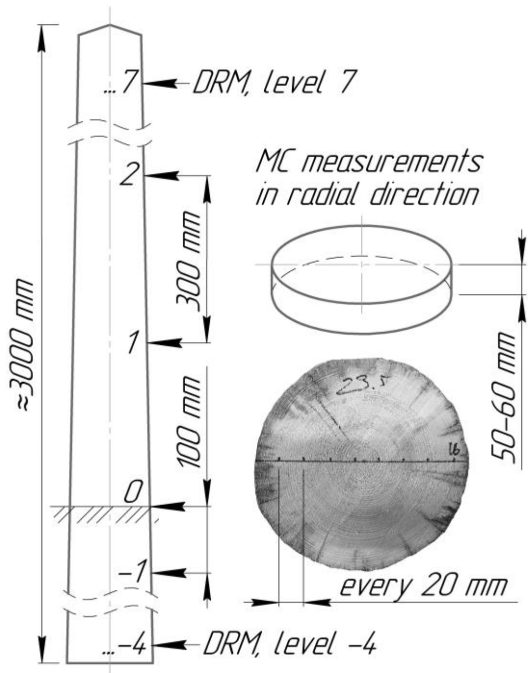



**Figure 3.** Schematic diagram of pole-analysis method. Positions of drilling-resistance measurements (DRMs, arrows in figure) and sites of moisture-content (MC) measurements along pole radius.

Upon completion of DR measurements, poles were dissected, and a 50–60 mm thick disc was obtained from each drilling position. MC measurements were then made using a resistance-type moisture meter. Measurements were radially taken from the end-grain surface of the discs every 20 mm along regions of drill-bit penetration (Figure 3).

Due to different amplitudes in DR and feeding resistance (FR) for the types of used drill bits, drill bit Type 1 was set to a feed rate of 1.5 m/min and a rotational frequency of 1500 $min^{-1}$, whereas drill bit Type 2 was set to feed rate of 1 m/min and a rotational frequency of 2500 $min^{-1}$. DR and FR were measured and digitally recorded for every 0.1 mm of drilling depth. DR data were saved and processed using PD-Tools PRO software (IML System GmbH, Wiesloch, Germany), Microsoft Excel® (Microsoft, Redmond, WA, USA), and SigmaPlot 14 (Systat Software Inc., San Jose, CA, USA). DR profiles obtained from each measurement included a relative DR curve reflecting the torsion force on the drill bit and an FR curve reflecting the force needed to push the needle into the wood. Mean DR and FR values from profiles of the entire length of the poles were compared between treated and untreated samples.

## 3. Results and Discussion

### 3.1. Moisture Content

Variation in mean MC over the length of the poles is presented in Figure 4a. Due to severe decay (Figure 5), it was not possible to measure the MC for underground parts of untreated poles with a resistance-type moisture meter. A higher MC was observed at the ground-level, top, and underground parts of treated and untreated poles. The MC in treated poles was around 40% in both the underground and top parts of the poles. Despite the top parts of the poles being covered in paint to eliminate moisture absorption because of precipitation, the protective layer wore out over time. The mean MC of the top parts was between 23%–31% in the untreated and 30%–46% in the treated poles (Figure 4a).

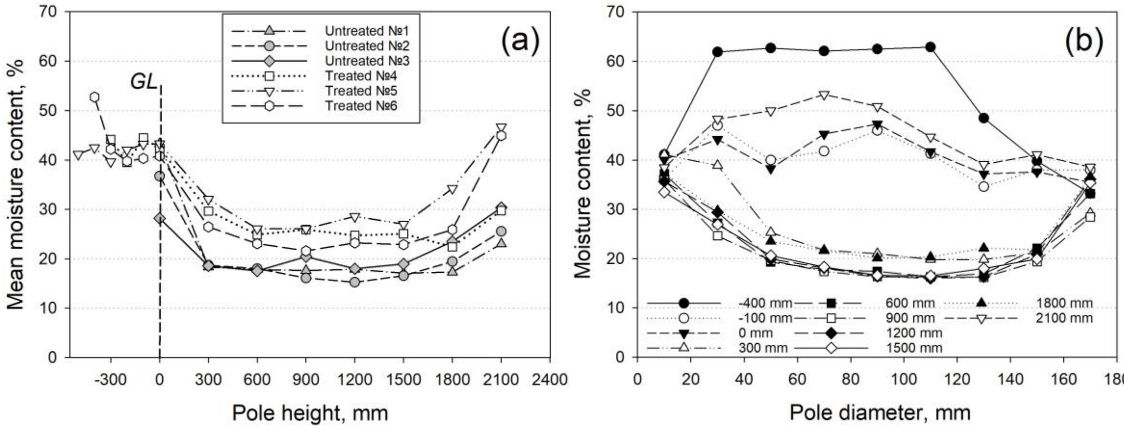



**Figure 4.** MC obtained from disc samples. (**a**) Mean MC over length of tested poles. Note: *GL*, ground level (0 mm). (**b**) MC variation along diameter of treated pole №3 at different heights in relation to *GL*.


**Figure 5.** Underground sections of treated (top) and untreated (bottom) poles.

Wood treated with preservative salts shows lower electrical resistance than untreated wood with the same MC [40]. Brischke and Lampen [41] showed that the accuracy of resistance-based MC measurements is not negatively affected by impregnation with inorganic salts. However, they found that accuracy decreased at an MC that was above fiber saturation.

The MC gradient in the radial direction differed between the underground, middle, and top parts of the poles (Figure 4b). The outer layers of above-ground and underground parts of the poles showed a similar MC of about 35%. This indicated that these parts were susceptible to a significant level of decay. MC decreased closer to the pith in the middle parts of the poles, but was higher near the pith in underground and top parts of the poles (Figure 4b). However, variation in wood MC along the length and diameter of the poles might have been affected by seasonal or current weather conditions. The data shown here are therefore just a snapshot of current conditions.

MC influences the mechanical [42] and cutting (drilling) properties of wood [43,44]. It was reported by Sharapov et al. [39] that the influence of MC on DR and FR depended on the rotational frequency and feed rates of the drill bit. These factors can both increase and decrease DR and FR. For Type 1 and the applied speed parameters, the feed rate per major cutting edge of the drill bit was 0.5 mm [45]. A significant influence of MC on DR could be expected given a lower DR is observed when MC is above fiber saturation. The effect of wood MC on DR when using Type 2 was not investigated. However, given the results for Type 1 [39], the impact of MC on DR should be lower (with a rotational frequency of 2500 min$^{-1}$ and a feed rate of 1 m/min).

### 3.2. *Typical Drilling Resistance Profiles*

We present typical DR and FR profiles of treated and untreated poles tested 600 mm above ground level with Type 1 in Figure 6. The oscillation of both datasets (Figure 6) was related to different densities of the early wood and latewood portions of the poles.

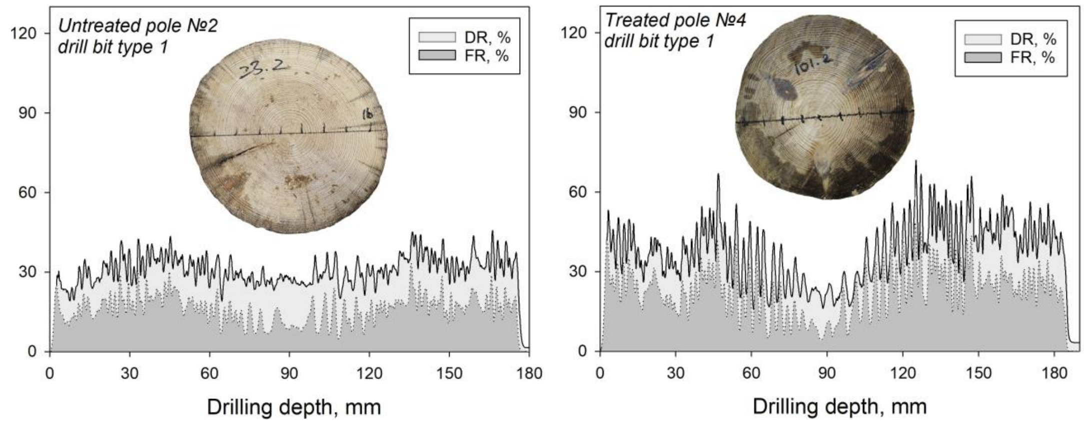



**Figure 6.** Typical drilling-resistance (DR) and feeding-resistance (FR) profiles obtained from untreated and treated poles using drill bit Type 1.

Poles were not fully impregnated in the radial direction. Impregnated layers showed a darker color compared to the untreated wood that was closer to the pith. The border between impregnated and untreated wood was more prominent for parts of the poles with a high MC (Figure 7b). DR and FR in regions close to the pith and DR variation within annual layers were different in untreated and treated poles (Figure 6). This may be attributed to imperfect drilling that was not in a precise radial direction in untreated poles (Figure 6). However, the outer layers of the treated wood generally showed a higher DR and FR than corresponding layers in untreated poles.

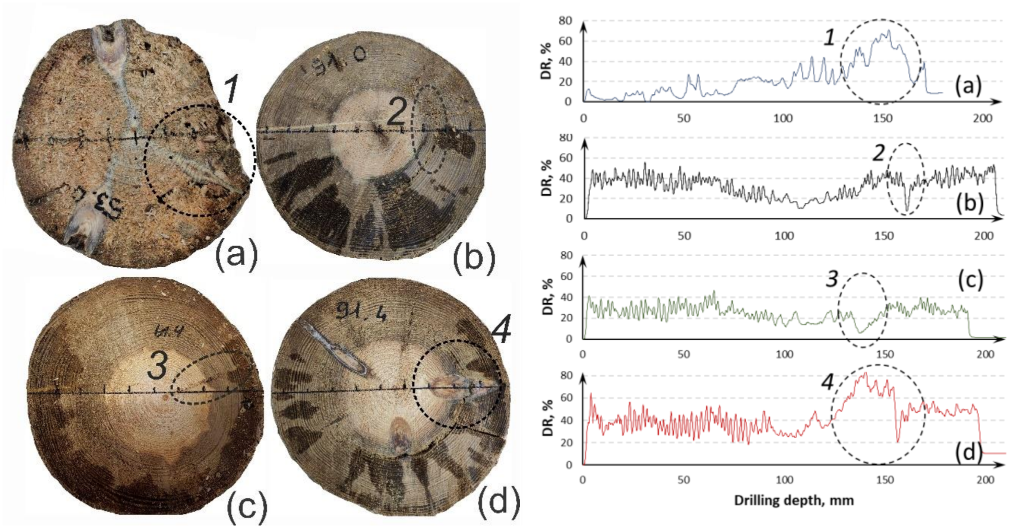



**Figure 7.** Cross-cut ends of poles and their DR profiles. (**a**) Untreated pole №3 at ground level. Note: 1, section with wood knot (see also Figure 9). (**b**) Treated pole №5 at ground level. Note: 2, region of cracked wood; (**c**) Treated pole №4 at 1200 mm from ground level. Note: 3, region of cracked wood (see Figure 9). (**d**) Treated pole №5 at 1200 mm from ground level. Note: 4, region with wood knot and cracked wood (see also Figure 8).

Many authors have reported that the treatment of wood with waterborne preservatives can affect its mechanical properties [33,46]: modulus of elasticity (MOE) is usually unaffected, maximum crushing strength is usually unaffected or slightly increased, modulus of rupture (MOR) is often reduced by up to 20%, and energy-related properties are usually reduced by up to 50%. However, the effect of preservative treatments on the elasto-mechanical properties of wood depends on the impregnation process and type of preservative. Ulunam et al. [47] showed that larch (*Larix decidua*) and black pine (*Pinus nigra*) treated with Korasit-KS (a preservative) demonstrated minor differences in static compression and bending strength after one year of weathering. Cutting resistance of Scots pine (*P. sylvestris* L.) treated with Korasit KS2 was higher compared to untreated wood in a laboratory setting when using a frame saw [48]. Based on a model for the prediction of cutting power, Chuchała and Orłowski [48] concluded that power consumption in the band-sawing of treated wood can be up to 50% higher compared to that of untreated wood. The higher DR and FR of treated wood can be explained by an increase in friction forces during drilling (cutting).

Typical internal defects detected in treated and untreated poles are presented in Figure 7. Untreated poles were severely degraded in the ground-level and underground parts (Figure 5). The DR and FR of degraded untreated wood were low. However, wood knots in the decayed wood were not degraded. This was evident in DR and FR data, presented in Figure 7a. The maximum DR of wood knots in the decayed wood of untreated poles was close to the DR of wood knots in treated poles (Figure 7a,d). Drilling of severely decayed wood that contains wood knots can result in a higher mean DR and FR. This therefore may not reflect the actual degree of destruction of the entire structure under inspection. Other internal defects, such as radial (Figure 7c) or annual ring (Figure 7b,d) cracks, were detected in drill-penetration paths.

### 3.3. Mean Drilling Resistance and Feeding Resistance

Variations in mean DR and FR across the length of treated and untreated poles are shown in Figure 8. Preservative treatment had a significant influence on wood durability in the underground part of the poles. Mean DR and FR were remarkably reduced in the underground parts of untreated poles with both drill bit types. The reduction in DR for Type 1 was more prominent than in Type 2 (Figure 8).

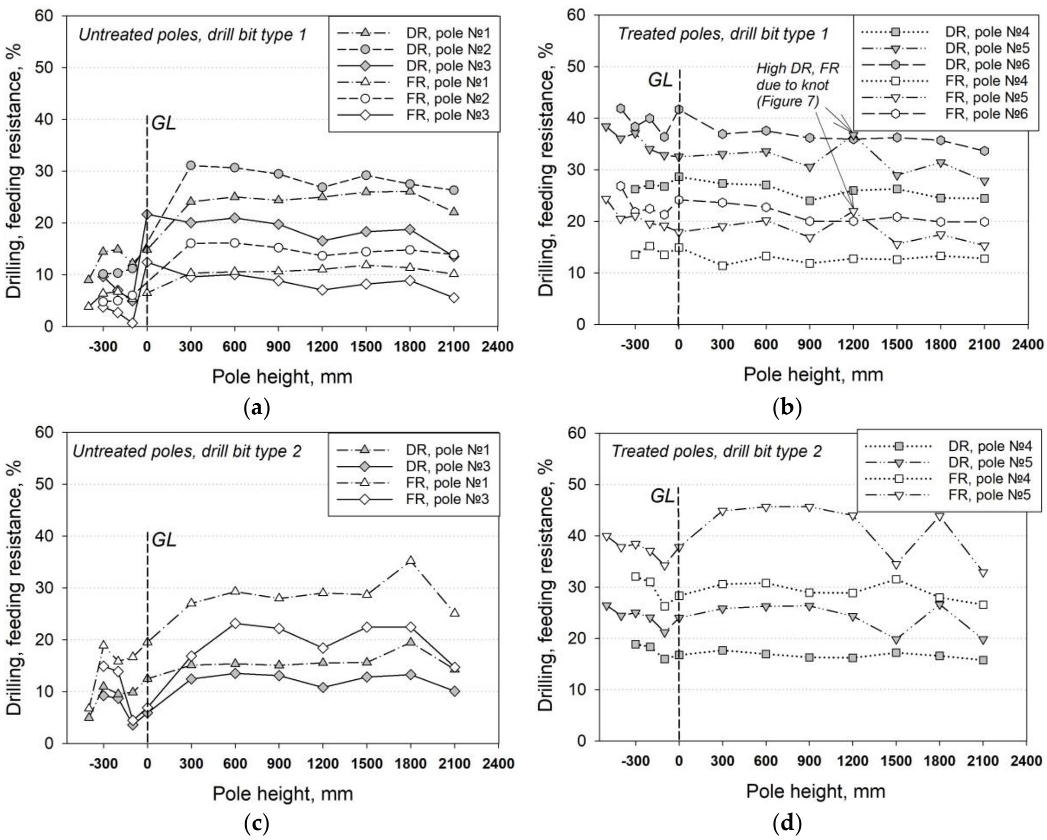
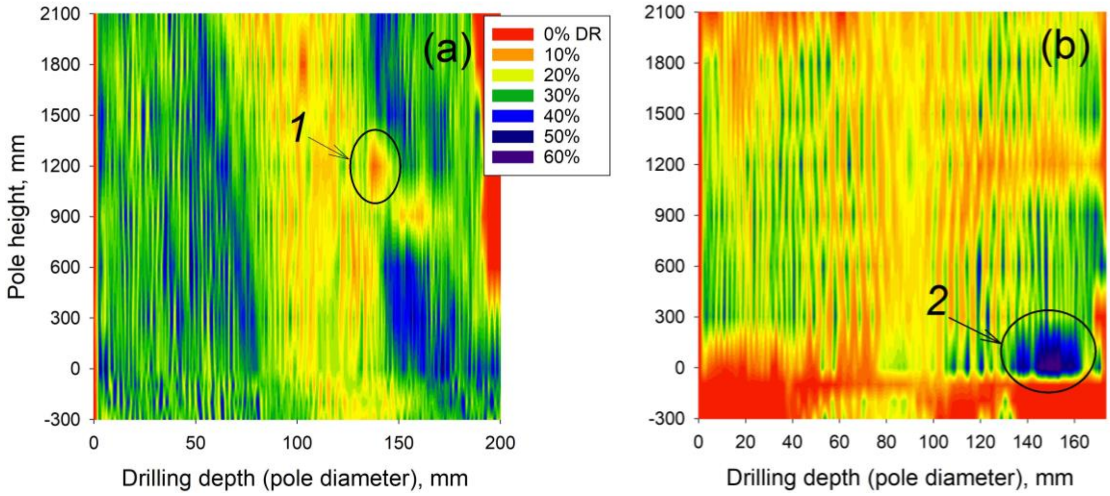



**Figure 8.** Mean drilling resistance (DR) and feeding resistance (FR) across length of tested poles. (**a**) untreated poles, drill bit type 1, (**b**) treated poles, drill bit type 1, (**c**) untreated poles, drill bit type 2, (**d**) treated poles, drill bit type 2. Horizontal dashed line, ground level (GL). Negative pole-height values indicate DR and FR data points observed for underground parts.

Differences in the design of the cutting part of drill bits had significant influence on mean DR and FR. Using the drill bit with one major cutting edge led to higher FR values compared to DR values. Different rotational frequencies and feed rates were used for both drill-bit types due to the high energy consumption of drills with one major cutting edge. Owing to its higher amplitude, FR is most often used to preselect the feed rate for drill bit Type 2. However, DR is a more accurate parameter for the prediction of the density and mechanical properties of wood [24]. The expected advantages of using a drill bit with one major cutting edge were not evident. The lower DR amplitude for the drill bit with two major cutting edges might be offset by an increased feed rate. DR and FR were generally not reduced in the underground parts of treated poles for both drill bits (Figure 5).

In general, mean DR and FR were higher in the above-ground parts of the impregnated poles (Figure 8). However, this may have been because the lower-density 3 m poles that were cut from the upper part of 9 m logs were used as untreated reference poles. This hypothesis was partly confirmed by the smooth decline in mean DR along the length of the poles from the small to large end (Figure 8). To confirm the hypothesis that DR and FR are significantly affected by preservative treatments, defect-free specimens need to be tested after conditioning at normal climate.

To represent DR measurements along poles in one plane in the same drilling direction, DR and FR data are presented as contour plots (Figure 9). DR and FR data profiles were interpolated between measurements across the length of the poles, including underground parts.




(**a**) (**b**)

**Figure 9.** Contour plots including all DR data obtained from (**a**) treated pole №5 and (**b**) untreated pole №3. Note: 0 on Y axis, ground level; 1, low DR in cracked wood; 2, high DR in a wood knot (see Figure 7).

Vertical colored lines corresponded to early wood and latewood portions as presented for individual DR profiles in Figure 6. This form of data presentation shows the distribution of variations in the mechanical properties of wood due to density differences, knots, cracks, decay, and other defects. As can be seen in Figure 9a, the central part of the treated pole, which was not impregnated with the preservative, had lower DR compared to the treated outer (sapwood) parts. This area might have been erroneously characterized as decayed. The DR of untreated poles (presented as a contour plot in Figure 9b) was more consistent in middle parts of the poles and significantly reduced in underground parts of the poles. This was likely due to decay.

## 4. Conclusions

MC of wood varied between approximately 15% and 60% in the radial and axial directions in treated and untreated poles. This can have a significant impact on DR and FR measurements. DR is a potential method for the development of standard tests for the in-situ or in-vitro assessment and monitoring of the quality of preservative treatment or wood durability. Internal defects in poles can both decrease and increase DR and FR. This should be considered when assessing the condition of wooden structures. The technological benefits of using a drill bit with one major cutting edge instead of a standard drill bit with a center-spiked tip and two major cutting edges have not been established. Contour graphs using DR measurements obtained from one element of a wooden structure are recommended for the presentation and analysis of the internal conditions of wood. Further studies should focus on the effect of different wood preservatives on DR measurements using defect-free specimens at different MCs. Similarly, DR may be used to assess the effect of modifying agents, adhesives, and other chemicals on the condition of wood and timber.

**Author Contributions:** E.S. and C.B. conceived and designed the experiments and wrote the original draft of the manuscript; E.S. performed the experiments and analyzed the data; H.M. reviewed and edited the manuscript. All authors have read and agreed to the published version of the manuscript.

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