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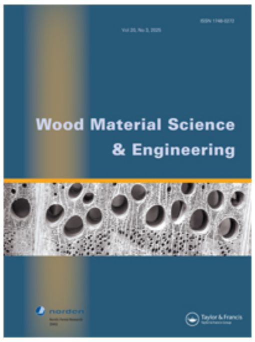

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BRIEF ORIGINAL

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Safeguarding Amsterdam's heritage: predicting sapwood width to preserve ancient wooden foundations

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ABSTRACT
Wooden piles are the most common foundation system in the historic city of Amsterdam (NL). The piles are fully submerged below water table and subject to bacterial decay. This study investigated sapwood and heartwood proportions in spruce, pine, and fir piles from different construction periods, in relation to their degradation. X-ray computed tomography scans on 49 wet discs were performed to measure the piles' sapwood width, which was then validated against an empirical model based on annual rings and growth rate. Degraded areas, identified with micro-drilling measurements, were found to affect sapwood only. These outcomes were further validated on 201 pile segments, with the predicted sapwood widths being greater than or equal to the decayed portions, even in 300-year-old piles. Therefore, estimating sapwood width can contribute to determine the remaining sound cross section of the piles, providing useful input for service life models for planning timely maintenance interventions.

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Wooden foundation piles; sapwood; decay; micro-drilling

1. Introduction

Millions of wooden piles still support existing infrastructures in Amsterdam (NL), making it crucial to estimate their remaining service life for timely maintenance interventions. Therefore, an experimental campaign supported by the municipality has been started (Mirra *et al.* 2024, Pagella *et al.* 2024a, 2024b), aimed at characterizing the current state of spruce (*Picea abies*), pine (*Pinus sylvestris*) and fir (*Abies*) foundation piles, and developing service life prediction models. Wooden piles in saturated soils are subject to bacterial degradation, which proceeds radially inward within their cross section, at first affecting sapwood, while heartwood tends to remain sound (Klaassen 2008, Björdal and Elam 2021). With regard to the piles from Amsterdam, biodeterioration due to erosion bacteria has been documented, limited to the outer portion of the cross section (Klaassen 2008, Mirra *et al.* 2024). Determining sapwood and heartwood proportions in the piles can thus be relevant for estimating the remaining sound cross section in service life models, and constitutes the focus of this work.

2. Materials and methods

This study comprised four phases: (i) determination of sapwood and heartwood proportions in 49 discs (Table 1), retrieved from foundation piles of different construction years and wood species in Amsterdam; (ii) prediction of the discs' sapwood widths with an empirical model (Sellin 1996), and validation against the measured values; (iii) comparison between the discs' sapwood width and their decayed areas, when present; (iv) prediction of sapwood width and comparison with decayed areas for a larger dataset of 201 pile segments (Pagella *et al.* 2024b, Table 2).

In phase (i), sapwood width was measured visually (only for pine discs) and through computed tomography (CT) scans (for all discs), performed in green conditions (Longuetaud *et al.* 2007).

In phase (ii), an empirical model from literature was employed (Sellin 1996), estimating the discs' sapwood width W_s based on the number a of annual rings and radial growth rate I_r (mm/year). For each disc, the annual rings were counted, and I_r was computed considering the number a' of growth rings over the outer 75% of the disc's radius, following NEN-EN 1309–3 (2018), thus $I_r = 0.75d/(2a')$, with the diameter d in mm. This empirical equation reads:

$$W_s(\text{cm}) = (3.48 \cdot I_r^{1.07})/[1 + 6.82 \cdot \exp(-0.064 \cdot a)] \quad (1)$$

The estimated sapwood width was then compared to that measured from CT scans, to assess the equation's accuracy.

In phase (iii), the sapwood widths were compared to the degraded portions in the discs, determined by performing two micro-drilling measurements per disc (98 in total), identifying the outer decayed layer in mm from the drilling amplitude (Pagella *et al.* 2024a).

All previous outcomes were combined in phase (iv), where a and I_r were determined for the 201 pile segments of Table 2. Sapwood widths were estimated with Equation (1), while decayed portions were determined by conducting two micro-drilling measurements per segment (402 in total). Finally, the estimated sapwood widths and degraded layers were

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Table 1. Properties of the 49 discs analysed in phases (i)-(iii).

		Number of discs per construction year				
Wood species	Diameter range (mm)	1727	1886	1922	1932	2019
Pine	150–240	-	-	-	2	15
Spruce	120–260	12	6	5	2	5
Fir	140–240	-	2	-	-	-

Table 2. Properties of the 201 pile segments analysed in phase (iv).

		Number of discs per construction year		
Wood species	Diameter range (mm)	1727	1886	1922
Spruce	98–276	90	41	50
Fir	123–260	-	20	-

compared to assess whether decay had only affected (part of) sapwood or had proceeded further into heartwood.

3. Results and discussion

The CT scans performed during phase (i) successfully highlighted sapwood and heartwood in the discs (Figure 1a-f). When comparing these sapwood widths and those predicted with Equation (1), a 9.2 mm (19.7%) standard error of the estimate (S.E.E.) was obtained in phase (ii), with a successful validation against measured values (Figure 1g-h).

Next, in phase (iii) the decayed layer determined from micro-drilling signals (Figure 2a) was compared to the sapwood width measured from CT scans (Figure 2b). Degraded layers were mainly limited to the outer 10 mm of the discs, with greater values observed in samples from 1727. The determined decayed portions featured a low drilling amplitude (Figure 2a), and microscopic observations confirmed that they had been degraded by erosion bacteria, as presented in a separate study (Mirra *et al.* 2024).

In all cases, bacterial degradation was limited to the sapwood width (Figure 2b), whose estimate through empirical models can thus provide an indication of the piles' remaining sound cross section. This was confirmed in phase (iv), involving a larger dataset, where sapwood widths were estimated through Equation (1), with S.E.E. = ±9.2 mm (19.7%) determined from phase (ii): this uncertainty is highlighted in Figure 2c. Next, the decayed layers determined from micro-drilling measurements were plotted against the sapwood widths of the segments. Bacterial decay was again found to mainly affect part of sapwood, with the largest degradation in piles from 1727. Only for two segments, the degraded portion was ≈5 mm larger than the predicted sapwood width, but still within the S.E.E. range (Figure 2c). Even

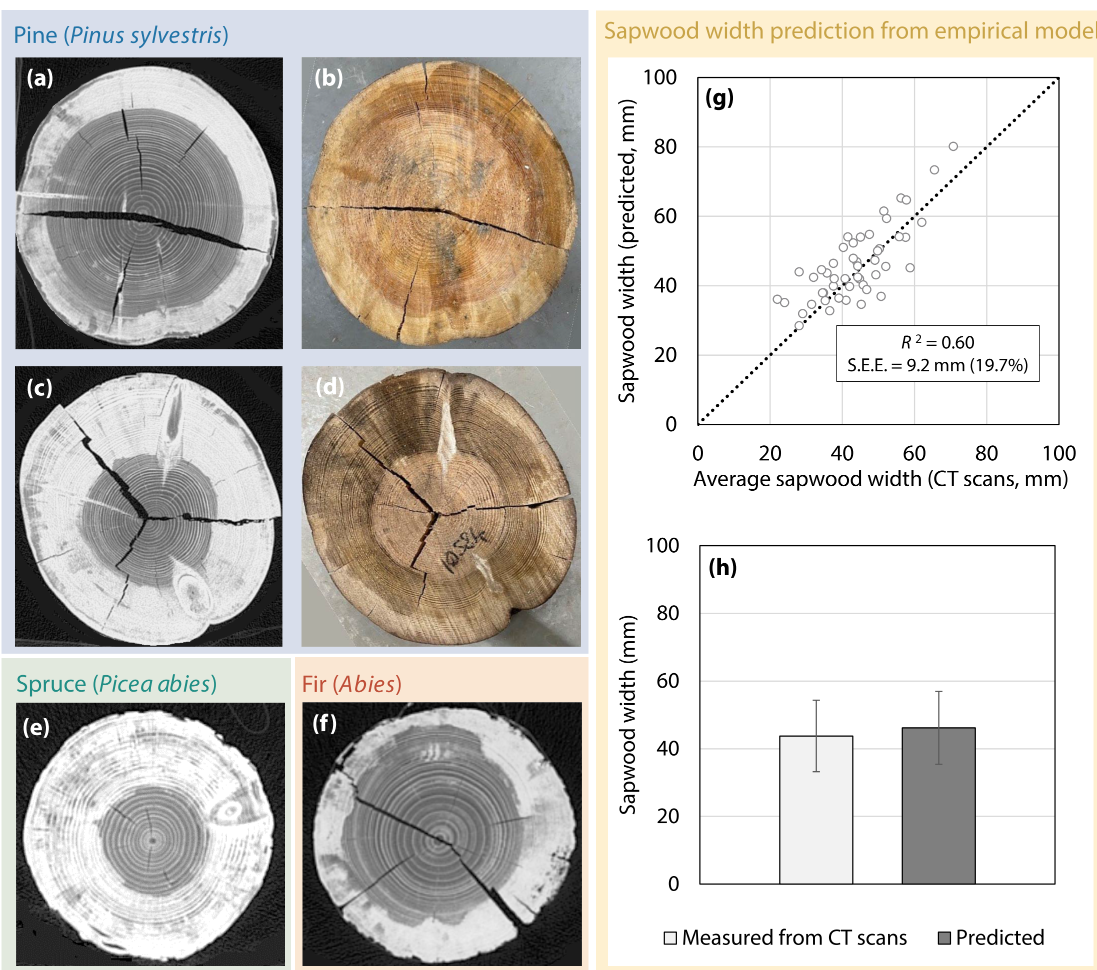

Figure 1. Comparison between X-ray CT scans and actual samples for pine discs (a-b, c-d) with different sapwood (brighter) and heartwood (darker) widths; spruce (e) and fir (f) discs' CT scans; sapwood width measured from CT scans versus that predicted with Equation (1), considering all datapoints (g) and their average and standard deviation (h).

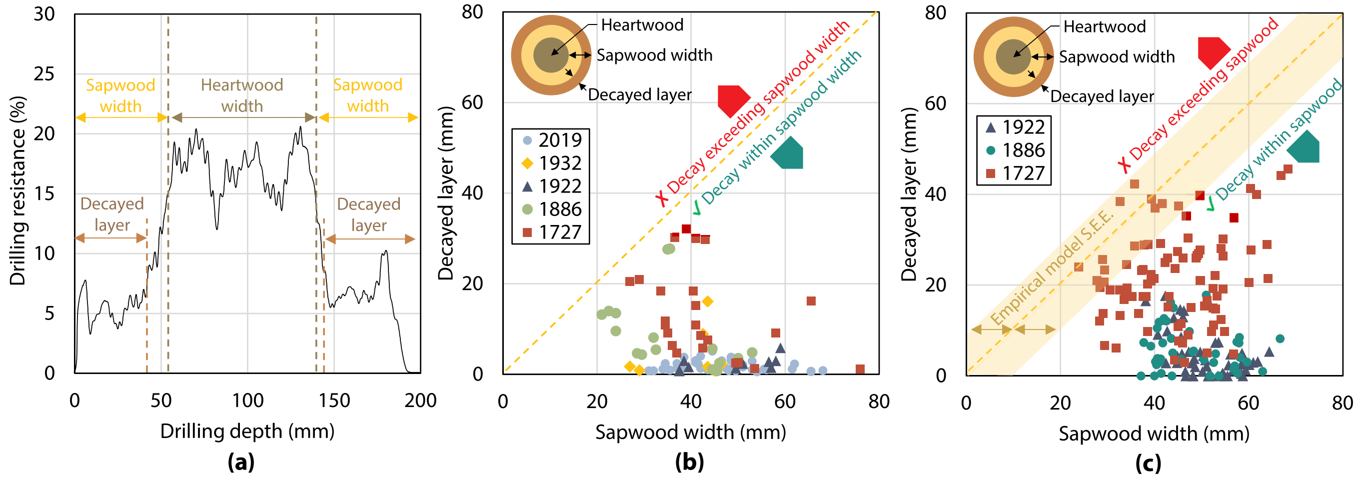

Figure 2. Decayed layers of a pile disc from 1727, identified from a micro-drilling signal, compared to sapwood and heartwood widths (a); decayed layers versus measured sapwood widths for the 49 discs used in phases (i)-(iii) (b); decayed layers versus sapwood widths predicted with Equation (1), including their standard error of the estimate (S.E.E.), for the 201 pile segments within phase (iv).

when considering all datapoints within the S.E.E., such decay extent was reached for only 11 segments (5% of the dataset).

4. Conclusions

This work has investigated sapwood and heartwood proportions in relation to bacterial decay in spruce, pine, and fir foundation piles in Amsterdam from different construction years. The results showed that areas degraded by erosion bacteria remained confined to sapwood, even in 300-year-old piles. Thus, estimating sapwood width in softwood piles could provide the maximum potential decay extension, i.e. the minimum remaining sound pile cross section, even when the degradation rate is unknown. Correspondingly, this outcome allows to determine the stress rate on the piles, given by the ratio between the loads applied to them and their (remaining) sound cross section: provided that this parameter is sufficiently low, as is often the case for foundation systems consisting of a large number of piles, such as those in Amsterdam, it is possible to preserve these ancient wooden structures for longer periods, or alternatively plan timely maintenance activities, with the help of purposely developed service life models. Hence, future research aims to investigate the prediction of sapwood and heartwood proportions directly from micro-drilling signals, enhancing the input data and accuracy of service life models for wooden foundation piles.

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Authors' contribution statement

CRediT: **Michele Mirra:** Conceptualization, Methodology, Validation, Formal Analysis, Investigation, Writing – Original Draft, Visualization. **Giorgio Pagella:** Methodology, Investigation, Writing – Review & Editing. **Wolfgang Gard:** Conceptualization, Writing – Review & Editing, Supervision. **Geert Ravenshorst:** Writing – Review & Editing, Project Administration, Funding Acquisition. **Jan-Willem van de Kuilen:** Supervision, Project Administration, Funding Acquisition. All Authors have accepted responsibility for the entire content of this submitted manuscript and approved submission.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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