Experimental prediction of the remaining strength of timber foundations in Amsterdam with micro-drilling

Pagella, Giorgio; van de Kuilen, Jan-Willem; Ravenshorst, Geert

Publication date
2025

Document Version
Final published version

Published in
IABSE Congress Ghent 2025

Citation (APA)
Pagella, G., van de Kuilen, J.-W., & Ravenshorst, G. (2025). Experimental prediction of the remaining strength of timber foundations in Amsterdam with micro-drilling. In D. Leonetti, H. H. Snijder, B. De Pauw, & S. van Alphen (Eds.), *IABSE Congress Ghent 2025: The Essence of Structural Engineering for Society* (pp. 2238-2246). International Association for Bridge and Structural Engineering (IABSE).

Experimental prediction of the remaining strength of timber foundations in Amsterdam with micro-drilling

Giorgio Pagella, Jan-Willem van de Kuilen, Geert Ravenshorst

Delft University of Technology, Delft, The Netherlands

Contact: g.pagella@tudelft.nl

Abstract

This paper presents an experimental study on predicting the remaining short-term compressive strength of timber foundation piles in Amsterdam using micro-drilling. A large-scale investigation was conducted on 201 pile segments from two bridges, dating back to 1727, 1886, and 1922. Micro-drilling measurements, supported by a TU Delft-developed algorithm, successfully assessed decay by calculating the degraded portion of the cross-section—the soft shell. Piles from 1727 exhibited approximately 50% strength reduction due to significant, consistent decay along their length. More recent piles from 1922 and 1886 exhibited a 10-15% strength reduction despite lower decay levels. The correlation between decay and strength led to the development of an experimental prediction model for the in-situ short-term strength of the pile head, middle section, and tip. These findings aid the city of Amsterdam in estimating the remaining service life of its timber pile foundations.

Keywords: timber, timber pile foundations, decay, micro-drilling, strength prediction, assessment.

1 Introduction

1.1 Background

Timber foundation piles have always played an important role in supporting buildings on soft soils, such as clay and silt with high water content and poor load-bearing capacity [1]-[7]. By inserting a large number of tree logs vertically through the first silty-soil layers, a stable support for the foundation can be made, with timber piles reaching the stiffer and deeper sand layer [7].

The application of wooden foundation piles was widespread in The Netherlands, in Delta-cities such as Amsterdam (NL) and Rotterdam (NL), as shown in Figure 1, but also across Europe in cities like Venice (IT) and Hamburg (DE), where similar timber foundations can be found [4],[6]. The city of Amsterdam (NL) constitutes one of the reference examples for such timber foundations, since it is estimated that more than eleven million timber piles are present [8]. One of the most famous buildings, still standing on 13659 spruce piles, is the Royal Palace on the Amsterdam Dam square built in the period from 1648 to 1655.

Nowadays, the assessment of the state of conservation and remaining load-bearing capacity of timber foundation piles has become important [2]. When timber piles are in the ground below the water table, they can be subjected to biological decay which can strongly reduce their load-bearing capacity, leading to safety issues in the supported buildings [1],[2],[4],[7]. Biological decay in waterlogged soils can be caused by either soft rot fungi (in low-oxygen conditions), or bacteria (even in anoxic conditions) [7]-[10]. The latter biodegradation type proceeds more slowly over time than fungal attack, which cannot survive underwater in the absence of oxygen [9]. This allows the piles to perform their function for centuries before showing a substantial reduction of the load-bearing capacity [8]. However, decayed

Back to Contents

timber piles can appear unaffected in the field, maintaining their shape and colour despite the degradation [7]. This poses a challenge in the engineering assessment of timber piles, exacerbated by the difficulty in inspecting the foundations hidden beneath the soil.

The material properties of saturated timber piles have not been widely studied in the literature, and presently, little or no design guidance can be found in the design standards [11],[12]. Timber piles have historically been designed with a load-bearing capacity ranging from 8 to 15 tons, with a maximum capacity of 20 tons [13]. Also in the present design [14], a reliable value of 10 tons (100 kN) has been used for design purposes, reflecting both historical practice and advancements in engineering understanding.

The knowledge gaps on the mechanical properties of saturated timber piles and the effects of biological decay on wood degradation processes over time, prevent engineers from adequately assessing timber foundation piles. This could have considerable implications on the safety of buildings supported by timber foundations, further impacting the safety of the citizens and economic activities.

1.2 Objectives

Given the essential function of timber pile foundations and their widespread presence in the city of Amsterdam, this study proposes a method to assess the remaining compressive strength of the piles in relation to their biological decay. This is crucial for arranging timely maintenance interventions.

This involves different objectives:

1. Assessment of decay in the piles with non-destructive micro-drilling measurements. Micro drilling allows to quantify the amount of decay throughout the whole cross section of the pile, involving the utilization of a drilling tool, where a drilling needle is pushed into the material with a chosen drill and feed speed, resulting in a graphical representation of the resistance encountered during the drilling process [15]. With micro-drilling, an assessment of the material can be conducted in different positions and directions, independently from the pile's moisture content [16], resulting in more available measurements, increased accuracy and faster in-situ testing. Based on the TU-Delft-developed algorithm for analysing micro-drilling signals of historic wooden piles, presented in [17], the decayed outer layer of the cross section of the piles can be accurately determined.
2. Analysis of the relationship between decay and remaining short-term compressive strength determined with mechanical tests conducted on 201 pile segments with different decay levels. The piles were extracted from two bridges in Amsterdam (Bridge 30 and 41), dated back to 1727, 1886, and 1922.
3. Development of an experimental model to predict the remaining short-term compressive strength of timber piles, based on the amount of decay within the pile at the position where the micro-drilling measurement is performed.

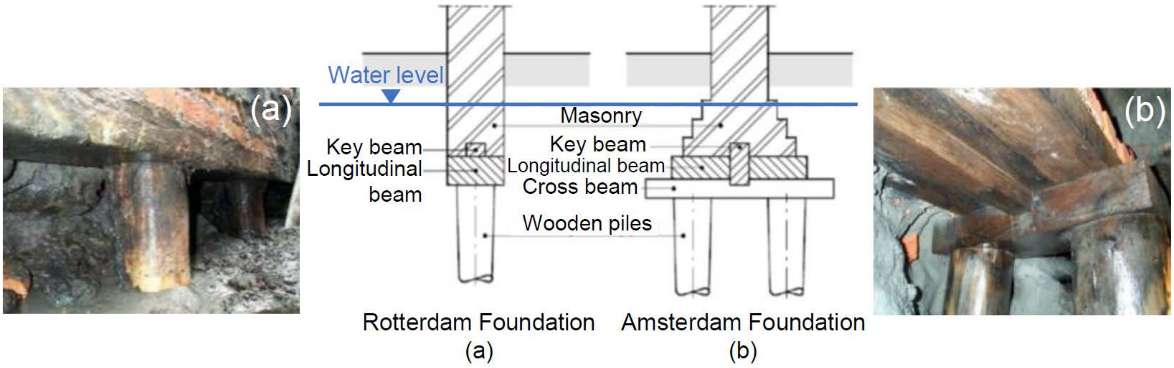

Figure 1. Wooden foundation types in Rotterdam (NL) and Amsterdam (NL): (a) Rotterdam foundation with a system of stand-alone wooden piles and only longitudinal beams; (b) Amsterdam foundation with cross beams and pair of piles (Adaptation from [13])

2 Materials and Methods

2.1 Materials

The test material comprised 55 full-length spruce (*Picea abies sp.*) and 5 fir (*Abies alba sp.*) foundation piles, originally part of the foundation system of two bridges (called bridge 30 and 41) in Amsterdam. The piles were tapered, with bigger diameter at the top (head) and smaller at bottom (tip). The piles were dated back to 1727 (30 piles), 1886 (16 piles), and 1922 (14 piles); the fir piles were all driven in 1886. All the piles were completely submerged under the water level. The piles were extracted in 2021 and stored in water tanks to preserve their saturated status.

Table 1: Data of full-length timber piles (Standard deviation reported in brackets).

Wood species	Year	Bridge (B) no. and Pile no.	L mean m	D_{head} mean mm	D_{tip} mean mm
Spruce	1922	B41 (14)	12.6 (0.8)	256 (12)	170 (16)
	1886	B30 (10); B41 (1)	12.0 (1.9)	248 (10)	172 (23)
	1727	B30 (15); B41 (15)	10.7 (1.1)	220 (39)	129 (29)
Fir	1886	B30 (3); B41 (2)	11.7 (1.9)	248 (13)	162 (32)

L = full length; D_{head} = head diameter; D_{tip} = tip diameter

2.2 Methodology

The extracted full-length piles were subdivided in three parts (head, middle, tip). From each part, a segment was tested in compression (as extensively explained in [2]), to determine the remaining short-term compressive strength parallel to the grain ($f_{c,0,wet}$). All segments had length equal to six times its average diameter, following EN 14251 [18]. All the segments were kept under water for 30 days, to represent the on-site submerged conditions, and subsequently tested in saturated conditions, with global moisture content (MC) for the whole cross section of all pile segments ranging from 60 % to 260 %, well above the fiber saturation point [2]. A total of 201 segments were mechanically tested.

Two micro-drilling measurements (A and B) were performed through the cross-section of each head, middle and tip segment, approximately 90 degrees to each other and 300 mm from the head of the segment, as shown in Figure 2b. In this way, it was possible to map the degradation pattern around the cross section and along the whole length of the pile. Each measurement was performed on fully saturated pile segments, where high moisture contents revealed to have no influence on the decay levels detected with micro-drilling [16]. All segments were micro-drilled before mechanical testing, to have an accurate correlation between the strength and decay.

The micro-drilling signal can give information on wood annual rings: maximum amplitudes correspond to latewood rings; minimum amplitudes represent early-wood [17], [19] (Fig. 2c). Isolated high or low peaks can be often associated to wood knots and other high density anatomical variation, such as compression wood [19], resulting in higher drilling amplitudes, and piths and cracks creating voids through which the drilling tool records zero or very low amplitude.

A TU Delft developed algorithm was developed to calculate the degraded portion of the cross section of the piles from signals A and B [17]. The algorithm

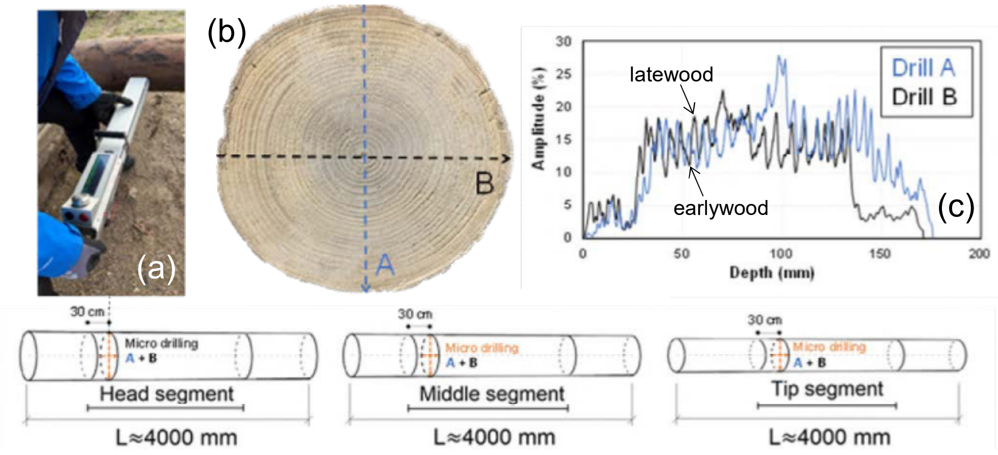

Figure 2. Representation of: (a) Micro-drilling measurements on a wooden pile; (b) drill A and B performed 30 cm from the head of the pile segment; (c) micro-drilling signal plotted as resistance (%) vs distance (mm).

analyses each signal and subdivides it in zones based on the signal amplitude. The algorithm is based on the differences in signal values and not on absolute values, starting from the assumption that the wood in the centre of the pile is sound. First, the signal is smoothened to a Moving Average (Drill_MA) calculated between 5 mm, before and after, a specific signal point. Subsequently, an Incremental Outwards Moving Average (IOMA) is calculated on both sides from the centre of the signal. The average of the Moving Average values is calculated starting from the centre, for both sides of the signal. The maximum IOMA value on both sides is considered to be the reference for sound wood. From this, 4 zones are determined through chosen ratios between the Drill_MA of the signal and the maximum value of the IOMA. Zones 1, 2, 3, and 4 on each side are determined as 20%, 40%, 60%, and 80% of the Drill_MA value considering the maximum value of the IOMA on that side taken as reference for sound wood (Fig. 3a). The degraded portion of the cross section – *soft shell* – is finally calculated as zones 1 + 2 (Fig. 3b), according to the calibration demonstrated in [17]. This allows to assess the zone allocation in a relative way for each micro-drilling measurement. The total soft shell of each pile was calculated as the average of the 4 lengths of the soft shell (SS), corresponding to zones 1+2 on the left and right sides of micro-drilling signals A + B. From this, the average length of the soft shell (al_{SS}) was calculated with Equation 1, with the assumption of a uniform distribution of decay around the pile's cross section. Subsequently, the remaining sound cross sectional area (A_{sound}), was calculated with Equation 2, by subtracting al_{SS} (Eq. 1) to the cross-sectional radius (r), and expressed as percentage of the full cross-sectional area (A_{tot}) – See Figure 3c.

$$al_{SS} = \frac{SSA,left + SSA,right + SSB,left + SSB,right}{4} \quad (1)$$

$$A_{sound}\ (\%) = (A_{sound} / A_{tot}) = [\pi\,(r - al_{SS})^2 - \pi r^2] \cdot 100 \quad (2)$$

3 Test results

3.1 Remaining strength of the piles

The results of the compression tests are presented for 201 pile segments extracted from 60 full-length spruce and fir piles, subdivided in head, middle-part, and tip. The $f_{c,0,wet}$ values of piles from 1727 were considerably lower than those from 1886, and 1922. This can be observed in the distribution of the data of $f_{c,0,wet}$ in Figure 4a, where the piles from 1886 and 1992 are grouped together, while piles from 1727 exhibit much lower $f_{c,0,wet}$. The box plot in Figure 4b shows the distribution of the data for head, middle-part, and tip. No significant

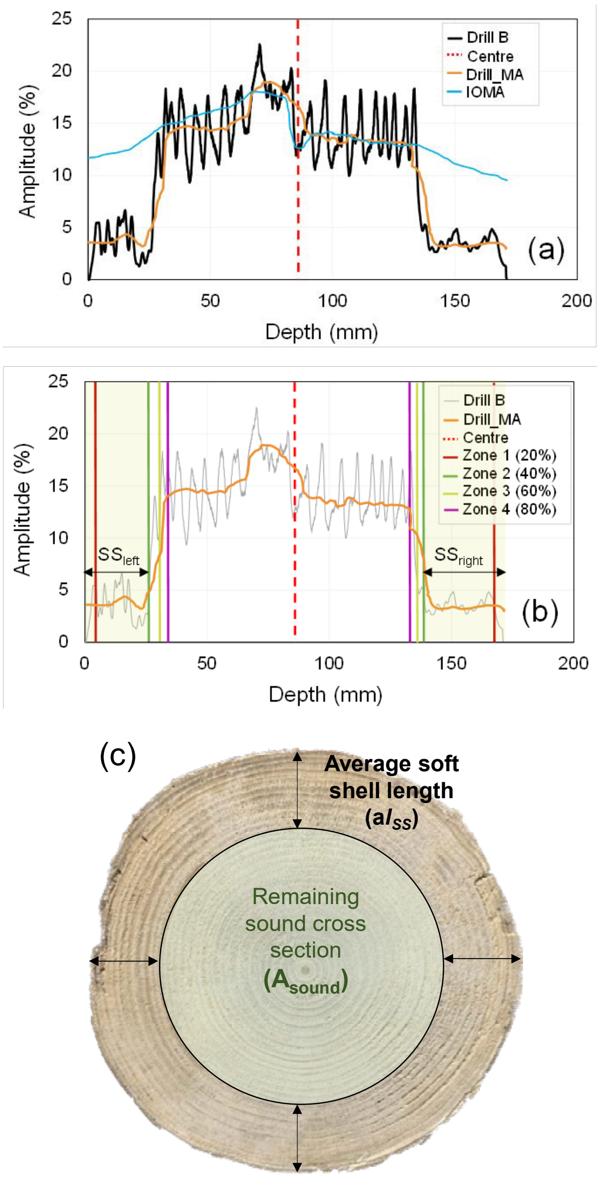

Figure 3: Example of a drilling signal (Drill) of a 300 years old spruce pile: a) Drill_MA and IOMA from which the 4 zones are calculated; (b) 4 zones and soft shell (SS_{left} and SS_{right}) associated to zones 1 + 2 according to [15]; (c) al_{SS} and A_{sound} calculated with SS left and right of micro-drilling signals A + B.

difference in $f_{c,0,wet}$ was found between the building year 1922 and 1886, and between head and middle-part of spruce and fir piles from 1922, 1886, and 1727. Head and middle parts had similar strength values for each category, while tips had always lower $f_{c,0,wet}$. This was determined after carrying out a statistical analysis (two-sample t-test, one-tailed) of two different groups (e.g., two different building years) to determine whether the mean value of one group was significantly greater or less than the other. The statistical analysis was not included in this paper due to length constraints.

Furthermore, the results showed that $f_{c,0,wet}$ of all tested wooden piles was lower than the strength values of 'new' spruce: $f_{c,0,wet,mean}$ = 17.2 ± 2.6 MPa characterized in Pagella et al. [20], and $f_{c,0,wet,mean}$ = 20 ± 2.2 MPa determined in 1994 by Van de Kuilen[21]. Piles from 1727 exhibited a more than halved $f_{c,0,wet}$ compared to new piles. This is partly due to extensive decay after being exposed to biodegradation for 300 years. Piles from 1886 and 1922 had 10-15% lower $f_{c,0,wet}$ than new ones. This difference could be related to the physical properties of the piles, natural variability of the mechanical properties, or presence of decay. These aspects will be further elaborated in paragraph 3.2.

3.2 Decay assessment with micro-drilling

al_{SS} and A_{sound} related to the remaining short-term $f_{c,0,wet}$ of the piles are presented for all historic pile segments in Table 2, based on the micro-drilling approach.

According to the small-scale characterization conducted in [22],[23], the decay was attributed to bacterial decay, confirming that the piles extracted from bridge 30 and 41 in Amsterdam remained submerged in anoxic conditions throughout their service life. Yet, it cannot be excluded a priori that other degradation types such as soft rot fungi (in low-oxygen conditions) might be present in other parts of the piles or in other piles in Amsterdam.

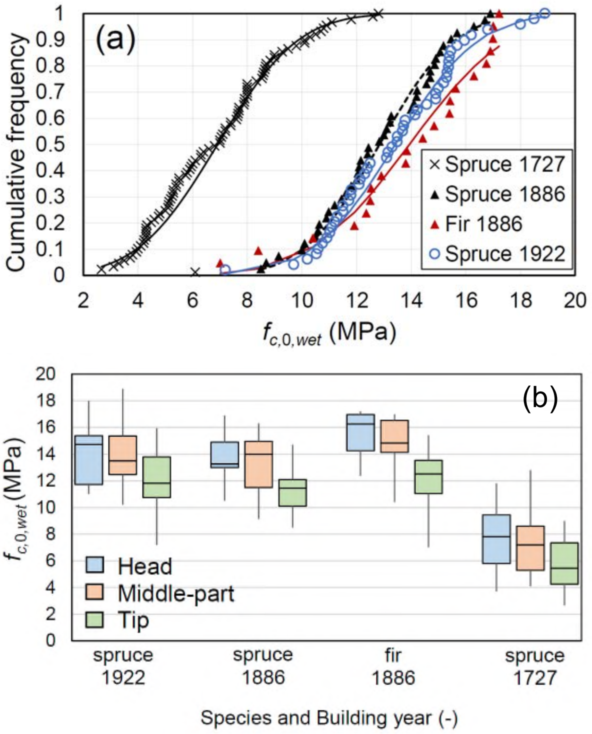

Figure 4: (a) Cumulative distributions of $f_{c,0,wet}$ for all pile segments from 1727, 1886, 1922 – The lines show the normal distribution fitted to the data; (b) Box plot with data distribution of $f_{c,0,wet}$ of head, middle-part and tip of all pile segments divided in the 3 building years.

Table 2: Remaining $f_{c,0,wet}$ in relation to A_{sound}, al_{SS} (standard deviation reported in brackets).

Wood species	Year	Part (No. segments)	$f_{c,0,wet}$ (MPa)	A_{sound} (%)	al_{SS} (mm)
			mean	mean	mean
Spruce	1922/ 1886	Head (29)	13.9 (2.0)	91 (8)	6 (5)
		Middle (30)	13.7 (2.3)	94 (7)	4 (4)
		Tip (32)	11.8 (2.1)	87 (10)	7 (5)
	1727	Head (30)	7.5 (2.3)	63 (14)	22 (11)
		Middle (30)	7.3 (2.4)	62 (20)	20 (11)
		Tip (30)	5.8 (1.8)	50 (15)	22 (9)
Fir	1886	Head (6)	15.2 (2.0)	97 (4)	2 (2)
		Middle (7)	14.8 (2.3)	97 (6)	1 (3)
		Tip (7)	12.0 (3.0)	96 (7)	2 (3)

A larger amount of decay was determined for piles from 1727 compared to 1886/1922, where al_{SS} ranged at 20-22 mm, with no significant difference across head, middle and tip of the pile. This highlights one important finding. Bacterial decay is potentially uniform along the pile length. A useful information for the in-situ assessment of historic wooden foundation piles. A_{sound} was lower in the tips, compared to head and middle-part, due to the inherent smaller tip cross-sectional area for the same $a l_{SS}$ values. The pile segments from 1922 and 1886 had $a l_{SS}$ below 7 mm, approximately constant along the pile. A_{sound} was on average uniform in head and middle-part from 1922 and 1886, with a slight decrease in the tips, due to their inherent smaller cross-sectional area. Fir piles had $a l_{SS}$ always below 2 mm, indicating a very low amount of decay for fir, in line with literature [4],[8]. This may be attributed to the inherently higher resistance of fir to decay [4],[22], the limited number of tested fir piles, or the fact that fir piles exclusively dated back to 1886.

4 Short-term strength prediction

The remaining short-term $f_{c,0,wet}$ of the piles was well correlated with A_{sound} as showcased in Figure 5. Piles from 1727 had a larger range of A_{sound} from 25 % to 85 %, while piles from 1886 and 1922 had a lower range 65% < A_{sound} < 100%.

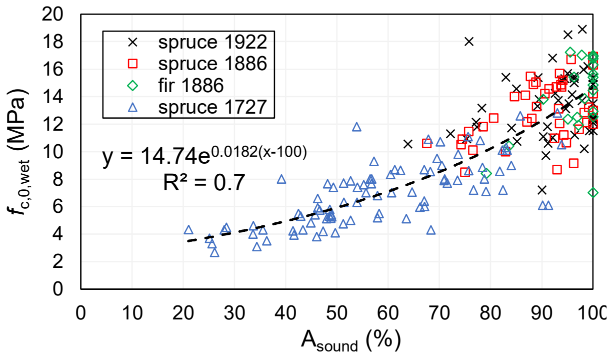

Figure 5: Relationship between $f_{c,0,wet}$ and A_{sound} of all the 201 tested spruce and fir pile segments.

Based on this correlation, the remaining short-term $f_{c,0,wet}$ of a timber pile can be estimated with Equation 3. This experimental equation is only based on A_{sound}, calculated through micro-drilling measurements, and the diameter of the pile at the measurement location. This gives the possibility to have a direct estimation of the remaining short-term $f_{c,0,wet}$ from in-situ micro-drilling of the piles.

$$f_{c,0,wet} = 14.74\, e^{0.0182\,(A_{sound}-100)} \qquad (3)$$

The comparison between the head and tip of all piles enables further analysis. Table 2 shows an average decrease of 2 MPa in $f_{c,0,wet}$ at the tips compared to the pile heads. This relationship between $f_{c,0,wet}$ at the head and tip can be utilized in the in-situ assessment of historic timber piles, to predict the remaining strength of the pile tip (*Pred.* $f_{c,0,wet,tip}$). This is important since the pile tip corresponds to the critical pile's section, featuring the lowest mechanical properties (See Table 2). This could have an influence on the load-bearing capacity of the pile, where depending on soil conditions, the tip could be subjected to high stresses during service, primarily due to its smaller cross section. In the case of an in-situ assessment of a pile under a bridge in Amsterdam, micro-drilling can be performed underwater by divers on the accessible part of the pile head (Figure 6). The signals retrieved from micro-drilling measurements A and B of the pile head can be analysed with the TU-Delft developed algorithm to determine $a l_{SS}$ and A_{sound}.

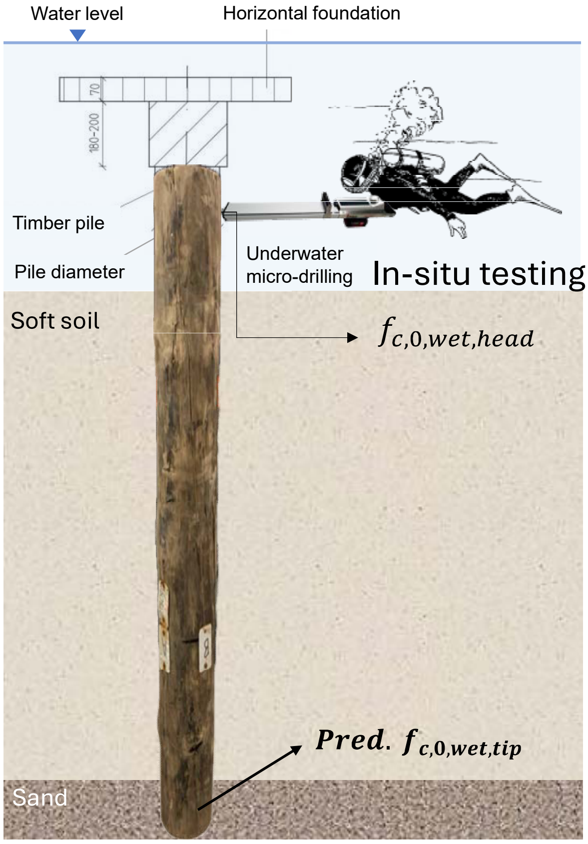

Figure 6. Relationship between $f_{c,0,wet}$ and A_{sound} of all the historic spruce and fir segments.

The experimental Equation 3 can be directly applied to predict the remaining short-term compressive strength of the pile head ($f_{c,0,wet,head}$). The same strength value can be taken for middle-parts, since no relevant difference was measured in the strength. Subsequently, based on the regression analysis of all the tested head and tip segments, Equation 4 can be used in practice to predict *Pred.* $f_{c,0,wet,tip}$ from $f_{c,0,wet,head}$. The correlation between *Pred.* $f_{c,0,wet,tip}$ and the actual $f_{c,0,wet,tip}$ determined with compression tests, is shown in Figure 7, revealing a strong relationship between the two parameters and supporting the applicability of Equation 4 in practice. This is based on the assumption supported by the results in Table 2, where the decay (al_{SS}) is constant along the length of the pile.

$$Pred.\ f_{c,0,wet,tip} = 0.88\, f_{c,0,wet,head} - 0.76 \quad (4)$$

The presented model for the direct prediction of the remaining short-term compressive strength on the basis of the micro-drilling signals is derived from the experimental analysis of the wooden piles presented in this study. The experimental prediction equations can be adopted in practice for an estimation of the remaining short-term compressive strength along the piles. It should be noted that the remaining strength of the piles could differ depending on the load levels acting on the foundations for centuries. Further research is envisaged on the remaining short-term strength of pine piles, also very diffused in Amsterdam.

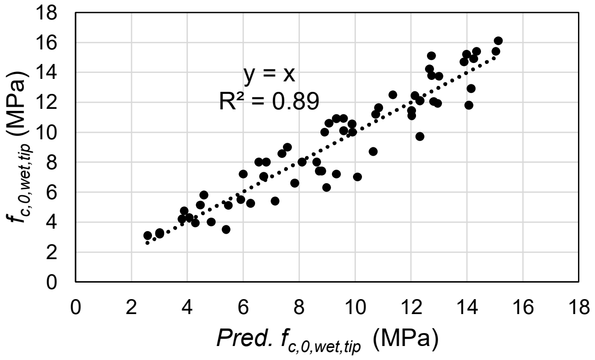

Figure 7. Relationship between *Pred.* $f_{c,0,wet,tip}$ and $f_{c,0,wet,tip}$ based on the regression Equation 4.

5 Conclusions

Promising results were obtained in relation to the use of micro-drilling measurements for in-situ monitoring of historic wooden foundation piles, supported by the unique opportunity to characterize the material and mechanical properties of piles dated back to different construction years and with different decay levels. The short-term compression strength of long-serving wooden piles is lower than that of new piles, partly due to decay. Piles from 1727, exposed to bacterial decay for nearly 300 years, retained only about half the short-term strength of new piles. However, even more recent piles from 1922 and 1886 (100 and 135 years of exposure, respectively) exhibited 10-15% reduced strength despite lower decay. These findings should be considered in future assessments of wooden foundation piles. Underwater micro-drilling analysis of the pile head allowed experimental prediction of the remaining short-term compressive strength of the pile middle-part and tip. This is a key step in assessing the load-carrying capacity of historic wooden piles, as the tip is the weakest section and may endure high stresses due to its smaller cross-section and depending on soil conditions. It should be noticed that this prediction model is based on the mechanical properties of the piles under two bridges in Amsterdam. The remaining strength of the piles may vary depending on the bridge configuration and load levels that have been applied to the piles for centuries.

Presently, the micro-drilling technique is widely used in Amsterdam to assess decay, supporting the estimation of the remaining load-carrying capacity of timber pile foundations. This research supports timely maintenance planning and contributes to the development of deterministic and timber damage models, including predictions for the remaining service life of timber pile foundations.

6 Acknowledgements

The Authors acknowledge the municipality of Amsterdam for having funded this research study.

7 References

[1] Van de Kuilen, J.W.G. Service life modelling of timber structures. 2007. Mat. & Struct. 40, 151–161.

[2] Pagella, G., Mirra, M., Ravenshorst, G., Gard, W., van de Kuilen, J.W. Characterization of the remaining material and mechanical properties of historic wooden foundation piles in Amsterdam. 2024. Construction and Building Materials, 450, Article 138616.

[3] Van de Kuilen, J.W.G., Beketova-Hummel, O., Pagella, G., Ravenshorst, G.J.P., Wolfgang G. An integral approach for the assessment of timber pile foundations. In: World Conference on Timber Engineering 2021, WCTE 2021, pp. 2–8, Santiago, Chile.

[4] Klaassen,_R.K.W.M. et al. Preserving cultural heritage by preventing bacterial decay of wood in foundation poles and archaeological sites. Final report EVK4-CT-2001-00043. Wageningen, 2005.

[5] Felicita, M., Pagella, G., Ravenshorst, G., Mirra, M., & van de Kuilen, J. W. Assessment of in-situ stress distribution and mechanical properties of wooden foundation piles instrumented with distributed fiber optic sensors (DFOS). *Case Studies in Construction Materials*, 2024; *20*, Article e03139.

[6] Macchioni, N., Pizzo, B., Capretti, C. Grading the decay of waterlogged archaeological wood according to anatomical characterisation. Int. Biodeterior. Biodegradation, 84 54-64, 2013.

[7] Elam, J., Björdal, C. A review and case studies of factors affecting the stability of wooden foundation piles in urban environments exposed to construction work, International Biodeterioration & Biodegradation, Volume 148, 2020, 104913, ISSN 0964-8305.

[8] Klaassen, R.K.W.M., Creemers, J.G.M. Wooden foundation piles and its underestimated relevance for cultural heritage. Journal of Cultural Heritage 13(3), 123–128, 2012.

[9] Singh, A.P., Kim, Y.S., Singh, T. (2016). Bacterial degradation of wood. Secondary Xylem Biology, Chapter 9, 2016.

[10] Irbe, I., Bikovens, O., Fridrihsone, V., Dzenis, M. Impact of biodeterioration on structure and composition of waterlogged foundation piles from Riga Cathedral (1211 CE), Latvia. Journal of archaeological science: reports 23, 196, 2019.

[11] F3O (2011) F3O Richtlijn: Onderzoek en beoordeling van houten paalfunderingen onder gebouwen. Rapportnummer: 978-90-816732-1-1. 2011. (in Dutch).

[12] NEN 8707 (2018)+C2 (2023). Assessment of the structural safety of an existing structure during renovation and rejection – Geotechnical constructions, NEN, 2023.

[13] Nieuwe Richtlijn Funderingen onder gebouwen (New Guideline for Foundations under Buildings), 2023. Kennis Centrum Aanpak Funderingsproblematiek – KCAF. in Dutch.

[14] Ruwan Rajapakse. Pile Design in Sandy Soils, Editor(s): Ruwan Rajapakse, Pile Design and Construction Rules of Thumb, Butterworth-Heinemann, 2008, pp. 41-73, ISBN 9780750687638.

[15] Nowak T. P., Jasieńko J., Hamrol-Bielecka K. In situ assessment of structural timber using the resistance drilling method – Evaluation of usefulness. Construction and Building Materials, 2016, 102: 403-415.

[16] Mirra, M., Pagella, G., Gard, W.F., Ravenshorst, G.J.P., van de Kuilen, J.W.G. Influence of moisture content on the assessment of decay levels by micro-drilling measurements in wooden foundation piles. World Conference on Timber Engineering, Oslo, Norway, 2023.

[17] Pagella, G., Ravenshorst, G., Mirra, M., Gard, W., van de Kuilen, J.W. Innovative application of micro-drilling for the assessment of decay and remaining mechanical properties of historic wooden foundation piles in Amsterdam, Developments in the Built Environment, Volume 19, 2024, 100514, ISSN 2666-1659.

[18] EN 14251 (2003) Structural round timber - Test methods. European Committee for Standardization (CEN).

[19] Kollmann F., Côté, W.A. Principles of Wood Science and Technology. Springer-Verlag, Berlin · Heidelberg 1968, Ed. 1, 1968, 592 p, ISBN 978-3-642-87930-2.

[20] Pagella, G., Ravenshorst, G.J.P., Gard, W.F., Van de Kuilen, J.W.G. Characterization of the mechanical properties of saturated spruce (Picea abies) and pine (Pinus sylvestris) foundation piles. Journal of Building Engineering. Forthcoming 2025.

[21] Van de Kuilen, J.W.G.: Bepaling van de karakteristieke druksterkte van houten heipalen. Toegepast-Natuurwetenschappelijk Onderzoek (TNO), order Nr. 94-con-RO271. Delft, The Netherlands. 1994. (in Dutch)

[22] Mirra, M., Pagella, G., Lee, M., Gard, W., Ravenshorst, G., Van de Kuilen, G.J.W.

Characterisation of bacterial decay effects on wooden foundation piles across various historical periods. Construction and Building Materials, Volume 421, 2024, 135670, ISSN 0950-0618.

[23] Pagella, G., Struik, M., Mirra, M., van de Kuilen, J. W. Small-scale testing of water-saturated wooden discs for determining the strength properties of timber foundation piles. Wood Material Science & Engineering, 2024. 1–3.