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INFLUENCE OF MOISTURE CONTENT ON THE ASSESSMENT OF DECAY LEVELS BY MICRO-DRILLING MEASUREMENTS IN WOODEN FOUNDATION PILES

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ABSTRACT: In the historic city centre of Amsterdam (NL), the most widespread foundation system consists of wooden piles. With the aim of modelling and predicting remaining service life of these foundations and the piles in particular, one of the possible methods for collecting data and monitoring their condition consists of micro-drilling (MD) measurements. This work evaluates the reliability of MD measurements in identifying decayed portions and specific features of wooden foundation piles, considering different moisture content (MC) values. To this end, 24 segments were selected, sawn from wooden piles extracted from site, and having time in service (TS) of 2 to 294 years (with reference to 2021, the year of extraction). 240 MD measurements were conducted at varying MC values of 7% to 212%. The obtained MD profiles showed for all TS a slight decrease in drilling resistance when increasing MC. However, from the MD signals it is possible to reliably detect the areas affected by biodegradation phenomena (e.g. bacterial decay) along the drilling depth, regardless the MC of the segment or its gradient along the drilling depth. The present study contributes to research aiming at utilizing (in-situ) MD techniques for reliably assessing and quantifying decay and to be used in remaining service life planning of wooden foundation piles.

KEYWORDS: Wooden foundation piles, Micro-drilling, Moisture content, Biodegradation, Service life prediction.

1 INTRODUCTION

The utilization of wooden piles as foundation system of historical or existing buildings has been widespread throughout Europe. In this context, the city of Amsterdam (NL) constitutes one of the reference examples for such foundation structures, since it is estimated that eleven millions wooden piles are present, still supporting existing and historical buildings as well as bridges and quay walls. Given the essential function of these foundations and their spatial extension, the estimation of the remaining service life of the piles is crucial for arranging timely maintenance interventions. Therefore, an extensive experimental campaign has been started in cooperation with the municipality of Amsterdam [1], aimed at characterising the current state of wooden foundation piles [2],[3], as well as providing solid input for service life prediction models [4].

Among the available techniques for monitoring timber piles, micro-drilling (MD) measurements are a promising option, because extensive in-situ sampling of a large number of piles could be realized. Yet, the use of MD signals for decay quantification requires still attention [5], thus a preliminary investigation of the reliability of this method for the specific context of wooden foundation piles in Amsterdam was necessary, including the development of a drill for underwater use.

When performing in-situ MD measurements on the piles, their moisture content (MC) is above fibre saturation point. Thus, it is important to ascertain that, also in submerged conditions, decayed portions of the cross section of the piles are correctly detected from the MD signals.

This work aims to assess whether MD measurements can provide reliable information on the decay levels of wooden foundation piles, independently of their moisture content (MC). These biodegradation phenomena on submerged wooden piles are caused by erosion bacteria [6]. The outer portion of the cross section is usually subjected to bacterial decay, since erosion bacteria can more easily attack the less durable sapwood [7]. Such decayed areas should also be visible from MD signals, independently of the actual MC, as this parameter is in principle unknown for the piles on site.

However, previous research works have shown opposite results on the effect of MC on MD measurements, showing that drilling resistance can both decrease [8] or

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increase [9],[10] with increasing MC. This is because the outcomes from MD measurements can be influenced by different parameters besides MC itself, such as drill and feed speed, drilling depth, wood species, all factors influencing the shaft friction along the drill [8]–[10]. In light of these uncertainties, the reliability of MD measurements in correctly identifying decay in wooden foundation piles was evaluated in the present study, considering different MC values.

More specifically, segments from wooden foundation piles with a time in service (TS) ranging from 2 to 294 years (with reference to 2021, when their extraction took place) were selected, and MD measurements were conducted at varying MC values between 7% and 212%. To confirm large decay levels identified with MD measurements, compression tests were also conducted on the pile segments, after submerging them under water.

2 MATERIALS AND METHODS

2.1 MATERIALS

In this work, 8 wooden foundation piles were selected:

- 2 piles from 1727 (TS = 294 years as of 2021);
- 2 piles from 1886 (TS = 135 years as of 2021);
- 2 piles from 1922 (TS = 99 years as of 2021);
- 2 piles from 2019 (TS = 2 years as of 2021).

The piles from 1727, 1886, and 1922 were retrieved from the foundations of the piers of two bridges in the city centre of Amsterdam [3], whereas those from 2019 were extracted from a separate testing field [2] in the Overamstel area (Figure 1).

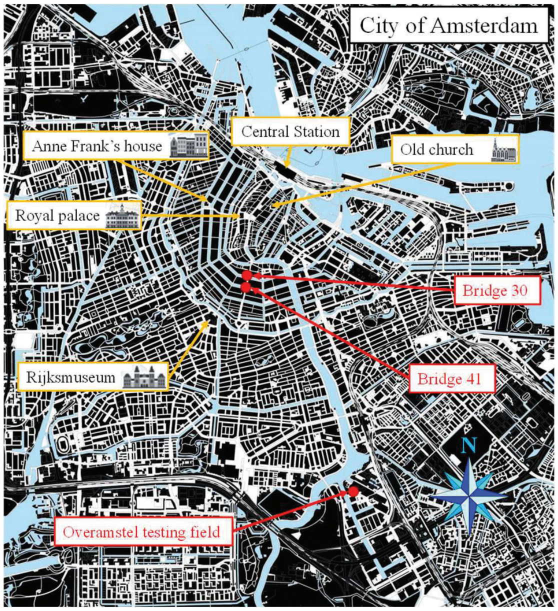


Figure 1: *Map of Amsterdam and locations (in red) from where the piles were extracted: to better highlight their position, some of the main monuments of the historic city centre are also reported as a reference. Adapted from [11].*

The piles had length of approximately 14 m, and diameters ranging from 175 to 290 mm at the head, and from 130 mm to 230 mm at the tip. All piles were made of spruce (*Picea abies*), with the exception of one pile from 1886, made of fir (*Abies alba*), and one from 2019, made of pine (*Pinus sylvestris*).

The retrieved piles were all subdivided in smaller segments, representative for the head, middle, and tip part of the piles (see also Section 2.2), for a total of 24 segments: Table 1 reports a detailed overview of the tested pile segments, their TS and MC range.

2.2 METHODS

2.2.1 General

The extracted full-length piles were cut in three parts (head, middle, tip), and delivered to TU Delft Stevin II Laboratory. From each part, a smaller segment to be tested in compression (Section 2.2.4) was sawn, having length equal to six times its diameter, following EN 14251 [12]. In this way, 24 segments were obtained (6 for each TS, see again Table 1) having lengths of 900, 1350, and 1800 mm, depending on their diameter. All segments were kept under water for two weeks to represent the on-site submerged conditions, and were characterised in terms of wet density [13] and moisture content, determined through the oven-dry method [14]. These compression tests allowed to mechanically characterise the pile segments, and to detect the presence of biodegradation phenomena (especially for the older piles), corresponding to a reduction of compressive strength with respect to fully sound samples.

MD measurements were performed on these segments, evaluating their reliability in capturing the features of the cross section (e.g. sound or decayed sapwood, knots, and so forth) for different MC values. This analysis was conducted considering the following two scenarios:

1. Assessment of the possible influence of different MC values referred to a whole segment on the corresponding drilling resistance (DR), thus an analysis at *global segment level* (see Section 2.2.3);
2. Evaluation, with reference to submerged conditions, of the possible influence of the MC gradient along the drilling depth on the MD signals, thus an analysis at *cross-sectional level* (see Section 2.2.4).

Table 1: *Overview of TS and MC of the tested pile segments.*

Number of segments	TS (years)	MC range (%)
6	294	14–212
6	135	8–57
6	99	12–100
6	2	7–84

2.2.2 Compression tests

Mechanical testing was performed to determine the compressive strength of the pile segments ($f_{c,0}$) in submerged conditions and confirm the information on the level of decay obtained with MD measurements. To this end, a displacement-controlled test setup was used (Figure 2), where the pile segments were subjected to an axial load in direction parallel to the fibres [12],[15].

The displacement between the two steel plates surrounding the pile segment was monitored with four linear potentiometers, placed on the four edges of the top plate and connected to the bottom plate. Four additional linear potentiometers, screwed to the segment, measured its deformation. The sensors were placed along the lateral surface of the piles, at 90° from each other, and had a variable length equal to 2/3 of that of the specimen.

The tests were conducted at a displacement rate of 0.02 mm/s, and the compressive strength was derived from the ratio between the maximum force reached in compression by each specimen and its average cross-sectional area.

2.2.3 Execution of MD measurements at different MC values (analysis at global segment level)

The MD measurements were conducted with an IML-RESI PD400 drill (Figure 3a). This device provides the profiles of drill and feed amplitude against drilling depth as output [8]. All measurements were taken 300 mm below the top of each segment, in two orthogonal directions (A and B in Figure 3b; see also [3]), and at approximately 1 cm distance from each other for every direction. A drill speed of 2500 r/min and a feed speed of 150 cm/min were adopted; the drill bit was 400 mm long, with a thin shaft of 1.5 mm diameter and a 3.1 mm wide triangular cutting part, with hard chrome coating.

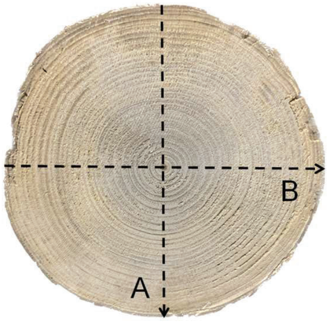
The first two MD measurements on a segment were executed in submerged conditions, immediately prior to its compression test (Section 2.2.2), and were also used to evaluate the influence of MC gradient along the drilling depth (see Section 2.2.4). Other four MD measurement-pairs were then taken during the drying process of each segment after the compression test, recording every time the weight of the segment and determining the corresponding global MC. Thus, a total of 240 MD measurements were conducted.

Since the outer decayed areas of the pile segments are linked to lower basic densities compared to sound wood, a correspondingly low drilling resistance is observed at the beginning and at the end of the MD signals, showing the degraded portion. In order to objectively define which part of the MD signal pertains to decayed areas, and which part to sound wood, the procedure already proposed in [3] was adopted. Thus, the average drilling amplitude (DA) of the drilling resistance (DR) profiles along the drilling depth H was firstly determined. Following [5], this is defined as:

$$\mathrm{DA} = \frac{\int_0^H \mathrm{DR}\ \mathrm{dh}}{H} \tag{1}$$

Figure 2: *Setup for compression tests.*

(a)



(b)

Figure 3: *Adopted MD device (a) and drilling directions (b).*

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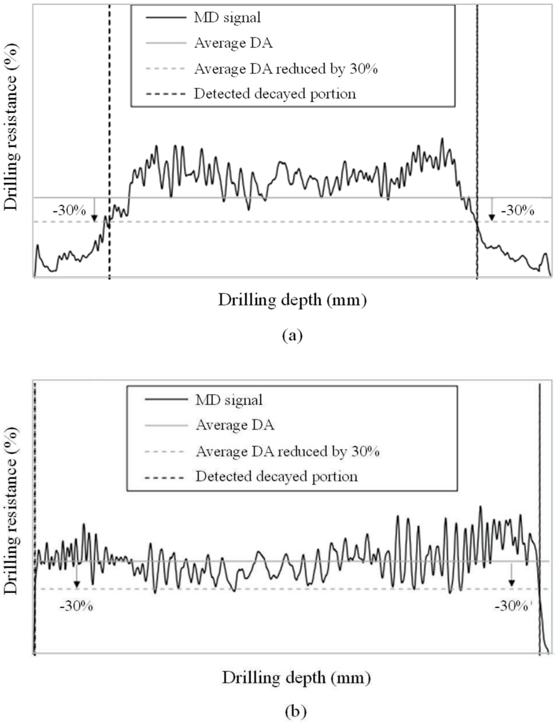
Then, the starting and ending sections of the signal portions identifying decayed areas were determined as the intersection between the average DA decreased by 30% and the MD profile [3] (Figure 4). This method has the advantage of detecting decayed areas relatively to the specific MD signal, without providing an absolute threshold in terms of DR. Finally, the independence from MC of the detected outer decayed portion was assessed.

2.2.4 Evaluation of MC gradient along the drilling depth (analysis at cross-sectional level)

After testing the segments in submerged conditions, the corresponding MC gradient along the drilling depth was determined as well [14], by retrieving five small prisms of dimensions 20×20×120 mm^3 (Figure 5). Sample 3 was taken in correspondence to the pith, whereas samples 1 and 5 included sapwood. These prisms allowed to detect the MC variations along the drilling depth: in this way, the influence of such variations on DR profiles could be evaluated for both sound and decayed pile segments.

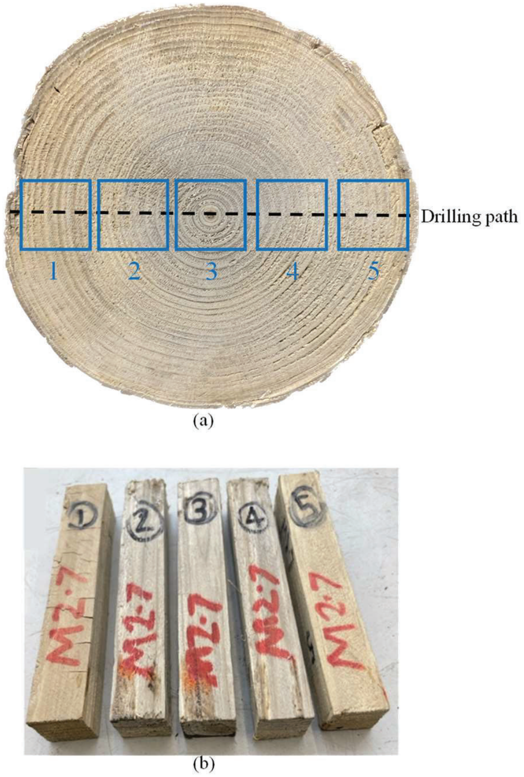
Sound sapwood is associated to a higher density, but also larger MC than heartwood, whereas in presence of decay the basic density is reduced due to bacterial degradation, and the MC locally increases further. Thus, this analysis allowed to check that MD signals retrieved in underwater conditions can still enable the distinction between sound and decayed sapwood, independently of MC gradients.



(a)

(b)

Figure 4: Procedure adopted for determining the degraded portion of the pile segments from MD signals, corresponding to low drilling amplitudes at the beginning and at the end. Examples are shown in the case of a heavily decayed pile (a) and a sound pile (b). Adapted from [3].



(a)

(b)

Figure 5: (a) Location of the samples taken to determine MC variations among sapwood, heartwood, and pith; (b) example of prisms retrieved from a pile segment along the drilling depth.

3 RESULTS

3.1 COMPRESSION TESTS

The 24 segments tested under compressive loading exhibited the values of compression strength $f_{c,0}$, wet density in submerged conditions ρ_w, and MC reported in Table 2.

A distinct drop in $f_{c,0}$ is observable for all pile segments from 1727, linked to large global MC values as well. Besides, as can be noticed, the wet density of such samples is comparable to that of piles from 2019: in combination with the large global MCs, this indicates a strong reduction of basic density due to bacterial decay for the pile segments from 1727. Such outcomes thus confirm the presence of biodegradation phenomena for the oldest piles, which were also detected with the MD measurements, as shown in the next section.

The other segments showed higher values of $f_{c,0}$, and closer to each other, suggesting that the extracted piles up to 1886 did not undergo significant decay. Only the 1886-2 segments exhibited lower compressive strengths, but these were also associated with low wet density and global MC.

Table 2: *Overview of the compressive strength of the tested pile segments after being submerged in water for two weeks; the corresponding wet density and moisture content is also reported. Samples with decay are reported in italic.*

Sample	$f_{c,0}$ (MPa)	ρ_w (kg/m^3)	MC of the segment (%)
2019-1-head	15.5	779	74
2019-1-middle	13.7	748	80
2019-1-tip	13.7	657	85
2019-2-head	20.1	767	72
2019-2-middle	16.4	675	73
2019-2-tip	17.3	670	81
1922-1-head	15.4	586	66
1922-1-middle	16.2	601	64
1922-1-tip	15.9	663	75
1922-2-head	16.9	750	81
1922-2-middle	16.3	702	77
1922-2-tip	15.4	818	76
1886-1-head	17.2	705	66
1886-1-middle	17.0	730	64
1886-1-tip	15.4	782	82
1886-2-head	11.5	553	77
1886-2-middle	12.3	703	87
1886-2-tip	7.2	625	98
1727-1-head	7.1	778	192
1727-1-middle	5.3	664	170
1727-1-tip	5.1	755	222
1727-2-head	6.1	770	197
1727-2-middle	4.1	648	179
1727-2-tip	5.8	784	139

3.2 MICRO-DRILLING MEASUREMENTS

Representative results from the 240 conducted measurements are shown in Figure 6 in terms of MD signals at different MC levels and TS.

In general, with the adopted drill and feed speed, it appears that a progressively lower drilling resistance is obtained when the moisture content increases. However, this does not influence the detection of specific features of a pile segment, such as denser sapwood for sound samples (Figure 6a-c), presence of an internal knot (Figure 6b), very low drilling amplitude when crossing outer decayed zones for the oldest pile segments (Figure 6d-e).

It is important to notice that this outer layer affected by decay and characterised by much lower drilling resistance could be detected, adopting the methodology described in Section 2.2.3, independently of the MC. This outcome, visible in Figure 6 for samples 1727-1-middle and 1727-2-head, was also obtained for all other segments from 1727, as shown in Table 3, reporting the detected decayed portions (calculated as average from those of each MD measurement-pair) as a function of the global MC of the segments.

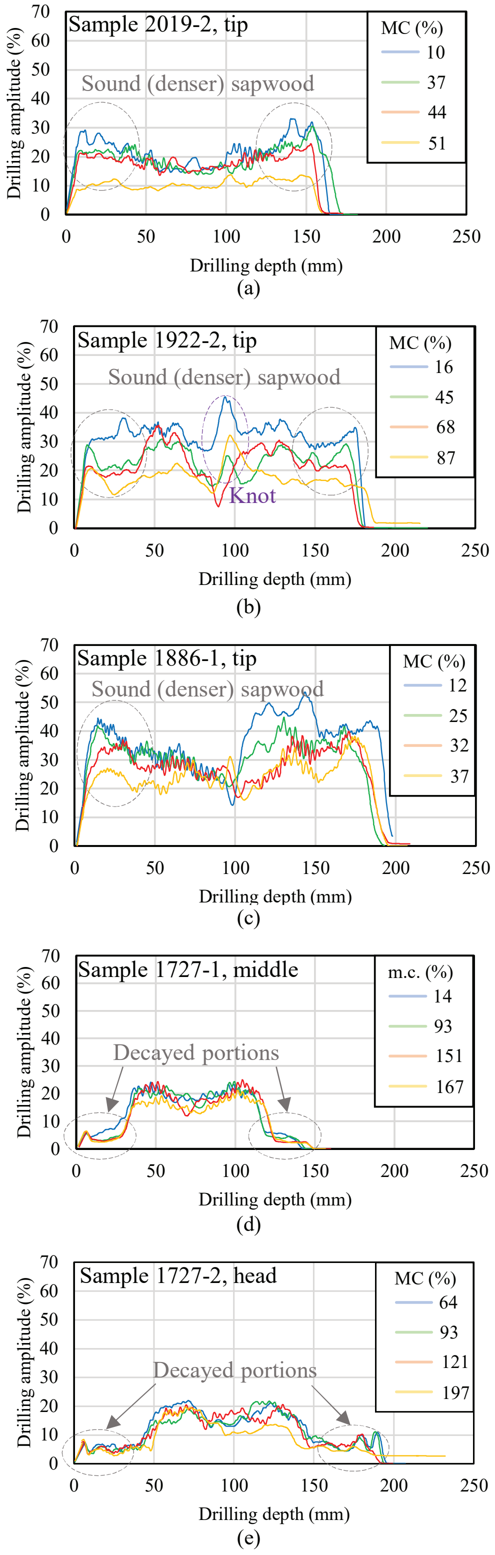


Figure 6: *MD signals (displayed in terms of a 100-mm moving average) ordered from lowest to highest MC for representative pile segments with TS = 2 years (a), 99 years (b), 135 years (c), and 294 years (d-e).*

Table 3: *Overview of the detected decayed portion, determined from the MD measurements according to the methodology presented in Section 2.2.3, as a function of MC for the 1727 samples.*

Samples with decay	Detected decayed portion (average from the two MD signals, mm)	MC of the segment (%)
1727-1-head	12	13
	10	94
	10	129
	9	153
	10	182
1727-1-middle	23	14
	25	93
	24	151
	24	167
	23	170
1727-1-tip	16	13
	17	88
	17	153
	17	188
	16	212
1727-2-head	40	64
	35	93
	36	107
	37	121
	36	197
1727-2-middle	34	105
	33	145
	36	164
	34	179
	35	184
1727-2-tip	24	84
	25	125
	26	139
	22	146
	26	175

As can be noticed, the zones of cross section affected by biodegradation phenomena only show small variations for different MC values (Table 3). This very limited scatter is unavoidable, as the MD measurements were conducted close to each other, but local variations along the drilling depth are very likely to be present.

The previous results referred to the MC of global segments, but they are also confirmed when examining at cross-sectional level the local MC gradients along the drilling depth (Figure 7). These MC gradients, determined with the five prisms retrieved from the cross sections of the segments (Section 2.2.4), show a typical profile, with larger MCs pertaining to the outer prisms (1 and 5 in Figure 5) containing sapwood.

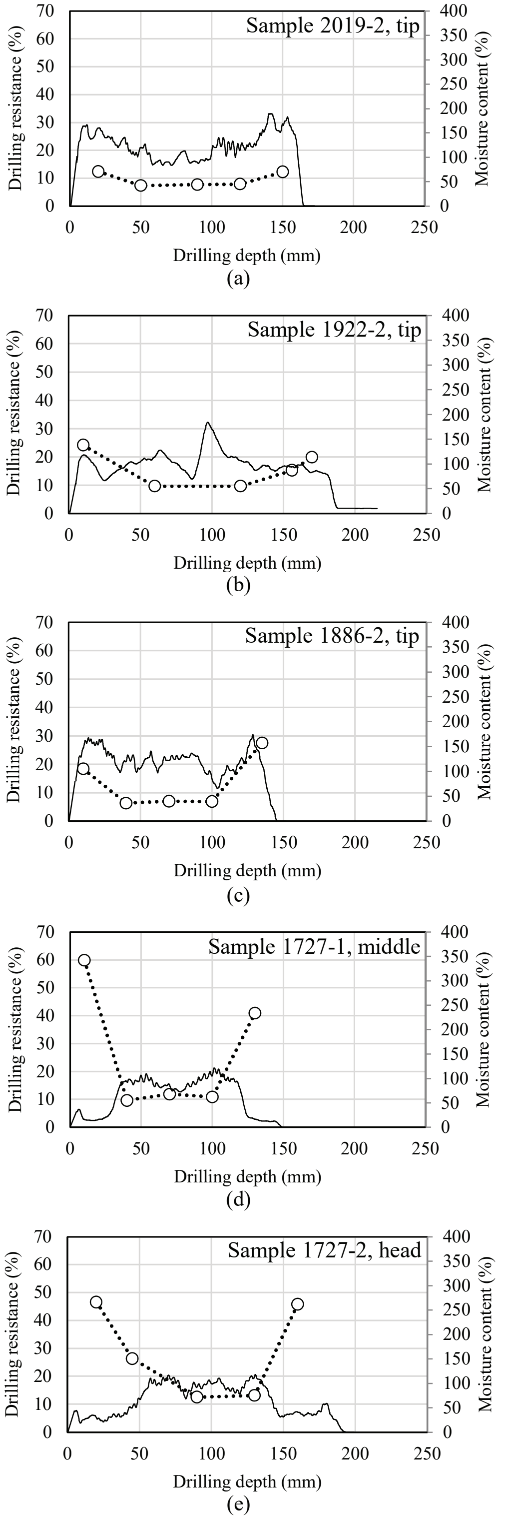


Figure 7: *Example of drilling resistance profile and MC gradient (dashed) for representative pile segments with TS = 2 years (a), 99 years (b), 135 years (c), and 294 years (d-e) in submerged conditions. For d-e, very large MC is observable in the decayed portions, which is not the case in sound samples.*

However, for sound cross sections (Figure 7a-c) the MCs range of prisms containing sapwood was 70–150%, whereas in decayed samples (Figure 7d), values up to 350% were determined.

On the contrary, when considering MCs of the heartwood and juvenile wood portions, these always fall in the range of 40–60%, also in the case of the decayed samples. This outcome is confirmed by the MD signals as well: the drilling resistance in the inner part of the cross section is in all cases close to 20%; for sound sapwood the larger amplitude correctly corresponds to its larger density, whereas in presence of decay a large drop in the drilling resistance is observed.

4 DISCUSSION

Based on the obtained results, it appears that MD signals can reliably identify decayed portions and their extent along the drilling depth independently of the MC (see once more Figure 6d-e). This outcome is relevant, since the determination of the actual MC of a large number of piles on site would not be practically feasible.

Furthermore, the distinction between sound and decayed parts of the cross section is also possible when comparing MD signals with the MC gradients determined in submerged conditions. All sound samples showed MC gradients in line with those expected for green spruce (around 50% in heartwood and 120% in sapwood [16]), confirming the results from MD signals and compression tests. Biodegradation phenomena seemed therefore to be limited to sapwood, since the heartwood and juvenile wood of the decayed pile segments featured MC and DR values comparable to those of the sound specimens (Figure 7).

Thus, the highly decayed portions of the degraded pile segments could be correctly identified with MD measurements, and were coherent with the low compressive strength obtained for these samples (see once more Table 2). Since the signals reported in Figure 7 refer to submerged conditions, it can be concluded that when performing MD measurements underwater, the specific features of the cross sections of the wooden foundation piles can be correctly captured, and independently of the MC gradient.

5 CONCLUSIONS

This work presented an extensive study to evaluate the underwater use of micro-drilling (MD) measurements for assessing the state of wooden foundation piles. In particular, the influence of their moisture content (MC) in the identification of largely decayed portions was evaluated for piles retrieved from the historic city centre of Amsterdam.

Thus, 24 pile segments having time in service (TS) from 2 years to 294 years were subjected to 240 MD measurements at various MC values, ranging from 7% to 212%. Compression tests were also performed on the segments after submerging them under water for two weeks, to determine their load-carrying capacity and compressive strength. These tests also allowed to confirm the decayed pile segments identified with MD measurements, for which a much lower compressive strength and a larger MC were determined.

For the adopted drill and feed speed, a decreasing drilling resistance with increasing MC was detected. Since in practice the on-site MD measurements would be conducted underwater by divers, the MC of the piles is in principle unknown. Yet, it has been proved that the detection of specific features or decayed portions of the cross section through the drilling profiles is not influenced neither by the global MC of a segment, nor by the MC gradient within its cross section. Thus, based on the obtained results, biological degradation phenomena can be reliably identified with MD signals also in underwater conditions, where it is not necessary to know the exact MC.

The results of this study can be further integrated with the data from the in-progress experimental campaign on additional pile segments, and can contribute to the research framework supporting the use of non-destructive testing for estimating decay, (residual) load-carrying capacity, and remaining service life of wooden foundation structures.

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REFERENCES

[1] J.W.G. van de Kuilen, O. Beketova-Hummel, G. Pagella, G.J.P. Ravenshorst, W.F. Gard. An integral approach for the assessment of timber pile foundations. Paper 597, *World Conference on Timber Engineering*, Santiago, Chile, 2021.

[2] G. Pagella, M. Mirra, G.J.P, Ravenshorst, J.W.G. van de Kuilen. Influence of knots and density distribution on compressive strength of wooden foundation piles. In *Current Perspectives and New Directions in Mechanics, Modelling and Design of Structural Systems*, 2022.

[3] G. Pagella, G.J.P. Ravenshorst, W.F. Gard, J.W.G. van de Kuilen. Characterization and assessment of the mechanical properties of spruce foundation piles retrieved from bridges in Amsterdam. *4th International Conference on Timber Bridges*, Biel, Switzerland, 2022.

[4] J.W.G. van de Kuilen. Service life modelling of timber structures. Mater. Struct. 40(1):151-161, 2007.

[5] T.P. Nowak, J. Jasieńko, K. Hamrol-Bielecka. In situ assessment of structural timber using the resistance drilling method – Evaluation of usefulness. *Constr. Build. Mater.* 102:403-415, 2016.

[6] R. Klaassen. Bacterial decay in wooden foundation piles—Patterns and causes: A study of historical pile

https://doi.org/10.52202/069179-0530

foundations in the Netherlands. *Int. Biodeterior. Biodegradation* 61:45-60, 2008.

[7] A.P. Singh, Y.S. Kim, T. Singh, Chapter 9 - Bacterial Degradation of Wood, *Secondary Xylem Biology*:169-190, 2016. ISBN 9780128021859, https://doi.org/10.1016/B978-0-12-802185-9.00009-7.

[8] E. Sharapov, C. Brischke, H. Militz, E. Smirnova. Combined effect of wood moisture content, drill bit rotational speed and feed rate on drilling resistance measurements in Norway spruce (Picea abies (L.) Karst.). *Wood Mater. Sci. Eng.* 15:198-204, 2018.

[9] C.-J. Lin, S.-Y. Wang, F.-C. Lin, C.-M. Chiu. Effect of moisture content on the drill resistance value in Taiwania plantation wood. *Wood Fiber Sci.* 35:234-238, 2003.

[10] J. Jaskowska-Lemańska, E. Przesmycka. Semi-Destructive and Non-Destructive Tests of Timber Structure of Various Moisture Contents. *Materials* 14, 2021.

[11] https://pixers.nl/fotobehang/zwart-wit-amsterdam-city-map-72351719. URL last accessed on 8th March 2023.

[12] EN 14251. Structural round timber - Test methods, CEN, Brussels, Belgium, 2003.

[13] EN 384. Structural timber – Determination of characteristic values of mechanical properties and density. CEN, Brussels, Belgium, 2016.

[14] EN 13183-1. Moisture content of a piece of sawn timber - Part 1: Determination by oven dry method. CEN, Brussels, Belgium, 2002.

[15] EN 408. Timber structures - Structural timber and glued laminated timber - Determination of some physical and mechanical properties. CEN, Brussels, Belgium, 2010.

[16] S.V. Glass, S.L. Zelinka. Moisture Relations and Physical Properties of Wood. *Wood Handbook – Wood as an Engineering Material*. United States Department of Agriculture, 2010.