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Characterization and assessment of the mechanical properties of spruce foundation piles retrieved from bridges in Amsterdam

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Abstract

Many bridges in Amsterdam are based on timber pile foundations due to the presence of weak soils, where timber piles have proven to be a very good and economic solution over the years. However, aging of the foundations, which can be up to 500 years, implies several challenges for the assessment of the current load carrying capacity and subsequent reliability of bridges. For piles completely below the water table, bacterial decay can occur. Based on the analysis of drill cores retrieved from piles under foundations, the city of Amsterdam concluded that this problem required a more in depth investigation to obtain reliable predictions of the remaining service life of timber foundations. Therefore, 12 spruce (*picea abies*) piles were extracted from foundations of two demolished bridges. Pile segments were sawn from each full-length pile, representing head, middle-part and tip of the pile, and tested in compression in saturated condition. Besides that, micro-drilling measurements were performed to investigate whether the decayed part of a cross section could be predicted with these measurements. On the basis of the results from micro-drilling, the pile segments could be divided in sound and decayed. A soft shell was estimated and the sound remaining cross section was determined for every segment. The load bearing capacity was assigned to the sound remaining cross section and approximately the same stiffness and strength could be observed for the sound parts of both the decayed and sound group. From the 12 assessed whole piles, 6 were assigned to sound and 6 to decayed group. However, also the decayed piles resulted to have a remaining load-bearing capacity. This indicates that for the final assessment of timber pile foundations of a bridge, detailed information about the distribution of decayed piles in relation to the load distribution has to be taken into account. The use of micro-drilling measurements gives promising results to predict the level of decay, and their application could be used for in-situ assessment of wooden piles.

1 Introduction

Many historic bridges in Amsterdam, The Netherlands, are founded on timber piles, but also in cities like Venice [1], Amsterdam, Hamburg, Boston and many others, similar timber foundations can be found. Service life analysis of bridges is complicated [2], since in order to assess the reliability and safety of a bridge, an in-depth analysis of the timber pile foundations is required. A reliable assessment of a bridge is of importance because of the implication on the economic activities in the city. Closing down bridges due to eventual failure of the foundations can cause considerable economical losses [3]. In particular, the city of Amsterdam has many bridges built on wooden foundation piles, which have been in service up to 500 years, and widespread due to their relative cost-efficient application [4]. Given the specificity of the problem, when it comes to characterization and assessment of existing timber foundations, there are many aspects that have to be taken into account; these include analysis of material conditions, age of the structure, assessment of the mechanical properties of wood, inspection techniques and biological degradation [5], [6]. Therefore, the quality of the entire foundation has to be analyzed starting with an assessment of the current state of the timber piles, from both a mechanical as well as a material point of view. Since in Amsterdam the timber piles remain entirely under the water table, the possible degradation is attributed only to bacterial decay, excluding the presence of fungal decay. In order to assess the state of wooden piles with respect to bacterial decay, the current practice in the Netherlands adheres to the F3O guidelines [7] and Dutch standard NEN 8707 [8]. According to these guidelines, drill cores with a diameter of approximately 9 mm and a length of half the pile diameter, are taken under water from the head of the pile. Subsequently, the drill cores are cut in sub-sections and viewed under a microscope to determine the degree of bacterial decay, and then used to determine the maximum achievable moisture content. Using the model from Klaassen

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(2008) [9], the compressive strength is estimated from the maximum achievable moisture content. Every subsection with a calculated compression strength lower than 8 N/mm^2 (which was arbitrarily chosen) is defined as being part of a so-called soft shell, to which no strength is assigned. The load bearing capacity of the remaining cross section is then calculated with the compression strength for new piles as determined by van de Kuilen [10] on a limited dataset. Based on the result of a large amount of drill cores retrieved from piles under bridges in Amsterdam, it emerged that a large number of wooden piles could be affected by bacterial decay. However, many uncertainties have to be taken into account, since the model from [9] was calibrated on limited data, based only on pine specimens, and only related to strength values of small specimens. In the light of this, the municipality of Amsterdam decided to set up a research project in which timber piles were retrieved from bridges that were planned to be demolished and replaced. The objectives of this project are:

- The investigation of the material properties of full-size specimens, to gain insight into the remaining strength properties, and the effect of decay on these properties.
- The investigation of the micro-drilling resistance technique for under-water use, as an alternative to the extraction of drill cores, to determine if these measurements could give a more reliable prediction of the soft shell.

To this end, this paper presents the results of the first investigation of timber pile foundations conducted on 12 spruce piles retrieved from two bridges in Amsterdam.

2 Materials and methods

2.1 Materials

In this paper the first results of a large experimental program was presented. This involved the assessment of the mechanical properties of 12 spruce (*picea abies*) foundation piles, driven in 1727, 1886 and 1922. The specimens were retrieved under different locations from the foundation of two bridges that were demolished in the city of Amsterdam (Bridge 30 and 41). The full-length specimens were ranging from 9500 mm to 13500 mm, with an average head diameter of 230 mm and average tip diameter of 145 mm. After in-situ preliminary tests, the full-length piles were subdivided in three parts: head, middle-part and tip, according to the procedure explained in section 2.2.1. From each of the 3 parts of the pile, a segment was sawn for the compression test, depending on the diameter of the average cross-section. The wood species, spruce in this case, was an important aspect to consider, since previous research investigated the properties of pine piles, which have a different distribution of sapwood. However, wooden piles in Amsterdam can be from either pine or spruce species, where, even if always below the water table, the transportation of bacteria through the cross-section could be different depending on the amount of sapwood. Thus, bacterial decay could cause a faster or slower degradation of the material depending on the species but also on different parts of the pile, where its severity had to be analyzed from the head to the tip of a pile, as the tip generally has a larger portion of juvenile wood, and consequently proves to be more vulnerable [11].

2.2 Methods

2.2.1 Mechanical testing

After the extraction of the wooden piles, in-situ preliminary tests were conducted on the 12 full-length specimens at the storage location of the municipality of Amsterdam. All piles were labelled and enumerated by dimensions and weight. At the same time, the dynamic modulus of elasticity parallel to the grain ($MOE_{dyn,wet}$) was evaluated through acoustic frequency response measurements. The $MOE_{dyn,wet}$ was calculated with Equation 1.

$$MOE_{dyn,wet} = 4\,\rho\, f^2\, l^2 \qquad (1)$$

where ρ = wet density; f = frequency; l = length of the specimen. After these preliminary tests, the specimens were subdivided in three parts: head, middle-part and tip, approximately 4000 mm long, and stored underwater in a container until shipping to the TU Delft was possible. Subsequently, the container was emptied out and the specimens were transported to the TU Delft laboratory for the assessment of the current mechanical properties by mechanical testing. From each of the three parts of the pile, a segment was sawn for the compression test, which length depended on the diameter of the average cross-section. Three categories of length were established: 900 mm, 1350 mm and 1800 mm, according to the standards EN 408 [12] and

EN 14251 [13], which prescribe an axial length of six times the smaller diameter of the cross section for a pile. The cutting procedure was performed with a laser placing system to get the pile in the straight position. After this, a frame-guided chainsaw was used to obtain a parallel plan on the ends, with a laser line indicating the exact position of the cut. Directly after the cut, the moisture content value was determined according to the standard EN 13183 [14] by cutting two 30-mm-thick discs from each side of the selected segment. The discs were dried at a temperature of 103 °C, until a constant mass was achieved. During this process, the moisture content (m.c.) was determined by oven-drying i.e. from the ratio between wet and dry mass. The dry and the wet masses of each pile segment were linked to this moisture content value, therefore any variation of the wet mass of the pile could be related with a dry mass and consequently a precise moisture content value could be estimated. The pile segments were weighted and subsequently submerged for approximately 30 days to achieve the water-saturated condition for the compression test, for aiming a moisture content higher than 70%. Before running full-scale mechanical testing on the pile segments, the specimens were taken out of the water, and the density of each pile was measured by determining volume and wet mass (EN 384 [15]). From this wet mass, the moisture content was calculated. Mechanical testing was performed to determine the short-term strength ($f_{c,0,wet}$) and the static modulus of elasticity ($MOE_{stat,wet}$). In this test campaign, the mechanical properties of 36 pile segments were determined. To this end, a displacement controlled set-up was used (Fig. 1), based on the standards EN 408 and EN 14251, where the specimens were subjected to an axial load in direction parallel to the fibers. The displacement between the two steel plates was monitored with four linear potentiometers placed on four edges of the top plate and connected to the bottom plate. The direct deformation on the specimens was measured with six linear potentiometers screwed on the surface of the piles: four of them were placed on each side of the pile, 90 degrees from each other, with a variable length equal to two-thirds of the length of the specimen; the other two sensors were placed on a knot and on a clear-wood part, in order to evaluate the deformation with and without the influence of a knot. The length of these last two sensors was set at 200 mm. Given the short stroke of the six sensors placed on the pile, they were removed before the peak load to avoid damages. In addition, a hinge, mounted on a steel plate, was placed on top of the specimen to have an uniformly distributed compression load on the pile. The compression test was carried out at a constant speed of 0.02 mm/s until the peak load was reached. The specimens were loaded to failure and the displacement was increased at higher speed until the cracks were visible. This was done to investigate the failure mechanism of water-saturated pile segments.

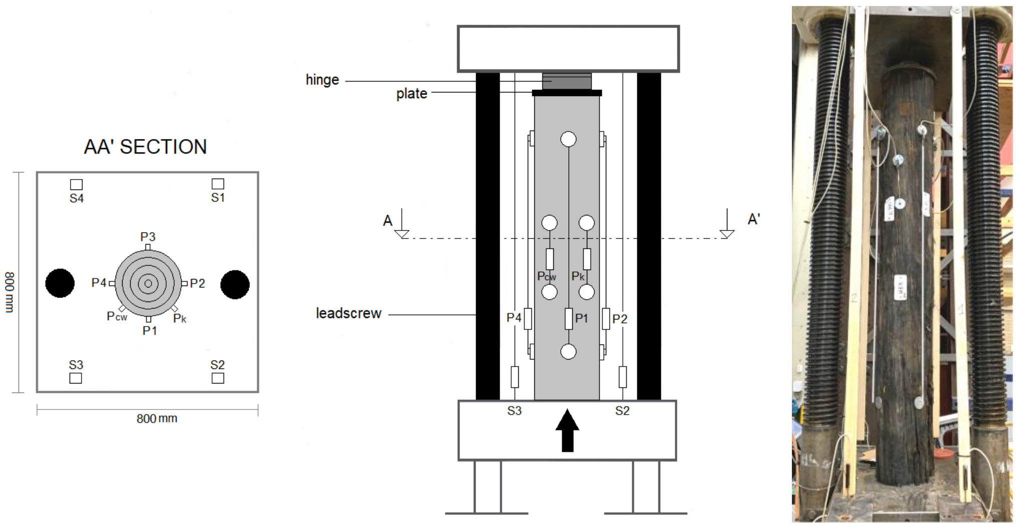

Figure 1: Set-up for mechanical testing of pile segments.

At the end of the test, the global behaviour of the pile was studied with the average stress-displacement curve of four linear potentiometers connected to the compression test machine (Fig. 2a), from which the compressive strength ($f_{c,0,wet}$) was calculated with the ratio between the maximum force, corresponding to the peak of force-displacement curves, and the average cross-sectional area of the pile. The static modulus of elasticity ($MOE_{stat,wet}$) was calculated in Equation 2, with the ratio between stress variation ($\Delta\sigma$) and strain variation ($\Delta\varepsilon$), between 10% and 40% in the slope of the linear elastic portion of the stress-strain curve, resulting from the four linear potentiometers attached on the pile (Fig. 2b).

$$MOE_{stat,wet} = \Delta\sigma/\Delta\varepsilon = (\sigma_2 - \sigma_1)/(\varepsilon_2 - \varepsilon_1) = (\Delta F/\Delta L)/(L_0/A_r) \quad (2)$$

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where $\Delta\sigma$ = stress variation between σ_2 and σ_1; $\Delta\varepsilon$ = strain variation between ε_2 and ε_1; ΔF = force variation between $F_2 = 0.4\ F_{max}$ and $F_1 = 0.1\ F_{max}$; ΔL = deformation variation corresponding to points F_2 and F_1; L_0 = length of the linear potentiometers (2/3 of the length of the pile segment); A_r = average cross-sectional area of the pile. At the moment of the test, all the specimens were above fiber saturation, with an average moisture content higher than 70%. In order to study the expected failure mechanisms, the displacement was kept after the peak load reached during compression tests. In general, the failure mechanisms were reported considering a global failure for crushing (Fig. 3a) and a local failure for buckling (Fig. 3b) related to local defects such as knots.

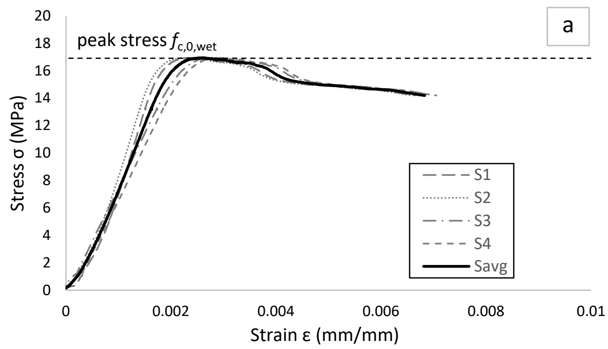

Figure 2: Example of axial compression tests of a water-saturated pile segment: a) global behaviour of the pile with stress-strain curves measured by S1, S2, S3, S4; b) stress-strain curves measured by P1, P2, P3, P4 to determine $MOE_{stat,wet}$.

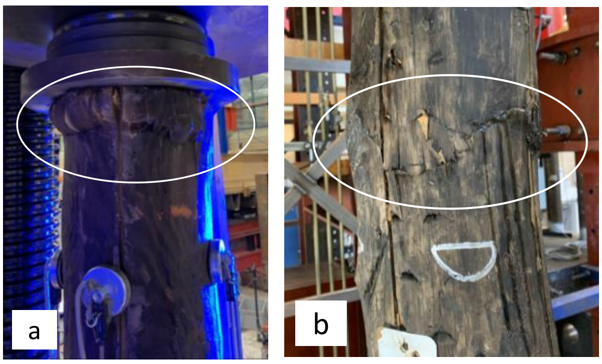

Figure 3: Failure mechanisms of a water-saturated spruce pile in compression: a) crushing; b) localized buckling.

2.2.2 Micro-drilling resistance measurements

Micro-drilling measurements fall within the non-destructive techniques used for wood inspection, commonly used for trees or electrical poles. From the measurements, it is possible to obtain a resistance profile which can give information about the annual rings of a tree and the density of the investigated section [16]. In Amsterdam, micro-drilling was initially used as an innovative inspection method to assess the level of degradation, by performing underwater measurements on the head on wooden foundation piles which were in the soil and completely under the water table. However, a drilling measurement on the head of the pile was not sufficient to predict the status of the material along the length. Therefore, in this study, a IML-RESI PD 400 tool (Fig. 4) was used to assess the level of degradation, performing micro-drilling measurements in different cross-section along the length of 12 extracted wooden foundation piles. For under-water measurements on piles under the bridges, the machine was adjusted by the manufacturer. The acquired data is used to investigate the feasibility to predict the decay in different parts of the pile. The comparison between the measurements carried out in-situ and those performed on extracted specimens is not presented in this paper, since in-situ micro-drilling belongs to a running project that will be subsequently reported. Thus, for the research conducted in this paper, only the IML tool for above-water measurements was used. The measurements were performed in the TU Delft laboratory, allowing to estimate the soft shell by micro-drilling on heads, middle-parts and tips of all the investigated piles. In this way, the decay level along the length of each pile could be studied.

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Figure 4: Micro-drilling measurements: a) underwater measurements on wooden piles; b) measurements after piles extraction.

Figure 5: Micro-drilling measurements performed on a pile segment before the compression test.

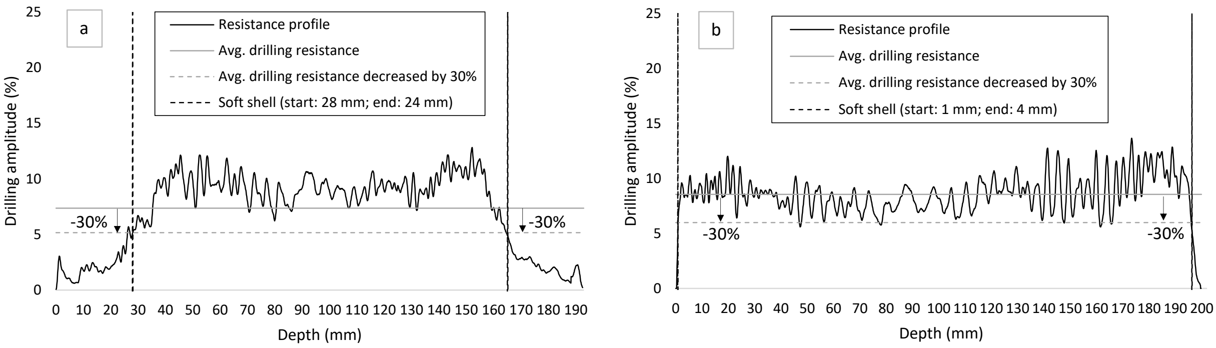

Figure 6: Resistance profile from micro-drilling measurements of a cross section of 2 different pile segments and procedure for the calculation of the soft shell: a) old decayed cross-section; b) old sound cross-section.

During micro-drilling, a drilling needle is pushed into the cross-section with a drill speed of 2500 r/min and a feed speed of 150 cm/min. The drill bit used for the measurements is 400 mm long, with a thin shaft of 1.5 mm in diameter and a 3.1 mm wide triangular shaped cutting part, with hard chrome coating. The acquired data, recorded every 0.1 mm of the drilling depth, was plotted as resistance vs distance, resulting in a wave plot in which amplitude displacements coincided with changes in density and moisture content [17], [18]. Once the 12 piles were subdivided in segments, two micro-drilling measurements were performed through the cross-section of each segment, approximately 90 degrees to each other and 300 mm from the head of the specimen (Fig. 5). These measurements were performed before testing the specimens in compression, therefore it was possible to inspect the material status right before the test. The resistance profile (Fig. 6) was obtained from putting together the two drilling measurements performed through the cross section. By observing the resistance profile, it was possible to distinguish the annual rings, with maximum amplitudes, corresponding to latewood rings, and minimum amplitudes, representing early-wood. Isolated peaks or lower values could be observed in resistance profiles, on the one hand caused by wood knots and other high-density anatomical variations of the material, on the other hand caused by piths and cracks in the cross-section. The possible decay in the cross-section was estimated on the basis of a new definition of the soft shell, defined as the outer decayed layer of the cross section. To this end, an average drilling resistance was determined from the resistance profile. The starting and ending point of the soft shell was manually calculated with the intersection between the average drilling resistance decreased by 30%

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and the resistance profile (Fig. 6a). A cross section of a pile was considered as decayed when the soft shell was >15% of the full cross section; it was instead considered sound when the soft shell resulted to be <15% of the full cross section (Fig. 6b). With this method, two categories were established: old sound pile segments and old decayed pile segments, based on the remaining sound cross-section, measured after subtracting the soft shell area to the total cross-sectional area. Pile segments were defined as: old sound piles when the remaining average sound cross-section was higher than 85% of the total cross-section; old decayed piles when < 85%. In order to compare the mechanical properties of old sound and decayed pile segments, an $MOE_{stat,sound}$ and $f_{c,0,sound}$ were calculated with the ratio between the measured $MOE_{stat,wet}$ and $f_{c,0,wet}$ of the segments and the percentage of remaining average sound cross-sectional area, respectively. With these two parameters it was possible to compare if the mechanical properties were correlated with the micro-drilling measurements, and understand if micro-drilling could be used as a predictor for decay. It should be noticed that micro-drilling is a local measurement, thus it can happen that the soft shell measured in a cross section may vary if measured in other positions over the length of the specimen. In order to minimize this effect, all the micro-drilling measurements were performed in positions without visible defects or irregularity of the material.

3 Results

3.1 Basic material properties

Prior to testing, the 12 full-length piles were retrieved from bridge 30 and 41 and tested at the storage location of the municipality of Amsterdam to estimate the basic material properties. Table 1 shows the results of the preliminary tests, listing the 12 full-length specimens by original code and the year in which they were driven in the soil. Each specimen was characterized by dimensions, mass, wet density, and $MOE_{dyn,wet}$ which was determined through frequency response measurements.

Table 1: Material properties of 12 full-length spruce (picea abies) piles tested after the extraction under bridge 30 and 41 in Amsterdam.

Pile ID	Year	Length (mm)	Mass (kg)	Avg. Φ (mm)	Wet density (kg/m³)	$MOE_{dyn,wet}$ (MPa)
BRU0030-PL1 P1.6	1727	9940	147	157	765	8840
BRU0030-PL1 P1.20	1886	10580	250	212	665	13790
BRU0030-PL1 P2.13	1727	10400	156	153	815	15530
BRU0030-PL1 P3.2	1886	11270	378	221	875	10120
BRU0030-PL2 P2.19	1727	9470	197	169	920	7050
BRU0030-PL2 P2.21	1727	10030	183	173	775	5850
BRU0041-PL1 P1.33	1922	13460	363	235	620	11620
BRU0041-PL1 P3.36	1922	13270	297	208	660	9840
BRU0041-PL2 P1.24	1886	13580	283	197	680	10130
BRU0041-PL2 P1.25	1886	12560	260	200	660	8890
BRU0041-PL2 P1.9	1922	11420	318	226	695	11220
BRU0041-PL2 P3.12	1922	11960	300	213	700	7540

3.2 Mechanical characterization of pile segments in relation to decay

The mechanical properties of 36 pile segments, divided in head, middle-part and tip, were characterized in relation to the level of decay estimated with micro-drilling measurements. The load-displacement behaviour of the water-saturated spruce specimens during the compression test was linear up to approximately 80% of the maximum compression load ($F_{c,0,max}$). Out of linearity, a nonlinearity phase was visible until peak load. When softening started, the load gradually decreased showing a quasi-plastic load plateau. In more than 70% of the cases, a failure mechanism for local buckling was observed, where cracks generally started in a section with presence of knots. For the other cases, a failure for crushing was detected, occurred mostly in the top part of the pile, and it was typically observed in pile segments without knots or with knots with diameters lower than 10 mm. The average values of $MOE_{stat,wet}$ and $f_{c,0,wet}$ for the head, middle-part and tip of each pile, were subdivided in two macro categories on the basis of remaining sound cross-section: old sound and old decayed piles (Tab. 2).

Table 2. Mechanical characterization of 36 water-saturated old sound and decayed pile segments tested in compression in relation to the remaining sound cross section determined with micro-drilling measurements.

Material status	Pile segments (number of specimens)	$MOE_{stat,wet}$ (MPa)		$f_{c,0,wet}$ (MPa)		Avg. sound cross-section (%)		$MOE_{stat,sound}$ (MPa)	$f_{c,0,sound}$ (MPa)
		Avg.	SD	Avg.	SD	Avg.	SD	Avg.	Avg.
Old sound	Head (9)	9850	1700	13.8	2.3	95	8	10370	14.5
	Middle-part (8)	9400	2250	13.2	2.1	98	7	9590	13.5
	Tip (5)	8450	2450	11.3	3.4	93	7	9090	12.1
	All segments (22)	9350	2050	13.0	3.0	95	7	9840	13.7
Old decayed	Head (3)	7950	700	9.1	1.8	78	6	10200	11.7
	Middle-part (4)	5400	1550	7.8	2.5	59	11	9150	13.2
	Tip (7)	5600	2350	8.6	3.1	57	14	9820	15.1
	All segments (14)	6050	2050	8.5	2.6	62	14	9760	13.7

More than 60% of the specimens were categorized as old sound material, with a soft shell <15% of the full cross section. Less than 40% of the specimens were classified as old decayed with a soft shell between 15% and 65%. However, only in six piles severe decay was observed, with an average remaining sound cross section lower than 50%. In case of old decayed specimens, it could be observed that the heads of the pile presented an average sound cross-section of 78%, while for middle-parts and tips a lower sound cross-section of 58% was estimated. Besides, the specimens not affected by decay were divided in: 75% heads, 65% middle-parts and 40% tips. This aspect indicates that decay increases progressively from the head to the tip of the pile, possibly because of the progressive decrement of diameter along the pile due to its tapered shape. The calculated values of $MOE_{stat,sound}$ are comparable for head, middle and tip parts of sound and decayed segments. For $f_{c,0,sound}$ this correlation is less clear when looking to head, middle and tip parts, but for all segments the calculated values for sound and decayed wood are similar. Although a more detailed analysis has to be performed. A first conclusion is that micro-drilling measurements have a high potential in the assessment of the level of decay of wooden piles.

3.3 Correlation between compressive strength and static modulus of elasticity

The compressive strength $f_{c,0,wet}$, obtained testing 36 pile segments in compression, was compared with the static $MOE_{stat,wet}$ (Fig. 7a). Heads and middle-parts of the full pile, which often presented a higher diameter and less decay, resulted in a value of $f_{c,0,wet}$ between 10 MPa and 17 MPa, which corresponded to a $MOE_{stat,wet}$ ranging from 7000 MPa to 13000 MPa. In the research of van de Kuilen [10] a mean value of 20 MPa with a standard deviation of 2.2 MPa was found for pile heads of new spruce piles, slightly higher than the values for the sound old piles. However, the research in [10] will be validated on a new series of tests on new piles. The tips of the pile, characterized by a smaller diameter and a higher level of degradation, presented a significant decrease both in strength and stiffness. A good correlation ($R^2 = 0{,}9$) can be observed between $MOE_{dyn,wet}$ and $MOE_{stat,wet}$ (Fig. 7b), proving that frequency response measurements can reliably estimate the modulus of elasticity of a wooden pile. Also the good correlation between $f_{c,0,wet}$ and $MOE_{stat,wet}$ (see again Fig. 7a) could be used to have a good prediction of the compressive strength once the $MOE_{stat,wet}$ or $MOE_{dyn,wet}$ is known. Especially the correlation between $MOE_{dyn,wet}$ and $f_{c,0,wet}$ could have in-situ practical implications potential, where by obtaining the $MOE_{dyn,wet}$ from acoustic measurements on the head of the pile, the compressive strength could be estimated.

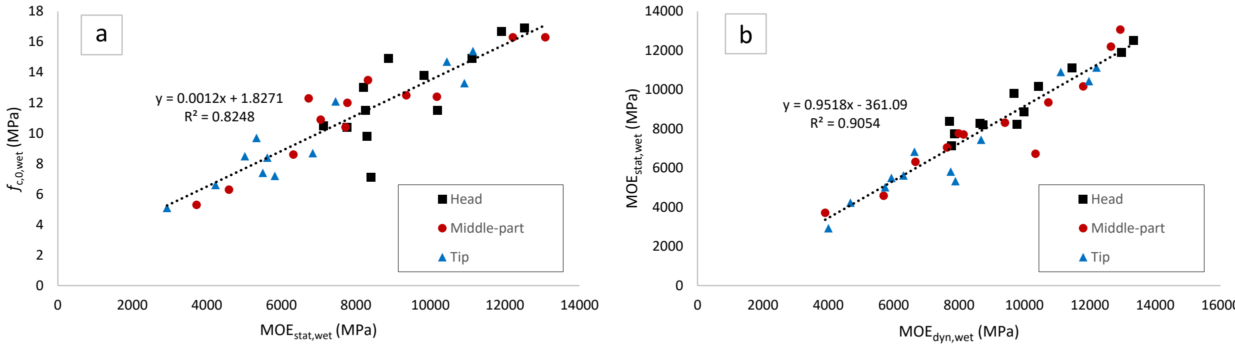

Figure 7: Correlation between: a) $f_{c,0,wet}$ and $MOE_{stat,wet}$; b) $MOE_{stat,wet}$ and $MOE_{dyn,wet}$ of 36 water-saturated spruce pile segments divided in head, middle-part and tip.

3.4 Correlation between wet and dry density, moisture content and mechanical properties

Dry and wet densities of 36 pile segments are presented in relation to moisture content values, to investigate whether the moisture content differs for decayed segments which have been submerged for the same period of time. The moisture content values were subdivided in two categories, again based on old sound and decayed material. Table 3 lists the average wet density (water-saturated condition) and dry density (at m.c. of 0%), by dividing the specimens in head, middle-part and tip. It can be observed that the average dry density value for old sound piles was 350 kg/m³. For old decayed pile segments, an average dry density of 310 kg/m³ was calculated. The decrease of density could be attributed to the lower density of the soft shell. An average m.c. of 90% was determined for old sound specimens and an average m.c. of 120% for old decayed specimens, therefore indicating that a higher moisture content is associated to a higher level of decay. Wet and dry densities of each pile segment were compared with $MOE_{stat,wet}$ and $f_{c,0,wet}$ in Figure 8 and 9. A correlation was found between dry density and $MOE_{stat,wet}$ ($R^2 = 0.42$), (Fig. 8b), and between dry

Table 3. Wet and dry densities in relation to moisture content of 36 water-saturated pile segments divided in head, middle-part and tip after the same period of submersion.

Material status	Pile segments (number of specimens)	Wet density (kg/m³)		Dry density at 0% of m.c. (kg/m³)		Moisture content (%)	
		Avg.	SD	Avg.	SD	Avg.	SD
Old sound	Head (9)	630	70	350	37	80	16
	Middle-part (8)	650	62	350	32	85	12
	Tip (5)	700	80	350	75	110	30
	Full pile (-)	650	72	350	45	90	20
Old decayed	Head (3)	670	95	310	36	125	60
	Middle-part (4)	650	50	300	38	120	38
	Tip (7)	700	67	320	51	125	52
	Full pile (-)	680	65	310	42	125	46

density and $f_{c,0,wet}$ (R^2 = 0.49), (Fig. 9b). It was not possible to find a correlation between wet density, $MOE_{stat,wet}$ and $f_{c,0,wet}$, since in each specimen the moisture content constantly changes. Similar dry densities were not always associated with the same value of $MOE_{stat,wet}$ and $f_{c,0,wet}$, since the density of a wooden pile could be affected by the natural variation between juvenile wood and mature wood along the length of the pile itself. In tips, a lower density was observed, due to a larger presence of juvenile wood. Moreover, it is often difficult to distinguish from a pile with lower density caused by degradation phenomena or a pile with lower density given by a large presence of juvenile wood. Therefore, further research will be carried out in order to minimise the variability of the data with the goal to obtain a higher correlation between dry densities and the mechanical properties of wooden piles.

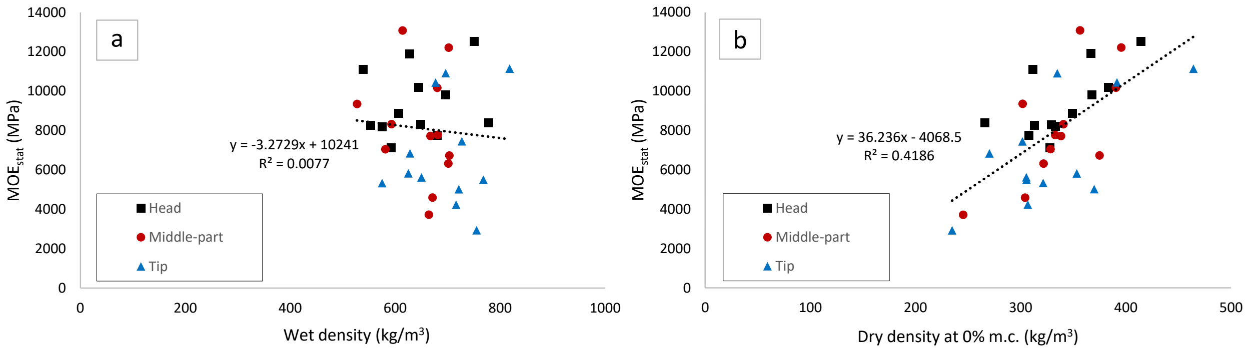

Figure 8: Correlation between: a) $MOE_{stat,wet}$ and wet density; b) $MOE_{stat,wet}$ and dry density (at 0% of m.c.), of 36 pile segments divided in head, middle-part and tip.

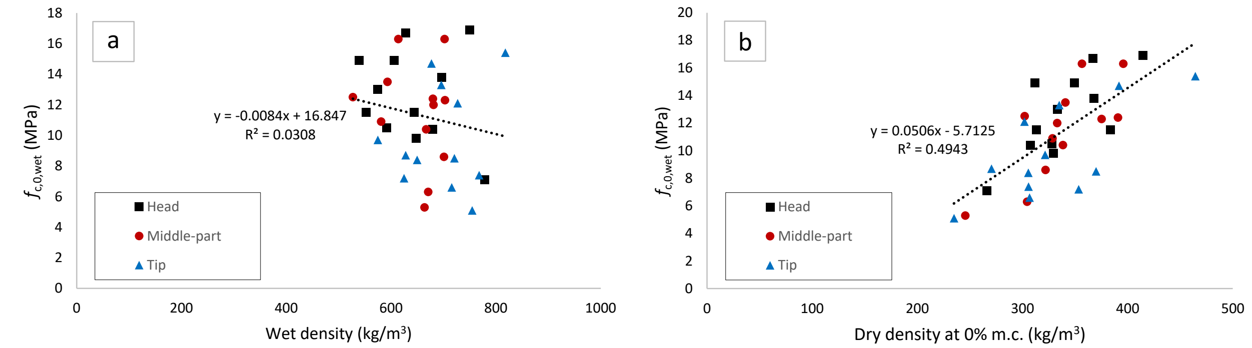

Figure 9: Correlation between: a) $f_{c,0,wet}$ and wet density; b) $f_{c,0,wet}$ and dry density (at 0% of m.c.), of 36 pile segments divided in head, middle-part and tip.

4 Conclusions

The mechanical properties of existing spruce foundation piles retrieved from two demolished bridges in Amsterdam were studied. The study had two objectives: the first was to investigate the material properties of full-size water saturated piles, in order to gain insight in the remaining strength properties and the effect that bacterial decay could have on these properties; the second one was to investigate whether micro-drilling measurements could be used as an alternative to the current practice of extraction and analysis of drill cores from the pile, according to the F3O guidelines [7] and Dutch standard NEN 8707 [8]. To this end, the mechanical properties of 12 full-length wooden piles were investigated, by subdividing the full piles in three segments (head, middle-part and tail) and testing each segment in compression. In addition, micro-drilling measurements were performed on all the segments. On the basis of the results obtained with micro-drilling, it was possible to obtain a reliable prediction of the soft shell, defined as the part of the cross section with no strength. The sound remaining cross section for every segment was estimated, based on the soft shell, and it was possible to distinguish the pile segments in sound and decayed. The load bearing capacity of each segment, measured with mechanical testing, was assigned to the sound remaining cross section, resulting that approximately the same stiffness and strength could be observed in the sound parts of both the decayed and sound group. From all the 12 studied full-length piles, 6 were assigned to sound and 6 to decayed. However, also the decayed piles resulted to have a remaining load-bearing capacity. Thus, for the final assessment of the pile foundation of a bridge, detailed information about the distribution of decayed piles in relation to the load distribution has to be taken into account. In addition, micro-drilling measurements allow to obtain promising results for the prediction of bacterial decay, opening up the opportunity of a more optimal use of micro-drilling for in-situ assessments of wooden foundation piles.

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