# STRENGTH CHARACTERISATION OF EXISTING WOODEN FOUNDATION PILES UNDER BRIDGES AND QUAY WALLS IN AMSTERDAM BY MECHANICAL TESTING AND ASSESSMENT THROUGH MICRO-DRILLING

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**ABSTRACT:** The majority of bridges and quay walls in the inner city of Amsterdam rely on wooden foundation piles. Most of these were constructed 100–300 years ago, implying several challenges for the assessment of the current residual load-carrying capacity and their reliability. In Amsterdam, the wooden piles supporting bridges and quay walls remain entirely under the water table, which means that only bacterial decay can occur. Bacterial degradation proceeds at a slow rate, allowing the piles to perform their function for many years, although causing a reduction of the load-carrying capacity over time. To this end, the municipality of Amsterdam started a large project where non-destructive micro-drilling measurements were employed, with the goal of capturing the in-situ level of decay and the remaining strength of wooden foundation piles. The applicability of micro-drilling was studied on 60 wooden piles with various decay levels, driven between 1727 and 1922, and retrieved from two bridges in Amsterdam. An algorithm was developed for analysing the micro-drilling signals, aimed at determining the decayed outer layer of the pile (soft shell). The micro-drilling approach was validated with the results of mechanical testing on the piles. This study contributes to reliably assessing the decay and remaining load carrying-capacity of wooden foundation piles utilizing in-situ micro-drilling measurements.

**Keywords: timber, wooden foundation piles, micro-drilling, full-size strength testing, assessment, algorithms**

## INTRODUCTION

Many historic bridges and quay walls in the city of Amsterdam rely on wooden foundation piles. Most of these were constructed 100–300 years ago, and the assessment of the material status and the remaining load-carrying capacity are important [1], [2]. This is because wooden piles that remain under the water table, in fully saturated conditions, are susceptible to bacterial degradation, potentially influencing the mechanical properties [3]–[5]. This could lead to a reduction of the safety level. Since the wooden piles supporting bridges and quay walls in Amsterdam remain entirely under the water table, they can benefit from a longer service life [6],[7]. Softwood species are used for the foundation piles that are normally not durable in wet conditions. However, in saturated soils, wood degradation is primarily related to bacteria, and proceeds much slower over time than aerobic fungal attack [8], allowing the piles to perform their function for many years. When wood is underwater, there is not enough oxygen for fungi to survive, however, wood degrading bacteria can flourish in this situation and penetrate into the wood, eroding the cell walls of wood fiber [9]–[11], causing a reduction of the strength and stiffness of the piles over time. Decayed wooden piles can appear unaffected in the field, maintaining their surface, layer, colour, and original dimensions, despite the degradation occurring [11]. In order to make a proper assessment of the remaining service life of wooden foundation piles, it is important to determine their decay level and mechanical properties. To this end, the municipality of Amsterdam started a large project with the goal of capturing aspects that determine the current state of wooden foundations under bridges and quay walls.

The currently adopted inspection techniques adhere to the F3O guidelines [12] and the Dutch standard NEN 8707 [13], involving the extraction of drill cores (with a diameter of 10 mm and a length of roughly half the pile diameter) from the head of the wooden piles, roughly 50 cm below the pile head. In Amsterdam, the drill cores were taken underwater by divers with a hand-driven increment borer (Ø10 mm), and collected in plastic tubes filled with water to preserve their physical properties. Subsequently, the drill cores were segmented into sub-sections and visually examined: type, gradient in the degree of deterioration, and wood species were determined under the microscope according to [14], [15], [3]. The classification was done in accordance with [3] and [5], where four decay classes were used: sound, weak, moderate, and severe. Based on this analysis, it was concluded that bacterial decay was present in a significant number of piles. Then, utilizing the maximum moisture content that a given sub-section could absorb, an estimation of the compression strength was derived according to the model for pine piles in Klaassen [3]. On this basis, the city of Amsterdam considered every sub-section of the drill core with a predicted compression strength lower than 8 N/mm$^2$ (arbitrarily chosen), as being part of a so-called "soft shell": the degraded part of the cross section to which zero strength is assigned. Finally, the compression strength for new piles, provided in the Dutch National Annex of Eurocode 5 [17] and NEN 8707, was assigned to the remaining assumed sound part, deriving the design compression force according to the coefficients used in [17], [18]. However, several drawbacks emerged from this approach: firstly, the derived compressive strength values of the piles could not be validated with the compressive strength of the piles that have been in service, since only very limited data was available. Secondly, the drill core analysis is often cumbersome and dependent on the technician´s expertise. Finally, the analysis does not give a continuous representation over the cross section.

In order to address the knowledge gap concerning the impact of bacterial decay on the mechanical properties of wooden foundation piles and to explore assessment techniques for efficiently mapping the radial distribution of decay within these piles, an extensive experimental campaign has been initiated in collaboration with the TU Delft and the municipality of Amsterdam [19]. The main objectives are:

a) Characterising the present condition of wooden foundation piles driven into the soil in three different time periods (1727, 1886, and 1922), retrieved from two bridges in Amsterdam that were demolished and replaced, through a large testing campaign involving mechanical tests on a full size specimen.
b) Exploring the applicability of a more efficient inspection technique, both in execution and in analysing, ensuring that measurements remain available for analysis now and in the future.

Among the available non-destructive techniques for assessing the material condition of timber piles, micro-drilling stands out as a promising method, offering the advantage of enabling extensive in-situ sampling across a large number of piles [20]–[23]. Micro-drilling allows inspection of the material status 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. The resistance profile can be directly evaluated in-situ, allowing one to check if the measurement is successful or has to be repeated. The measurements can be performed in different positions and directions, resulting in more available measurements, increased accuracy, faster in-situ testing, reducing costs and applicability. The data can be stored an analysed at any moment.

In this paper, the results of this research are presented. The main objectives of the research were to develop an algorithm for analysing the micro-drilling signals of each pile, through which the decayed portion (zones) of the pile could be determined. On this basis, the short-term strength of wooden piles that have been in service for a long time could be predicted.

# MATERIALS

The materials comprised 55 spruce (*Picea abies*) and 5 fir (*Abies*) wooden foundation piles, which were part of the foundation system of the piers of two bridges (called bridge 30 and 41) in the city of Amsterdam that were planned to be demolished and reconstructed. The retrieved full-length piles were driven in three different building years: 1727, 1886 and 1922. The data of the full-scale timber piles are listed in Table 1.

**Table 1: Coding, building year and dimensions of full-scale spruce and fir piles retrieved from bridge 30 (B30) and bridge 41 (B41) in Amsterdam (Standard deviation reported in brackets)**

| Wood species | Building year | Bridge (No. of piles) | Length mean m | Diameter $D_{head}$ mean mm | Diameter $D_{tip}$ mean mm | Avg. tapering mm/m |
|---|---|---|---|---|---|---|
| Spruce | 1922 | B41 (14) | 12.6 (0.8) | 256 (12) | 170 (16) | 6.9 (1.5) |
| | 1886 | B30 (10); B41 (1) | 12.0 (1.9) | 248 (10) | 172 (23) | 6.4 (2) |
| | 1727 | B30 (15); B41 (15) | 10.7 (1.1) | 220 (39) | 129 (29) | 8.5 (2.9) |
| Fir | 1886 | B30 (3); B41 (2) | 11.7 (1.9) | 248 (13) | 162 (32) | 7 (2.5) |

# METHODS

## *Compression tests parallel to the grain*

The full-scale logs were cut into head, middle and tip segments with a length of approximately six times the smallest diameter of the tapered log sections (Fig. 1) according to EN 408 [24]. This was done to investigate the compressive strength profile over the length of the tapered piles. During handling and cutting procedures, until the time of the test, the piles were kept submerged in water to avoid drying and consequent cracking, with average moisture content higher than 70%, well above fiber saturation point [25]. This was done to recreate the same in-soil conditions where the piles were fully under the water table, in order to obtain comparable mechanical and physical properties during testing. The moisture content was determined with the oven-dry method, according to EN 13183 (2002) [26], for two 30-mm-thick discs taken from both sides of each selected segment. Compression tests were performed to determine the short-term wet compressive strength ($f_{c,0,wet}$) of the pile segments in direction parallel to the grain in submerged conditions. To this end, a displacement-controlled test setup was used, where the pile segments were subjected to an axial load in direction parallel to the grain [27], as in [28]. A hinge, mounted on a steel plate, was placed on top of the specimen to have a uniformly distributed compression load on the pile. Four linear potentiometers were screwed to the segment to measure its deformation, along its lateral surface, at 90° from each other, and with a variable length equal to 2/3 of the length of the specimen. The tests were conducted at a displacement rate of 0.02 mm/s until the peak load was reached. After the peak load (reached at approximately five minutes), the test continued at a higher speed until the cracks were visible, and to show the post-peak behaviour of the pile [27]. $f_{c,0,wet}$ was derived from the ratio between the maximum force reached in compression and the average cross-sectional area of the each specimen.

## *Micro-drilling*

Micro-drilling measurements were adopted as an assessment technique to investigate the potential degraded portion of the cross section of timber piles in service. Micro-drilling measurements fall within the non-destructive techniques used for wood inspection [20]–[23]. In this study, an IML-RESI PD 400 tool was used. During micro-drilling, a drilling needle is pushed into the material with a drill speed of 2500 r/min and a feed speed of 150 cm/min. The drill bit is 400 mm long, with a thin shaft of 1.5 mm in diameter and a 3.1-mm-wide triangular shaped cutting part. The acquired data, recorded every 0.1 mm of the drilling depth, are plotted as resistance versus distance. 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 (Fig. 1a; Fig. 1b). In this way, it was possible to map the degradation pattern in the cross section and along the whole length of the pile. Each measurement was performed on fully saturated piles. The exact level of moisture content, as long as it is far above fiber saturation point, revealed to have no influence on the decay levels detected with micro-drilling signals, as demonstrated in [29]. All segments were micro-drilled before mechanical testing, to have an accurate correlation between the material status and its mechanical properties.

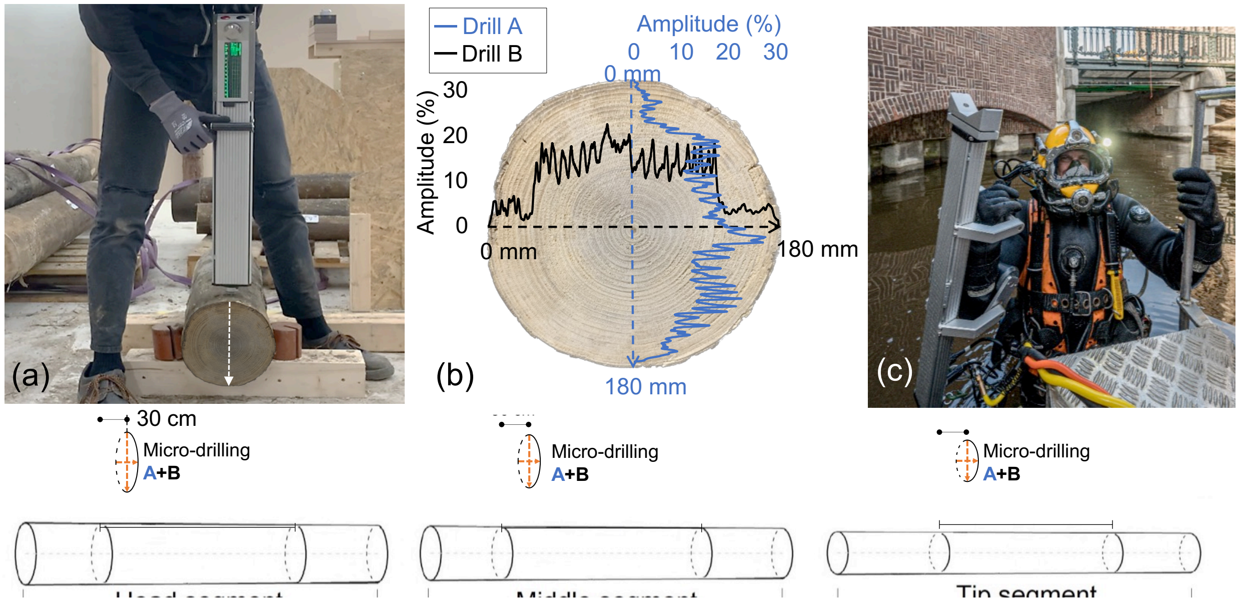

**Figure 1: (a) Micro-drilling performed 30 cm from the head of the pile; (b) Micro-drilling signals A and B (90° degrees apart). The amplitude (%) represents the percentage of maximum power of the drilling tool engine while drilling through the pile; (c) Micro-drilling performed underwater on pile heads by a diver in Amsterdam.**

### *Determination of decay with micro-drilling*

In order to evaluate the degraded portion of the cross section of the historical piles, the micro-drilling signals A and B performed on each pile segment were analysed with an algorithm developed by TU Delft. The purpose of the algorithm is to analyse the micro-drilling signal and to subdivide 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 Drilling Moving Average (Drill_MA), giving the average of the length of the signal between 5 mm before and 5 mm after a specific signal point. After that an Incremental Outwards Moving Average (IOMA) is calculated on both sides from the centre. Thereby the average of the Moving Average values is calculated starting from the centre, for every signal point. This is done for both sides. The maximum IOMA value on both sides is considered to be the value for sound wood. Then, four zones are determined through chosen ratios between the regular moving average of the signal and this maximum value of the IOMA. Zones 1, 2, 3, 4 on each side correspond to the point in which the Moving Average, seen from the outside part, reaches 20%, 40%, 60%, 80% of the maximum value of the IOMA on that side (Fig. 2). The soft shell—the degraded portion of the cross section—is finally calculated as the sum of a number of zones, which number is determined according to the next paragraph and presented in the section "Analysis." In Figure 2 an example is given when the soft shell is assigned to zones 1+2. In this way, for each micro-drilling measurement, it was possible to assess the zone allocation in a relative way. It should be noticed that micro-drilling is a local measurement, thus, it may happen that the soft shell determined in a specific cross section of the pile may differ 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 irregularities of the material. The total soft shell of a decayed cross section was calculated as the average of the four lengths of the soft shell (SS), determined according to the next paragraph, corresponding to left and right sides of micro-drilling signal A + B. From this, the average length of the soft shell ($al_{SS}$) was calculated with Equation 1. Subsequently, the remaining sound cross sectional area ($A_{sound}$), i.e., the part of the cross section that did not exhibit degradation, was calculated by subtracting $al_{SS}$ to the radius ($r$) of the whole cross section, and expressed as percentage of the full cross-sectional area ($A_{tot}$) in Equation 2.

$$\text{Average soft shell length (mm)} = al_{SS} = (SS_{A,left} + SS_{A,right} + SS_{B,left} + SS_{B,right})/4 \qquad [1]$$

$$\text{Remaining sound cross sectional area (\%)} = A_{sound} / A_{tot}\,(\%) = [\pi(r - al_{SS})^2 / \pi r^2]*100 \qquad [2]$$

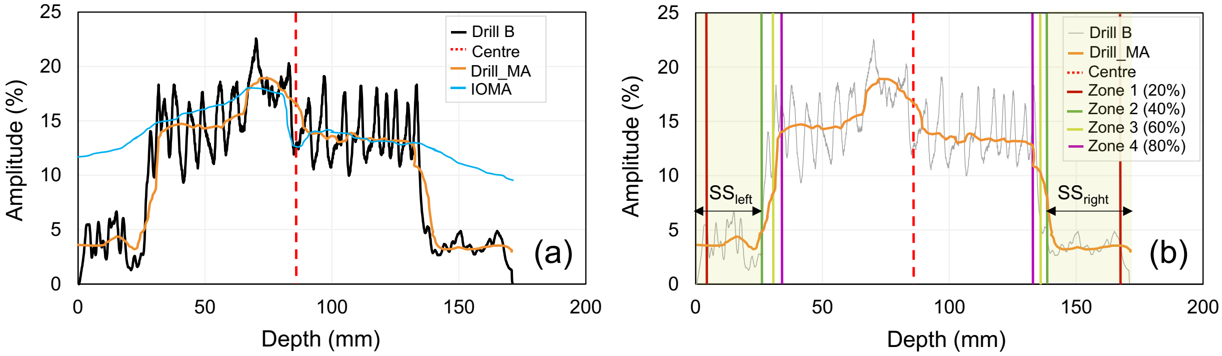

**Figure 2: Example of the analysis of the drilling signal (*Drill B*) for the decayed spruce pile a) Drilling moving average (*Drill_MA*) and IOMA from which the zones are calculated; (b) Four zones and soft shell ($SS_{left}$ and $SS_{right}$) associated to zone 1+2.**

### *Validation of the zones associated with the soft shell based on the results of mechanical testing*

In order to validate the zones correlated to the soft shell (to which zero compression strength is assigned), the following procedure was followed:

- The pile segments extracted from the retrieved piles that did not exhibit decay were identified. These sound segments revealed a sound cross-sectional area ($A_{sound}$) between 95–100% of the full cross-sectional area ($A_{tot}$). This means that the sum of zones 1+2+3 of both sides was less than 5% of the diameter of the pile. The full cross-sectional area was used to calculate the average sound compression strength ($f_{c,0,wet,sound}$) of these segments, for head, middle-part and tip.
- The selected sound segments only belonged to 1922 and 1886. Thus, the average $f_{c,0,wet,sound}$, i.e., the sound compressive strength of non-decayed piles, was taken from the test results of a total of 62 pile segments from 1922 and 1886.
- For all piles from 1922 and 1886, $F_{c,0,mod}$ was calculated according to Equation 3, with the average $f_{c,0,wet,sound}$ of the 62 pile segments and $A_{sound}$ of each pile, determined by subtracting $al_{SS}$ (Eq. 1) to the full radius, calculated with Zone 1, Zone 1+2, and Zone 1+2+3, respectively.

$$F_{c,0,mod} = f_{c,0,wet,sound} * A_{sound} = f_{c,0,wet,sound} * \pi(r - alss)^2 \qquad [3]$$

- A correlation analysis was conducted between the maximum force measured with compression tests of the pile segments ($F_{c,0,test}$) and the force ($F_{c,0,mod}$) calculated with Zone 1, Zone 1+2, and Zone 1+2+3, respectively. With this, the number of zones describing the soft shell are determined.
- With the chosen number of zones associated with the soft shell, which revealed to be zones 1+2 (See section "Analysis"), the soft shell is calculated for all segments including those from 1727. Also, for segments with a sound cross section above 95%, the soft shell is calculated. The soft shell of each pile is subtracted from the whole cross section, resulting in the final sound compressive strength, including all piles, also from 1727. This is named equivalent sound compressive strength (EQ $f_{c,0,wet,sound}$) derived for every building year and for head, middle and tip.
- Finally, $F_{c,0,mod}$ was calculated, by applying Equation 4 to all pile segments, with the soft shell corresponding to zones 1+2, and plotted against all $F_{c,0,test}$ values.

$$F_{c,0,mod} = \mathrm{EQ}\, f_{c,0,wet,sound} * A_{sound} = \mathrm{EQ}\, f_{c,0,wet,sound} * \pi(r - alss_{zone1+2})^2 \qquad [4]$$

## RESULTS

### *Mechanical properties of retrieved historical piles*

The results of large-scale mechanical testing are presented in Table 2, including a total of 201 pile segments extracted from 60 full-length spruce and fir piles. Spruce piles from 1922 and 1886 were incorporated in one category, since no significant difference in $f_{c,0,wet}$ was found. No significant difference was also found in $f_{c,0,wet}$ of head and middle part, which were presented together. The values of $f_{c,0,wet,sound}$ for head, middle-part and tip of 62 sound piles from 1922 and 1886, that did not exhibit decay, were selected as strength reference for sound wood (Table 3). No significant difference was found between 1922 and 1886.

**Table 2: Compressive strength ($f_{c,0,wet}$) determined with mechanical testing of piles from 1922, 1886 and 1727**

| Wood species | Building year | Part (No. segments) | $f_{c,0,wet}$ (MPa) | |
|---|---|---|---|---|
| | | | mean | SD |
| Spruce | 1922/1886 | Head/Middle (59) | 14.0 | 2.2 |
| | | Tip (32) | 11.9 | 2.3 |
| | 1727 | Head/Middle (60) | 7.5 | 2.4 |
| | | Tip (30) | 5.8 | 1.8 |
| Fir | 1886 | Head/Middle (13) | 15.1 | 2.1 |
| | | Tip (7) | 12.7 | 2.4 |

**Table 3: Reference for sound compressive strength $f_{c,0,wet,sound}$ for 62 sound piles from 1922/1886**

| Material status | Building year | Part (No. segments) | $f_{c,0,wet,sound}$ (MPa) | |
|---|---|---|---|---|
| | | | mean | SD |
| Sound ($A_{sound}$ > 95%) | 1922/1886 | Segments head (21) | 15.4 | 1.5 |
| | | Segments middle (30) | 14.9 | 2.2 |
| | | Segments tip (11) | 13.7 | 2.2 |

## ANALYSIS

### *Determination of the soft shell and relative zones to which zero strength can be assigned*

For each tested segment, the length of the zones 1, 2, 3, 4 on both sides of the micro-drilling signal were determined. The correlation analysis between $F_{c,0,\mathrm{test}}$ and $F_{c,0,\mathrm{mod}}$, calculated with zone 1, zones 1+2 and zones 1+2+3 according to Equation 3 of the micro-drilling signal is shown in Figure 3, with $F_{c,0,\mathrm{mod}}$ determined with $f_{\mathrm{c,0,wet,sound}}$ values in Table 3. It emerged that zone 1+2 represented the best correlation in terms of $\mathrm{R}^2$ and slope of the line that is closer to the bisector. Based on this, zones 1+2 of the micro-drilling signal were chosen to determine the soft shell. The approach assumes $f_{\mathrm{c,0,wet}} = 0$ MPa of zones 1+2.

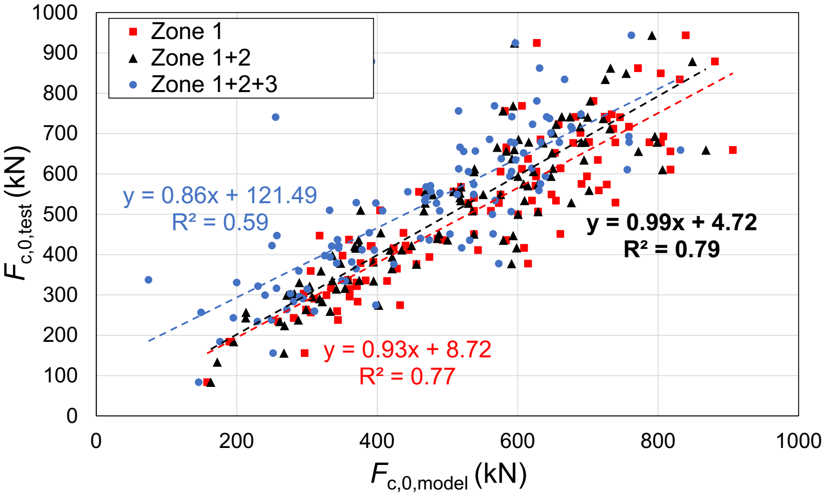

**Figure 3: Correlation between $F_{\mathrm{c,0,test}}$ *and* $F_{\mathrm{c,0,mod}}$, calculated with $f_{c,0,\mathrm{sound}}$ assuming zero strength associated with zone 1, zone 1+2 and zone 1+2+3 of the micro-drilling signal**

### *Equivalent sound compressive strength values*

The area of zones 1+2 is now designated as the "soft shell." The mean equivalent sound compressive strength (EQ $f_{c,0,wet,sound}$) related to the remaining sound cross-sectional area ($\mathrm{A}_{\mathrm{sound}}$), assuming zero strength associated with the soft shell, is presented in Table 4.

The results in Table 4 show an EQ $f_{c,0,wet,sound}$ for all piles from 1922/1886 in line with the reference $f_{c,0,wet,sound}$ in Table 3, and a lower EQ $f_{c,0,wet,sound} = 12.0$ MPa for all segments from 1727. For the segments from 1727, no significant difference was found between head, middle and tip for the EQ $f_{c,0,wet,sound}$ values.

**Table 4: Equivalent sound compressive strength (EQ $f_{\mathrm{c,0,wet,sound}}$) calculated with zone 1+2 for piles from 1922, 1886 and 1727**

| **Material status** | **Building year** | **Part (No. segments)** | **EQ $f_{\mathrm{c,0,wet,sound}}$ (MPa)** | |
|---|---|---|---|---|
| | | | **mean** | **SD** |
| Sound cross section | 1922/1886 | Head/Middle (72) | 15.0 | 2.3 |
| | | Tip (39) | 13.7 | 2.4 |
| | 1727 | All Segments (90) | 12.0 | 2.8 |

### *Validation of the soft shell for all piles based on the equivalent sound compressive strength*

The relationship between $F_{\mathrm{c,0,test}}$ and $F_{\mathrm{c,0,mod}}$ calculated with zone 1+2 of the micro-drilling signal is shown in Figure 4, comprising all the pile segments from 1922, 1886 and 1727. The difference with Figure 3 lies in the application of the algorithm to determine the soft shell of all pile segments, including the 62 non-decayed segments from 1922/1886, initially designated as sound (for which no soft shell at all was assumed in the first calibration step). Furthermore, Figure 4 includes the pile segments from 1727. The graph shows that the allocation of zones 1+2 to the soft shell also fits for the piles from 1727.

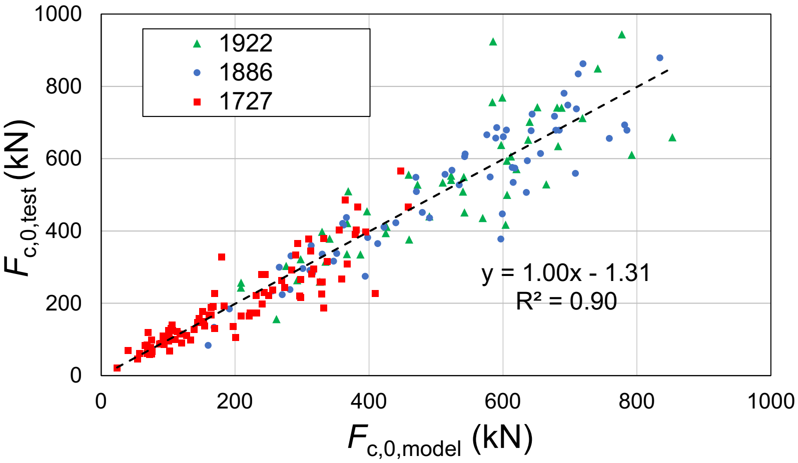

**Figure 4: Relationship between $F_{c,0,test}$ *and* $F_{c,0,mod}$ calculated from EQ $f_{c,0,sound}$ and $A_{sound}$ based on the soft shell related to zone 1+2 of the micro-drilling signal of all pile segments from 1922, 1886 and 1727**

## DISCUSSION

The applicability of the presented algorithm to determine the zones (and from that a soft shell) of a micro-drilling signal, and predict the short-term strength of the tested pile segments based on equivalent sound compressive strength values, has been demonstrated. The equivalent sound compressive strength values of historical piles revealed to be different (lower) than the values for 'new' piles reported in the Dutch national annex of EC 5 [17] and NEN 8707 [13]. For the assessment of existing piles, the strength values presented in this paper can be used. The equivalent sound strength values for the piles from 1727 were lower than those of piles from 1922/1886. Investigations in the basic quality of the material showed no clear difference between these two building years. The difference could be caused by long-term loading effects, since the piles from 1727 were longer loaded, and the stress level was potentially higher than for the piles from 1922/1886, since the load was taken up by a smaller remaining sound cross section due to larger presence of decay.

The results presented in this paper are based on micro-drilling measurements conducted in the laboratory. After a test phase, the micro-drilling technique is now applied on a large scale in the city of Amsterdam. Analyses of in-situ micro-drilling measurements show the same quality as the laboratory measurements, and thus they can be used for the analysis of the soft shell of the wooden foundation piles. However, the micro-drilling in-situ applicability, with measurements performed underwater on timber foundation piles (Fig. 1c), could have measurement errors associated with it, such as the difficulties of conducting underwater measurements and the accuracy and precision of the operator. It is always recommended to use at least two (A, B) orthogonal micro-drilling measurements. All signals used in this analysis were acquired using the setting of 2500 r/min for drilling speed and 150 cm/min for the feed speed. In addition, an accurate measurement of the diameter of the pile section where micro-drilling is conducted is of importance for an adequate estimation of the soft shell. The analysis of the signal is also sensitive to the location where micro-drilling is performed: the presence of wood knots, cracks, dirt or other irregularities could influence the signal and the estimation of the soft shell. To overcome these issues, the divers who conduct the measurements need clear instructions. When an underwater micro-drilling measurement is taken, the signal has to be simultaneously checked by a technician above water in order to decide whether the measurement was adequately performed and seemed reliable, or whether a new measurement has to be conducted.

## CONCLUSIONS

The main objectives of the presented work were to characterise the mechanical properties of historical wooden foundation piles that have been in service for approximately 100–300 years, and to develop an algorithm for analysing the signals retrieved from micro-drilling measurements to identify the level of decay and to predict the short-term compression strength of these piles. A total of 55 spruce (*Picea abies*) and 5 fir (*Abies*) piles retrieved from two bridges in Amsterdam were characterised, by conducting large-scale mechanical testing on pile segments. The results showed that the short-term compressive strength of wooden piles that have been in service for a long time is lower than the strength values provided for 'new' piles. This is partly due to the presence of decay, especially for piles from 1727, with a service life of ca. 300 years. However, lower short-term compressive strength values were also determined for non-decayed piles from 1922/1886. These strength values have to be taken into account in future assessments of wooden foundation piles. The assessment of bacterial degradation was carried out by using micro-drilling measurements. Micro-drilling allowed to estimate the "soft shell" of each pile: the degraded outer layer of the cross section to which zero strength is assigned. An algorithm was developed to determine the degraded parts of the cross section based on the micro-drilling signal, calibrated on the full-size compression test results of sound piles from 1922/1886, from which the length of the soft shell could be determined. Based on the soft shell, the equivalent sound compressive strength for piles of all time periods could be determined. For the piles from 1727, the equivalent sound strength values were lower than for the piles from 1922/1886, which might be caused by the fact that the stress level during the service life of piles from 1727 was higher, due to a larger presence of decay and thus a smaller sound load-bearing cross section. This was verified by applying an average equivalent sound compressive strength to the sound remaining cross section of all piles, assuming zero strength of the soft shell layer: with this, the short-term compressive strength could be accurately predicted for all the pile parts from all the time periods. The micro-drilling technique is now used on a large scale in Amsterdam to retrieve signals that are useful for determining the soft shell. For an adequate analysis, divers who perform underwater micro-drilling need clear instructions from technicians above water to anticipate irregularities in the measurements.

## ACKNOWLEDGEMENTS

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