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Techniques for the assessment of their state of conservation

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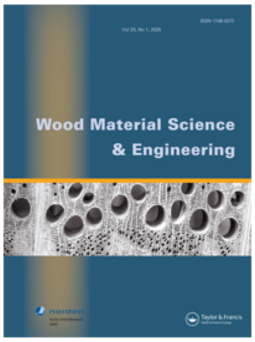

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Traditional wooden foundation piles in Amsterdam and Venice: techniques for the assessment of their state of conservation

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ABSTRACT
This study explored the most employed techniques for the assessment of the state of conservation of traditional wooden foundation piles in Amsterdam and Venice. The techniques were evaluated for their relevance and effectiveness in assessing decay impact on centuries-old waterlogged wooden piles. The techniques adopted in Amsterdam and Venice were complementary. In Amsterdam, underwater micro-drilling was employed to accurately estimate the amount of decay and the remaining strength of the piles. In contrast, the techniques in Venice were based on microscopic and mechanical testing of small wood samples to provide a detailed decay analysis. The successful use of underwater micro-drilling in Amsterdam, which allows for fast and accurate pile decay assessment, presents an opportunity to enhance the piles conservation database of Venice. Adopting this technique in Venice could support more timely and effective preservation strategies.

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Wooden foundation piles; biodegradation; conservation of architectural heritage; micro-drilling

1. Introduction

1.1. Background

Wooden foundation piles have always played an important role in engineering construction. Especially in areas with soft soils, timber piles were used extensively in the past, to improve the stability of buildings, proving to be a very efficient and economical solution over the years (Klaassen *et al.* 2005). In Europe, many historic buildings and infrastructures still rely on timber piles. The cities of Amsterdam (NL) and Venice (IT) show interesting examples of waterlogged wooden pile foundations (Klaassen 2008, Cavaggioni and Lionello 2009, Klaassen and Creemers 2012, Van de Kuilen *et al.* 2021, Pagella *et al.* 2022a).

Despite their shared foundational system of timber piles, significant similarities and differences exist between the two cities (Naldini *et al.* 2010). In both cities, the soil is a mixture of peat, clay, loam, and sand, characterized by a low bearing capacity. In Amsterdam, mostly pine, spruce, and alder piles were traditionally used, typically 10–12 m long and tapered, with head diameter of 180–200 mm and tip diameter of 120–140 mm (Figure 1(a)), whereas in Venice, shorter piles (1–3.5 m) were employed (Figure 1(b and c)), made of larch, oak, alder, and elm, with rather straight shape and diameters between 100 and 250 mm (Macchioni *et al.* 2016). The short friction piles used in Venice were placed closely together, with the gaps between them filled with sand to form a stable support. This system continues to uphold the weight of substantial heritage structures in the city. A similar system of short friction piles was also used in Amsterdam, between the fourteenth and fifteenth centuries (Klaassen 2008). However, from the sixteenth to the beginning of the twentieth century, the majority of the buildings present in the city relied on the foundation system made by long timber piles inserted in 25–50 cm of dense sand layers (end-bearing piles), (Klaassen *et al*. 2005).

The wooden foundations in the two cities were constructed 100–500 years ago and the assessment of their state of conservation and remaining load-bearing capacity are important (Van de Kuilen 2007, Pagella *et al.* 2022a). Biological decay in waterlogged soils can be caused by either soft rot fungi (in low-oxygen conditions), or bacteria in anoxic conditions (Holt and Jones 1983, Daniel and Nilsson 1986, Kim and Singh 2000, Irbe *et al.* 2019, Björdal and Elam 2021). Fungal attack in water-submerged wooden piles progresses very slowly due to the lack of oxygen in such environments. However, wood-degrading bacteria in anoxic conditions can flourish and penetrate the wood matrix, eroding the cell walls of the wood fibres (Varossieau 1949, Macchioni *et al.* 2013, Singh *et al.* 2016, Gard *et al.* 2024), potentially influencing its mechanical properties and leading to a reduction of the safety level (Pedersen *et al.* 2013). Fully submerged piles tend to have a longer service life, since the degradation of wood in waterlogged anaerobic soils is mainly related to bacteria, and proceeds slower over time than aerobic fungal attack (Mirra *et al.* 2024). This allows the piles to function for centuries before showing a substantial reduction of the load-bearing capacity.

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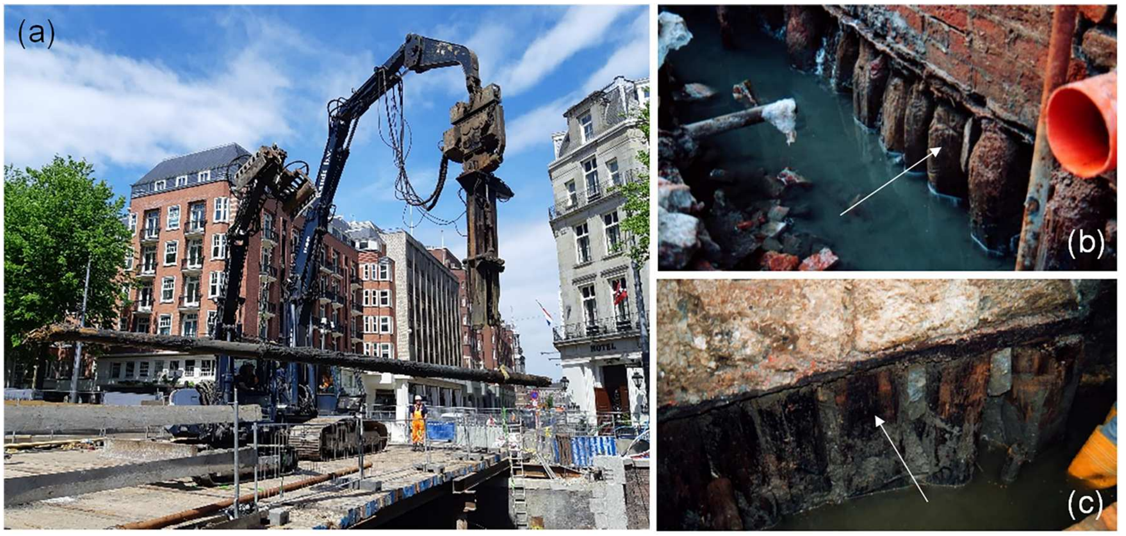


Figure 1. (a) Wooden foundation pile retrieved from the historical foundation of a bridge in the centre of Amsterdam; (b) foundation piles in Venice, visible after lowering the water level of the canal; (c) rough-hewn piles (rectangle shaped) in a foundation in Venice.

In this context, this study investigated techniques to assess the state of conservation of the wooden foundation piles in Amsterdam and Venice, as a continuation of earlier studies on the decay of wooden piles in the two cities conducted by Naldini *et al.* (2010), through a collaboration between the Delft University of Technology (NL) and the University of Padova (IT). The investigation techniques adopted in the two countries were presented and discussed, taking into account the peculiarities of the different foundation methods and the knowledge available on the causes and mechanisms of wood decay.

1.2. Characterization of wooden piles in Amsterdam

Wooden foundation piles in Amsterdam, mostly comprise softwood species (Klaassen 2005, 2008, Pagella *et al.* 2022a, 2022b). The durability of wooden piles in waterlogged soils is vulnerable to bacterial erosion, which typically progresses radially inward, initially affecting the non-durable sapwood, while the heartwood remains less decayed or sound (Kim and Singh 2000, Mirra *et al.* 2024). Decayed wooden piles may appear unaffected in situ, maintaining their surface texture, layers, colour, and original dimensions, despite the degradation progresses (Bjordal and Elam 2021).

On this basis, the city of Amsterdam initiated a research and monitoring project, aimed at assessing the current state of the wooden foundations (Klaassen *et al.* 2005, Pagella *et al.* 2024c, 2024d). The inspection techniques involved the extraction of drill cores (with a diameter of 10 mm and a length of roughly half the pile diameter) with a hand-driven increment borer (Ø10 mm), as shown in Figure 2a, and collected in plastic tubes filled with water (Figure 2(b)), to preserve their physical properties (Klaassen *et al.* 2005). The cores were taken from ca. 50 cm below the pile head, following F3O guidelines (2011) and the Dutch standard NEN 8707 (2023). A total of 3713 drill cores were extracted from the piles of 181 bridges in Amsterdam (Figure 3(a)), which were built across various historical periods, with pile ages ranging from 50 to 400 years (F3O Richtlijn 2011). Subsequently, the drill cores were segmented into sub-sections and visually examined. The wood species,

Figure 2. Sample collection: (a) extraction of a drill core from the tip of a retrieved timber foundation pile in Amsterdam, and (b) drill core collected in a plastic tube filled with water.

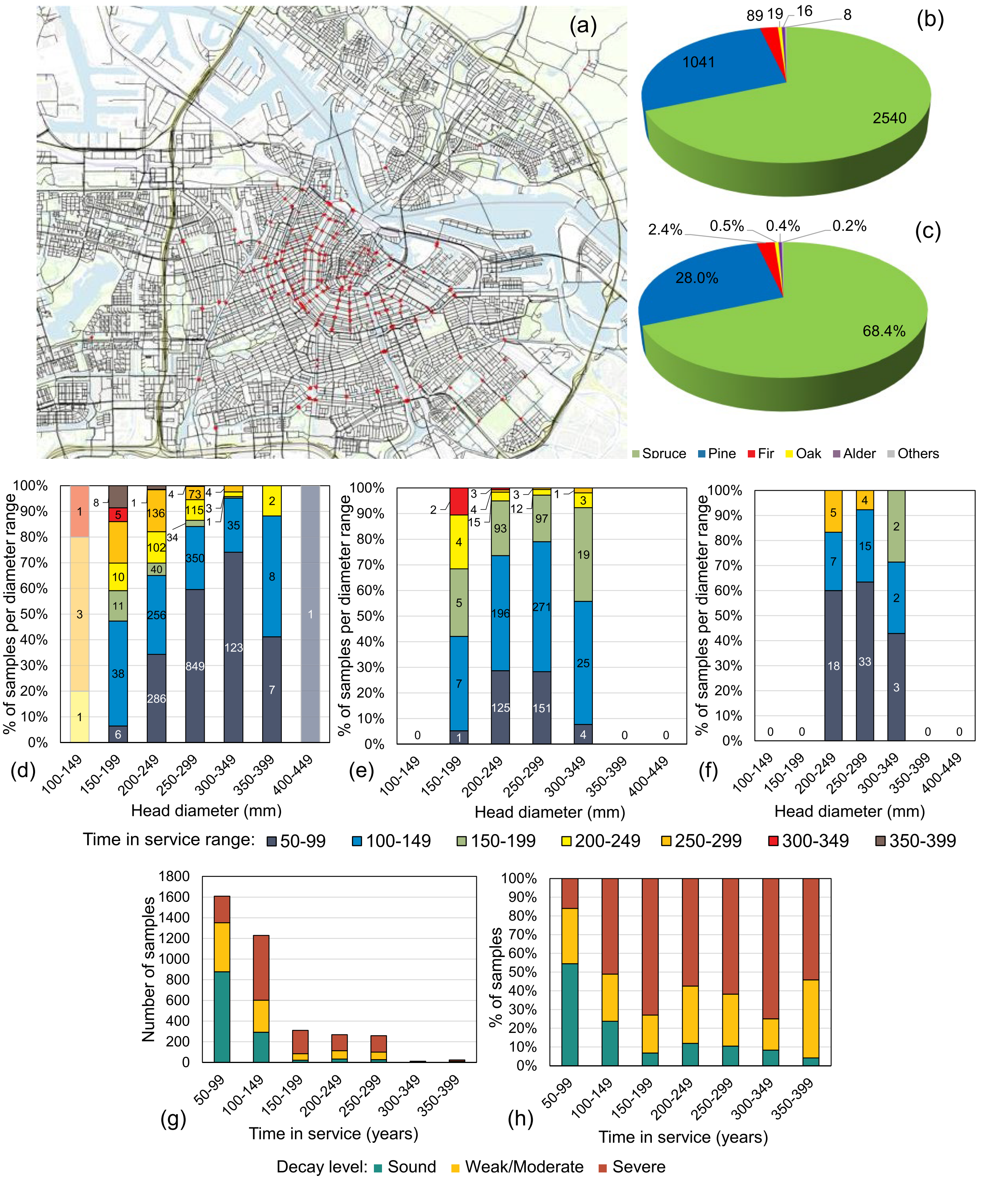


Figure 3. Sample collection: (a) map of Amsterdam with locations (in red) of the bridges in which drill cores were taken from the wooden piles, (b) wood species distribution of 3713 samples per number of drill cores, (c) per percentage of wood species. Distribution of the % of (d) spruce, (e) pine, (f) fir samples, based on head diameter of the piles for 7 ranges of time in service. The number in the rectangles represents the sample number of each range. Decay classification for 3711 drill cores: (g) number of samples, and (h) percentage of samples for each time-in-service group.

type, and degree of deterioration were examined through microscopic analysis, following the classification method outlined by Klaassen (2008), Heinz (2004), and Schweingruber (1990), where 4 decay classes were used: sound, weak, moderate, and severe.

The wood species mainly involved spruce, pine, and fir, with a smaller proportion of alder and oak (Figure 3(b, c)). The range of head diameters, mostly 200–300 mm, is provided for the most used wood species: spruce (Figure 3(d)), pine (Figure 3(e)), and fir (Figure 3(f)). From the analysis of the drill cores, it was concluded that bacterial decay was present in a significant number of piles. Subsequently, the remaining compression strength of the piles was estimated by measuring the maximum moisture content that a sub-section of the drill core could absorb, according to the model for pine piles in Klaassen (2008), where high moisture contents above ca. 230% are correlated to total disrupted wood structure. Using this model, the city of Amsterdam considered every sub-section of the drill core with predicted compression strength lower than 8 N/mm^2 (correspondent to disrupted wood), as being part of a so-called "soft shell": the degraded part of the cross section to which no strength is assigned. Assuming that the soft shell would be constant around the cross section, the percentage of remaining sound cross-sectional area was calculated. Three decay classes were identified:

- remaining cross section ≥ 85%: sound pile,
- 65% ≤ remaining cross section < 85%: moderately decayed pile, and
- remaining cross section < 65%: severely decayed pile.

The soft shell detected from the drill cores was related to the parameter time in service as shown in Figure 3(g, h).

Finally, in order to calculate the remaining load-bearing capacity of the piles, the compression strength values for 'new' piles, determined in Van de Kuilen 1994 and reported in the Dutch National Annex to Eurocode 5 (NEN-EN 1995-1-1/NB 2013) and NEN 8707 (2023), were assigned to the remaining assumed sound part, deriving the design compression force according to the modification factors (k-factors) used in the Eurocode 5 EN 1995-1-1 (2010). However, the derived compressive strength values of the piles could not be validated with the compressive forces acting on the piles that have been in service, since only very limited data was available (Pagella *et al.* 2024d).

In Amsterdam, the aforementioned inspection technique relying on the drill cores' analysis facilitated the sampling of numerous piles within the city, providing a comprehensive overview of the status of the material. However, this method was based on local measurements conducted at a specific localized spot, limited to the pile head and dependent on the diver's expertise. Thus, a continuous representation over the cross section of the pile was not given. Moreover, the analysis of the possible decay of the drill cores required specific expertise and extensive (laboratory) investigations, since after the extraction, microscopic analyses and application of experimental models needed to be conducted.

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 was initiated in collaboration with the TU Delft and the municipality of Amsterdam (Ravenshorst 2024). The main objectives were:

(1) Characterizing the present condition of wooden foundation piles driven into the soil in 3 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 full-size specimens.
(2) Exploring the applicability of a more effective inspection technique to be used in practice.

Micro-drilling measurements were employed to determine the potential degraded portion of the pile cross sections. 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 (Zobel and Buijtenen 1989, Gao *et al.* 2012, Nowak *et al.* 2016, Gard and van de Kuilen 2018, Sharapov *et al.* 2018, Humar *et al.* 2021, Mirra *et al.* 2023). Micro drilling allows inspecting 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. With micro-drilling, an assessment of the material can be conducted in different positions and directions, independently from the pile's moisture content (as demonstrated in Mirra *et al.* 2023), providing more measurements, increased accuracy, and faster in-situ testing. Based on the TU-Delft-developed algorithm for analysing micro-drilling signals of historic wooden piles (Pagella *et al.* 2024b, 2024d), the decayed outer layer of the cross section of the piles can be accurately determined.

1.3. Material properties of wooden piles and assessment techniques in Venice

Similarly to Amsterdam, in Venice, the timber piles remain under the water table. The city is persistently threatened by floods, locally known as "acqua alta" (Enzi and Camuffo 1995), increasing the water table over the years by the rate of relative sea level rise since the 1930s (Lionello *et al.* 2021, Zanchettin *et al.* 2021). Short wooden foundation piles (up to 5 m long) are prevalent in Venice underneath almost all historical buildings, dating back to the twelfth century or even older (Cavaggioni and Lionello 2009, Macchioni *et al.* 2016). However, numerous modifications or expansions have been undertaken in the past, complicating the estimation of the current time in service of the wooden pile foundations. Typical Venetian tall and slender structures currently present several risks for structural stability, due to potential uneven settlement of the foundations, exemplified in the past by the bell towers of the churches of Santa Maria Gloriosa dei Frari and Santo Stefano (Gottardi *et al.* 2008, Lionello 2008).

The assessment techniques adopted in Venice for the analysis of the state of conservation of the wooden foundations, are based on different sampling methods, involving the extraction of wood samples (with both chisel, drilling tools, and borers) or entire portions of piles. Samples are typically extracted approximately 30 cm below the top of the pile, which, like the entire pile, remains often submerged in water and below ground level (Macchioni *et al.* 2016). However, in certain parts of the city, water levels may fluctuate, occasionally exposing the tops of the piles to oxygen accelerating the development of fungal decay. The sampling methods depend on the accessibility of the foundations. The samples were mainly extracted from the bank walls, representing the only accessible parts of the Venetian wooden foundations. The inspection and sampling of the piles were carried out simultaneously with the routine maintenance of the canals, which involves draining the canals to provide access to the foundations. The wooden samples were kept in plastic tubes or bags, submerged into the original sediment and water. The investigations include physical, chemical and, in minor part, mechanical characterization of the wooden piles, by means of microscopical analysis and small-scale mechanical testing in the laboratory. In particular, maximum moisture content, basic density (BD), and Residual Basic Density (RBD) were always reported by Macchioni et al. (2016), Bertolini *et al.* (2006), and Pizzo *et al.* (2016), providing information about the state of conservation of wood. A procedure for the micromorphological observation of decayed wooden samples was introduced in 2013, based on the method detailed in Macchioni *et al.* (2013). This allowed grading samples into 5 Classes, from 0 (not decayed) to 4 (wood tissue significantly destroyed).

In total, as reported in studies from 2006 to 2016, the wooden piles in 6 historical sites in different districts of Venice (named "Sestiere") were assessed as shown in Figure 4a. A total of 69 samples were collected from the wooden piles of the bell towers of Frari (11 samples) and Santo Stefano (10 samples) in 2006 (Bertolini *et al.* 2006); Rio Ca' di Dio (8 samples), Rio Acque Dolci (4 samples), San Martino (3 samples) and Santa Chiara (6 samples) in 2009 (Cavaggioni and Lionello 2009), and 2016 (Macchioni *et al.* 2016, p. 653); Santa Maria Maggiore church (27 samples) in 2016 (Pizzo *et al.* 2016). The distribution of the species of the wooden piles is shown in Figure 4b, mostly comprising alder (*Alnus sp.)* and larch (*Larix decidua* Mill.), and less often oak (*Quercus* sp.), elm (*Ulmus* sp.), and pine (*Pinus sylvestris* L.). It should be noted that no spruce species were found. In these studies, it was not possible to determine the service life of the inspected wooden foundations. Although it was possible to determine the initial construction time of the buildings and the age of the first stable settlements in each Sestiere of Venice, the variations of each settlement could not be traced back due to the several enlargements of the buildings carried out over time (Macchioni *et al*. 2016). The service life of all 69 samples from wooden foundations assessed in Venice was estimated to be between the tenth and the fifteenth century.

BD and RBD of all the samples are presented in Figure 4d and e, respectively. The majority of the samples exhibited BD ranging from 0.1 to 0.25 g/cm^3 and RBD between 30% and 50%, indicating significant levels of decay with extensive destruction of the wood tissue. The samples examined across all studies in Venice were collected from various positions along the piles. Overall, the results revealed a relatively uniform level of decay along the length of the piles. The outcomes of the compression tests conducted under saturated conditions are shown in Figure 4f. These tests included 65 samples measuring $20 \times 20 \times 35$ mm^3 from Santa Maria Maggiore Church and 6 samples measuring $13 \times 13 \times 20$ mm^3 from the bell towers of Frari and Santo Stefano. The compressive strength values ranged from 0.6 to 5 MPa, indicating a reduction in compressive strength of 80–90% compared to the reference value of $f_{c,0,wet} = 23$ MPa for fresh alder (Pizzo *et al.* 2016).

The inspection techniques employed in Venice were limited by the inherent difficulty in accessing foundation sites, consequently limiting the number of samples available for testing. Following the extraction, physical, chemical and mechanical characterizations were conducted, contributing to the extended duration of the process. In general, the assessment of the state of conservation of the material retrieved from the wooden piles in Venice indicated a very high level of decay. The applicability of other assessment techniques was mentioned in Bertolini *et al.* (2006), where micro-drilling measurements were employed for the estimation of the residual density and the state of conservation of the material. However, micro-drilling was not adopted in further studies. One of the significant challenges in the assessment of the wooden foundation piles in Venice arises from the inability to determine the exact age of the foundations, which underwent multiple modifications and enlargements over time. This hinders the possibility of relating the time in service of the piles to the degradation processes. In order to expand the in-situ analysis of wooden piles in Venice, the effect of bacteria on the wooden foundation piles of 4 sites in Venice (Arsenal, Riva di Biasio, Rio S. Giustina and Rio Greci) will be outlined in this paper. The experimental campaign, conducted in collaboration with the University of Padova, ACTV S.p.A., SELC Soc. Coop. and Insula S.p.A, will have the objective of characterizing the present condition of wooden foundation piles supporting the Arsenal of Venice, Riva di Biasio, Rio S. Giustina, and Rio Greci, with reference to the wood species and presence of biodegradation.

1.4. Scope of the research

The objectives of the research are:

- The comparison and review of the assessment techniques used in Amsterdam and Venice for the state of conservation of wooden piles, analysing their advantages and limitations.
- Studying the amount of decay with micro-drilling and the remaining strength properties of 60 historic wooden piles from Amsterdam (Mirra *et al.* 2024, Pagella *et al.* 2024b).
- The analysis of the extent of decay determined through microscopic analysis of 19 cores extracted from wooden foundation piles supporting four strategic areas of Venice.

The research provides insights into the effectiveness and applicability of micro-drilling measurements supported by large- and small-scale mechanical testing, and microscopic analysis supported by small-scale laboratory testing, for mapping the decay throughout the cross section of historic wooden piles.

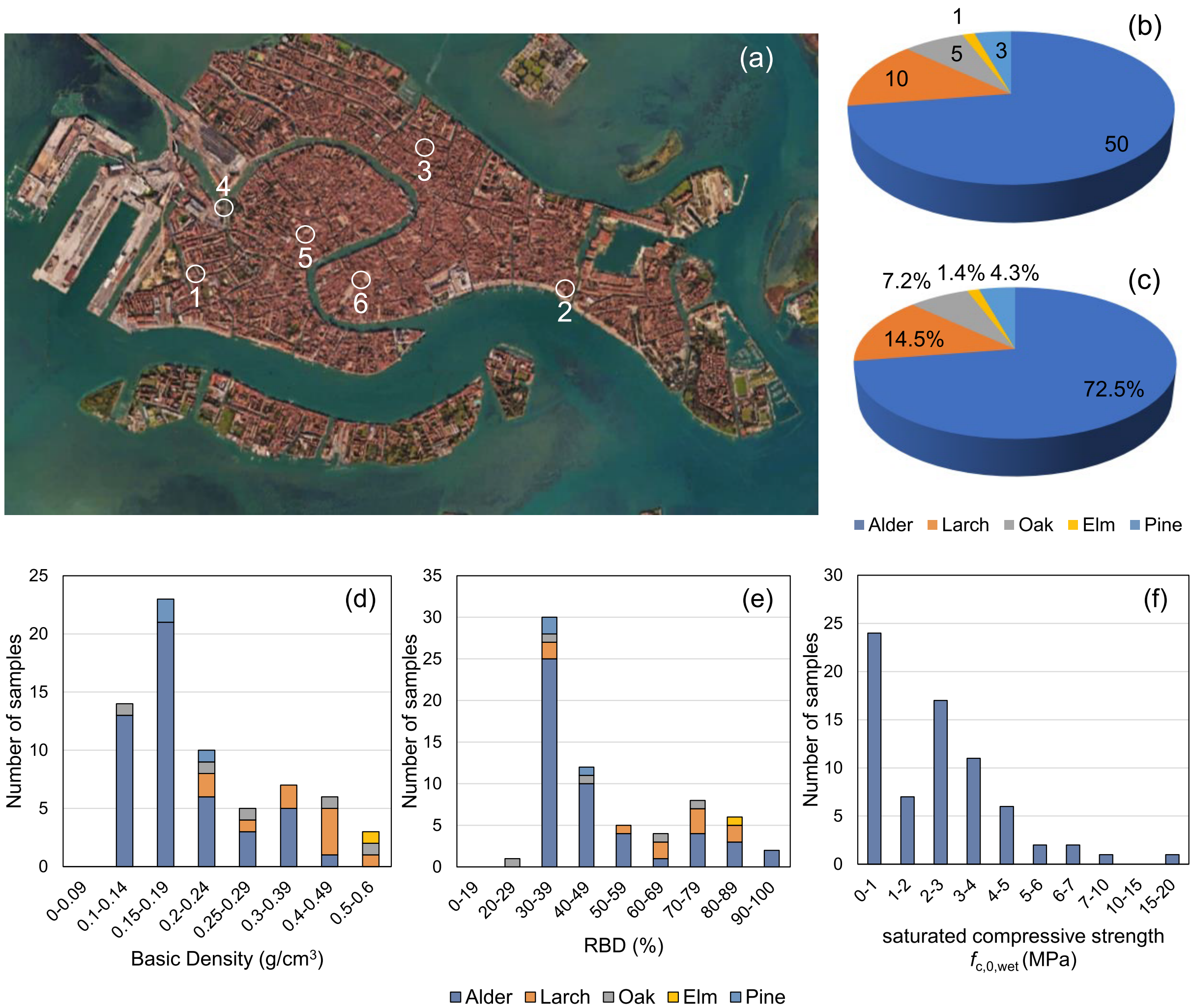


Figure 4. Sample collection: (a) map of Venice with historical sites: (a1) Church of Santa Maria Maggiore, (a2) Rio Ca' di Dio & San Martino, (a3) Rio Acque Dolci, (a4) Santa Chiara, Belfry of (a5) Frari, and (a6) Santo Stefano. Wood species distribution for all 69 wooden piles sampled: (b) per number of samples, (c) percentage of wood species. Distribution of samples based on: (d) basic density, (e) residual basic density (RBD), and (f) distribution of saturated compressive strength ($f_{c,0,wet}$) for all the wood species of wooden foundation piles in Venice.

2. Materials

2.1. Wooden piles tested in Amsterdam

The materials comprised 55 spruce (*Picea abies*) and 5 fir (*Abies alba*) 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 (Figure 5). The retrieved full-length piles were inserted in 3 different building years: 1727, 1886 and 1922. The species, building years, and dimensions of the piles are listed in Table 1.

2.2. Wooden piles tested in Venice

The materials consisted of 19 samples extracted from wooden foundation piles in four different foundation sites in Venice

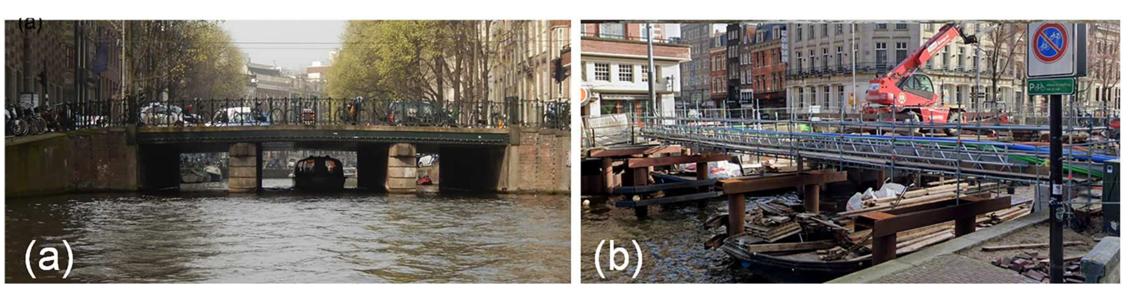


Figure 5. Bridges were the piles samples were collected: (a) Bridge 30 and (b) Bridge 41 (b) in the historic city centre of Amsterdam.

Table 1. Species, building year and dimensions of 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)	Average taper (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 (2.0)
	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)

Table 2. Number, code, and extraction depth of 19 timber pile samples extracted from 4 foundation sites (A1, A6, A8, A9, A10) of the Arsenal, from Riva di Biasio (RB), Rio S. Giustina (RSG), and Rio dei Greci (RG) in Venice.

Site	No.	Sample code	Extraction depth (m)
Arsenal	1	A1-1	4.5–4.9
	2	A1-2	5.0–5.6
	3	A1-3	6.4–7.0
	4	A6-1	4.5–4.9
	5	A6-2	5.0–5.2
	6	A6-3	5.6–6.0
	7	A8-1	5.9–6.0
	8	A8-2	6.3–6.6
	9	A8-3	6.6–7.0
	10	A9-1	5.8–5.8
	11	A9-2	5.8–6.3
	12	A9-3	6.3–7.0
	13	A10-1	3.7–4.2
Riva di Biasio	14	RB1	1.6
	15	RB2	1.6
Rio S. Giustina	16	RSG1	2.0
Rio dei Greci	17	RG1	1.8
	18	RG2	1.8
	19	RG3	1.8

(Arsenal, Riva di Biasio, Rio S. Giustina, and Rio dei Greci). The samples were extracted from piles at different depth from the ground level (Table 2), in fully saturated conditions, in order to study the distribution of bacterial decay in different locations along the piles. It should be noted that the piles in Venice were not removed from the soil or the foundations. Instead, samples in the form of drilled cores were extracted from the piles on site.

3. Methodology

3.1. Characterization of physical and mechanical properties of piles in Amsterdam

The full-scale logs retrieved from bridges in Amsterdam were cut into head, middle, and tip segments with a length of approximately 6 times the smallest diameter of the tapered pile sections (Figure 6) according to EN 408 (2010) (2012). 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 fibre saturation point (Ross 2021). This was done to recreate the same in-situ conditions where the piles were fully under the water table, in order to obtain comparable mechanical and physical properties during testing. The dry mass and moisture content were determined with the oven-dry method, according to the EN 13183 standard (CEN 2002), for two 30-mm-thick discs taken from both sides of each selected segment. Subsequently, basic density (BD) and Residual Basic Density (RBD) were determined, in order to assess the quality of the material in relation to potential degradation. BD was calculated as the ratio between the dry mass (MC = 0%) and the wet volume (fully saturated) of the discs. RBD was determined as the ratio between the measured BD, and the average basic density of sound spruce (*Picea abies*) and fir (*Abies*) from the same species (BD = 0.4 g/cm^3) derived from literature (Giordano 1988, Schweingruber 1990). In general, RBD gives an indication on the wood quality in relation to the average sound wood: RBD lower than ca. 70% indicates that the material is likely degraded (Macchioni *et al.* 2013).

3.1.1 Compression tests

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 according to the EN 14251 standard (2003), as in Pagella *et al.* (2022a, 2022b). 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 (Figure 7). 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 5 min according to the EN 408 standard 2012) the test continued

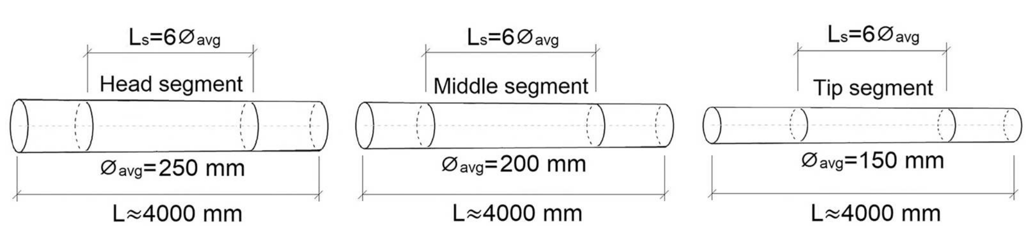
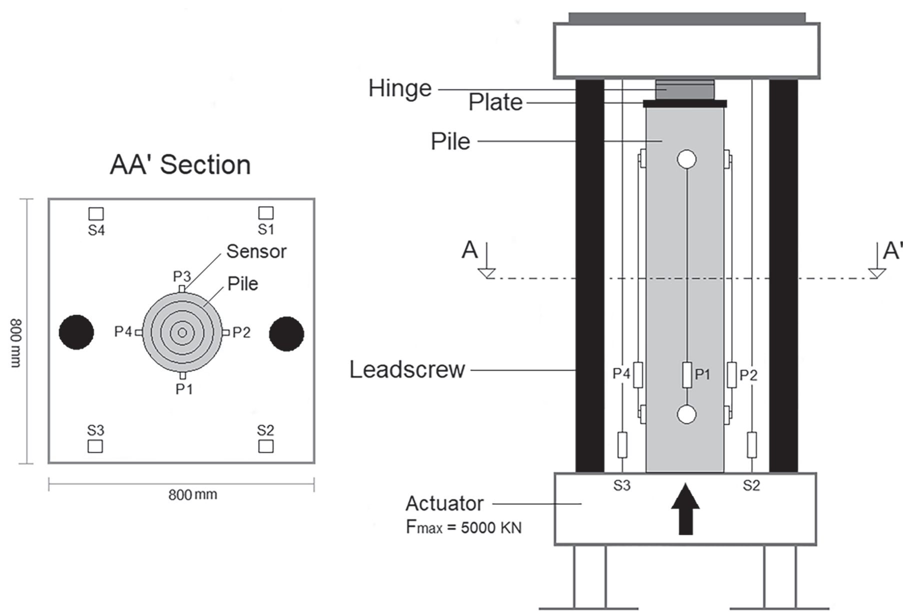


Figure 6. Cutting scheme and subdivision of the full-scale pile into head, middle and tip segments.



Name	Description	Sensor Type	Stroke (mm)
Actuator	Vertical actuator. Max force 5000 kN.	Hydraulic actuator	+/- 100
S_1, S_2, S_3, S_4	Vertical displacement between top and bottom steel plates of the compression machine	Linear potentiometers	+/-50
P_1, P_2, P_3, P_4	Deformation of the wooden pile measured on each side of the pile. The sensors span 2/3 of the length of the pile.	Linear potentiometers	+/-20

Figure 7. Compression test for a wooden pile segment tested at TU Delft and data measurements details.

at a higher speed until cracks were visible, and to show the post-peak behaviour of the pile (EN 14251, CEN 2003). Then, $f_{c,0,wet}$ was derived from the ratio between the maximum force reached in compression and the average cross-sectional area of each specimen.

3.1.2 Micro-drilling measurements

Micro-drilling measurements were adopted as an assessment technique to investigate the potential degraded portion of the cross section of timber piles in Amsterdam. Micro-drilling measurements fall within the non-destructive techniques used for wood inspection (Zobel and Buijtenen 1989, Gard and van de Kuilen 2018, Sharapov *et al.* 2018, Humar *et al.* 2021, Mirra *et al.* 2023). In this study, an IML-RESI PD 400 tool was used (IML 2024). During micro-drilling, a drilling needle was pushed into the material with a drill speed of 2500 r/min and a feed speed of 150 cm/min. The drill bit was 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, were plotted as resistance vs distance. Two micro-drilling measurements (A and B) were performed through the cross-section of each head-, middle- and tip-segment (Figure 8(a)), approximately 90 degrees to each other and 300 mm from the head of the segment (Figure 8(b)). 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 was far above the fibre saturation point, had no influence on the decay levels detected with micro-drilling signals, as demonstrated in Mirra *et al.* (2023). All segments were micro-drilled before mechanical testing, to have an accurate correlation between the material condition and the remaining strength properties.

A TU Delft-developed algorithm analyses micro-drilling signals A and B (Figure 8(c)), to assess degraded portions of historical pile cross-sections. The calibration and validation of the approach are described in Ravenshorst *et al.* (2024), and Pagella *et al.* (2024d). The algorithm utilizes Moving Average and Incremental Outwards Moving Average (IOMA) of the drilling signal to identify specific zones based on signal amplitude differences, assuming the centre of the pile is sound wood (Figure 8(d)). Four zones (z1-z4) are determined on each side of the signal, representing different 20% (z1), 40% (z2), 60% (z3) and 80% (z4) of maximum IOMA values on each side. The soft shell, indicative of degradation, is calculated as the sum of zones 1 and 2 (Ravenshorst *et al.* 2024). The total soft shell of a decayed cross-section is averaged from measurements on both sides, aiding in determining the remaining sound cross-sectional area (Figure 8(e)). Subsequently, the total soft shell of a decayed cross section was calculated as the average of the 4 lengths of the soft shell (SS), corresponding to left and right sides of micro-drilling signal A + B. From this, the average length of the soft shell ($a l_{SS}$) was calculated with

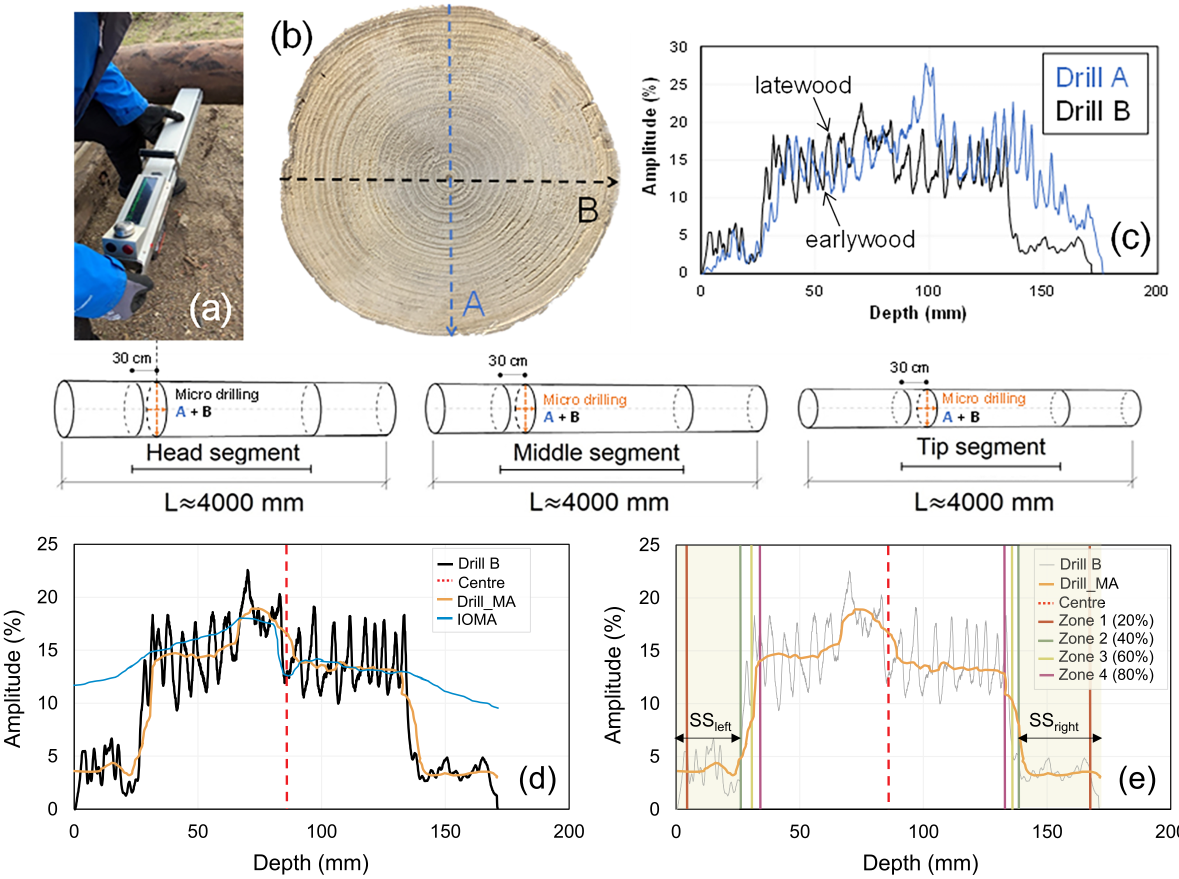


Figure 8. Test procedure: (a) micro-drilling measurements on a wooden pile, (b) drill A and B performed 30 cm from the head of the pile segment, (c) micro-drilling signal plotted as resistance (% of the maximum output engine power) vs distance (mm), (d) example of the analysis of the drilling signal (Drill B) with drilling moving average (Drill_MA) and IOMA from which the zones are calculated, and (e) 4 zones and soft shell (SS_{left} and SS_{right}) associated to zone 1 + 2.

Equation (1). al_{SS} derived using Equation (1) for the pile head can be considered the same along the entire pile, as the decay length obtained from the pile head closely match the decay length of the whole pile. This has been demonstrated in previous studies (Mirra *et al*. 2024, Pagella *et al.* 2024d).

$$al_{SS} = (SS_{A,left} + SS_{A,right} + SS_{B,left} + SS_{B,right})/4 \qquad (1)$$

3.2. Microscopical analysis and determination of wood species of foundation piles in Venice

The wood species identification was conducted with light microscopy observations in accordance with the Standard UNI 11118 (2004). Approximately 15-µm-thick sections were cut both manually and with a Leica RM2145 microtome along the 3 anatomical directions (transversal, radial-longitudinal, and tangential-longitudinal) of the wood samples collected from the 4 foundation sites (see Table 2) in Venice. The sections were stained with safranin, dehydrated, and then permanently mounted on slides. Each section was analysed with a Leitz Laborlux S microscope using normal and polarized light. The use of polarized light enabled the detection of birefringence, a typical feature of cellulose. Degradation of cellulose by bacteria results in a loss of birefringence, which was observed in previous studies (Klaassen *et al.* 2005, Singh *et al.* 2016, Björdal and Elam 2021, Mirra *et al*. 2024). In order to study in depth the amount of degradation, a Scanning Electron Microscope (SEM) was used for investigation. A Cambridge Stereoscan 250 connected to an analysis system Philips EDAX 9800 was used, located at the laboratory of the C.U.G.A.S. (Centro Universitario Grandi Apparecchiature Scientifiche) of the University of Padova. All samples collected from the four foundation sites in Venice were examined using SEM. From the dry samples, 15-µm-thick polyhedral sections were obtained. These were fixed with conductive adhesive tape to a metal plate, ensuring electrical conductivity by applying a layer of silver paste between the wood sections and the metal plate. Finally, a thin layer (10–30 nm) of gold was spread on the surface of the wood sections to improve the imaging and resolution of the samples.

The decay grade was determined by examining wood anatomical features such as holes, erosion channels, deterioration in cell walls, wall removal and detachments. These features were associated with specific decay levels, similar to the classification outlined in reference literature for wooden foundation piles (Varossieau 1949, Macchioni *et al.* 2013):

- No decay (class 0): All cell walls are smooth, and show clear, intensive birefringence under polarized light.
- Light decay (class 1): In earlywood, isolated tracheid cell walls are degraded, showing grooved-like erosion; in latewood, tracheids are free of degradation; Rare attacks visible on longitudinal cell walls.

- Moderate decay (class 2): Diffuse isolated degraded tracheids in a matrix of sound cells can be observed; in most earlywood tracheids, grooved-like eroded areas following the microfibrils angle are present, and these areas are sharply separated from sound cell walls. Latewood tracheids feature triangular-shaped notches;
- Severe decay (class 3): The majority of cell walls are decayed. Isolated sound cells in a matrix of degraded cells can be observed, with almost all tracheid cell walls fully eroded and often filled with amorphous residue material; in earlywood, grooved-like erosion channels in cell walls are present, following the microfibril angle. Since almost all cell walls are eroded, no birefringence is observed in them.
- Total disintegration (class 4): The identification of wood species can be very difficult due to complete detachments of the cell wall from the compound middle lamella together with collapses and distortions (visible both in cross and longitudinal sections) of cells.

BD and RBD were determined only from samples 14 to 19, collected from Riva di Biasio, Rio S. Giustina, and Rio dei Greci (see Table 2). Measurements for BD and RBD were not taken for the Arsenal foundations (A1 – A10) because the initial project, assigned to the University of Padova, exclusively focused on microscopy analysis for species identification and assessing decay type and level on the outer part of the cross-section. For samples 14–19, a reference average BD = 0.67 g/cm^3 was used for oak piles, and an average BD = 0.56 g/cm^3 was considered for larch (Giordano 1988). All samples were above fibre saturation with MC ranging from 60% to 160%.

4. Results

4.1. Strength properties in relation to the decay of wooden piles in Amsterdam, The Netherlands

The results of large-scale mechanical testing are presented in Figure 9, including a total of 201 pile segments extracted from 60 full-length spruce and fir piles. No significant difference in the mechanical properties was found between spruce and fir from building years 1886 and 1922, after carrying out a statistical analysis (two-sample t-test, one-tailed) two different groups (e.g. representing two different building years) to determine whether the mean value of one group was significantly greater or less than the other. However, the results are not included in this paper due to length constraints.

The results showed that the short-term compressive strength ($f_{c,0,wet}$) of all tested wooden piles (Figure 9(a)) was lower than the strength values of 'new' spruce: $f_{c,0,wet,mean}$ = 17.2 ± 2.6 MPa characterized in Pagella *et al.* (2024a), and $f_{c,0,wet,mean}$ = 20 ± 2.2 MPa determined in Van de Kuilen (1994). A considerable difference was measured between building years 1922/1886 (grouped as one category) and 1727. The $f_{c,0,wet}$ values of spruce piles from 1727 were approximately half those of the spruce and fir piles from 1922/1886, reflecting larger amounts of bacterial decay, causing pronounced reductions of $f_{c,0,wet}$ as demonstrated in Mirra *et al.* 2024. This can be attributed to the higher average soft shell determined with micro-drilling (Figure 9(b)), above 20 mm for piles from 1727. The average values of BD (Figure 9(c)) and RBD (Figure 9(d)) of piles from 1727 were also lower, confirming the presence of decay. The micro-drilling analysis conducted on head, middle-part, and tip of the pile segments, and supported by the TU Delft-developed algorithm (Pagella *et al.* 2024b), highlighted that the spruce pile segments from 1727 had a rather constant soft shell along the length of the pile. The soft shell was also measured in piles from 1922/1886, but on average limited to 5 mm. Finally, fir pile segments from 1886 exhibited minimal bacterial decay. This may be attributed to the inherently higher resistance of fir to decay (Klaassen *et al.* 2005, Mirra *et al.* 2024), the limited number of tested fir piles, or the fact that they exclusively dated back to 1886.

The highly decayed portions of the degraded pile segments could be correctly identified with micro-drilling measurements, and were coherent with the low compressive strength determined with compression tests of the segments, BD, and RBD. All the micro-drilling signals were performed on piles in saturated conditions. However, the wood decay can also be accurately analysed with micro-drilling independently of the MC gradient, as extensively demonstrated in Mirra *et al.* (2023). The results from small-scale compression tests on wood samples extracted along the piles' cross section, Computed Tomography (CT) scans of the piles' cross section, and light microscopy observations on thin radial sections retrieved from the cross section in correspondence to the micro-drilling measurements (extensively reported in Mirra *et al.* 2024), revealed that the investigated piles were decayed by bacteria. It was demonstrated that micro-drilling measurements are an effective method to analyse wood cross sections over a range of densities, either in the case of sound or decayed wood. The micro-drilling signals were well correlated with the material properties of the piles, providing both qualitative and quantitative information on the degradation state of the pile. However, bacterial degradation in wooden piles is still not well understood (Nowak *et al.* 2016, Singh *et al.* 2016), and it should be noticed that it cannot be excluded a priori that other degrading agents, such as soft rot fungi (in low-oxygen conditions), may be present in isolated areas of the piles or in other timber piles in Amsterdam.

The remaining short-term compressive strength was well correlated with the soft shell length, as shown in Figure 10, especially for piles from 1727, which exhibited a larger soft shell length, spanning from ca. 10 to 45 mm. The relationship between remaining compressive strength and soft shell of the piles can be implemented in future research, to build damage accumulation models taking into account the effect of decay over time on the strength properties of wood (Van de Kuilen 2007, Pagella *et al.* 2024d). This gives the possibility to have a direct estimation of the remaining short-term compressive strength from in-situ underwater micro-drilling of the piles.

4.2. Species identification and decay level of wooden piles in Venice, Italy

The microscopical analysis of the 19 samples extracted from the foundation piles of the four sites in Venice, showed very diverse wood species (Table 3). The majority of the piles of the Arsenal

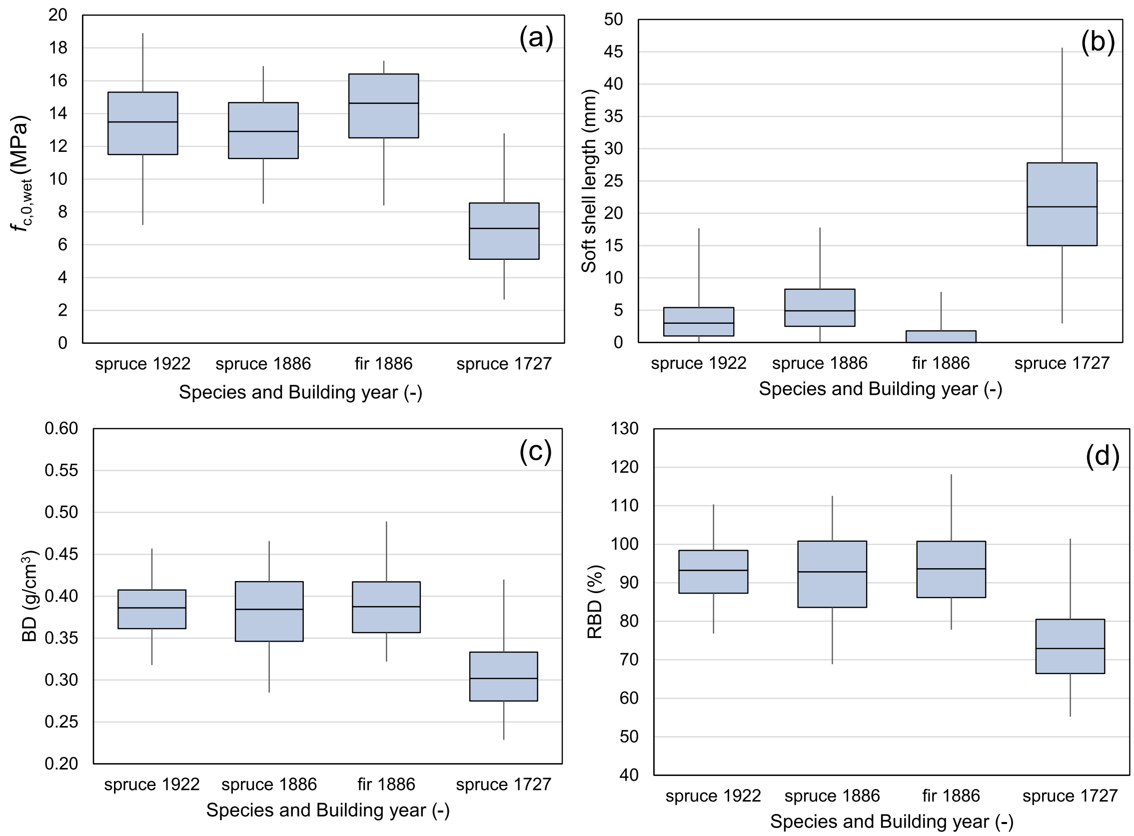


Figure 9. Box plots for (a) $f_{c,0,wet}$, (b) soft shell length, (c) BD, and (d) RBD of spruce and fir pile segments divided in 3 building years (1922, 1886, 1727).

(AY-X in Table 3) comprised hardwood, such as alder, elm, oak, and willow, but also softwood piles of larch were found. BD and RBD of the piles were measured only for three sites (Riva di Biasio, Rio S. Giustina, and Rio dei Greci), except from the Arsenal. The time in service of the piles could not be precisely determined. Based on literature studies of the Arsenal of Venice (Cecchini 2022, Bellavitis 2009), the building period could be estimated between 1100 and 1600. Due to multiple renovation works and expansions happened during the years, it remains difficult to determine the age of the individual investigated pile. However, a dendrochronological analysis would be recommended, to relate dating to the mechanical properties as in previous studies (Bernabei *et al.* 2019).

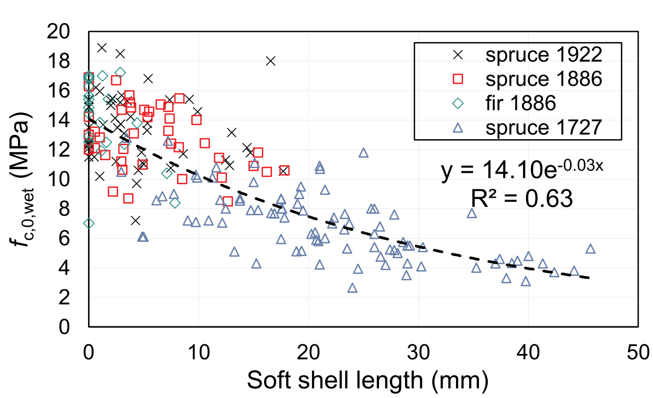


Figure 10. Relationship between $f_{c,0,wet}$ and the length of the soft shell of all the historic spruce and fir segments in Amsterdam.

The assessment of the decay level showed different levels of decay within the piles. However, the extension of the degradation within the cross-section of the pile in Venice could not be assessed, in contrast to the studies in Amsterdam, where micro-drilling allowed the characterization of the condition of the material throughout the whole cross section of the piles.

In general, softwood such as larch was more degraded than hardwoods, due to its inherent non-durable sapwood (Klaassen *et al.* 2005). Figures 11a, b show an example of species identification of a sample of larch viewed with the microscope. Figures 11c, d show SEM images of a severely degraded larch pile. In contrast, light decay was observed in all oak, elm and alder, suggesting a good conservation of these piles. Only larch and willow showed moderate to severe bacterial decay. No correlation was found between the extraction depth of the samples and the decay level, in line with the literature (Klaassen *et al.* 2005, Björdal and Elam 2021, Mirra *et al.* 2024) where bacterial decay is in general uniformly distributed along the pile.

It should be noted that the identification of bacterial decay patterns may be influenced by the employed methodology and wood type. Most reports in the literature focus on softwoods, where bacterial decay is easier to detect and visualize using standard staining and sectioning methods (Klaassen *et al.* 2005, Singh *et al.* 2016, Björdal and Elam 2021). This is primarily due to the relatively uniform structure of softwoods, which are composed of 90–95% tracheids with thick cell walls (Varossieau 1949). In contrast, identifying bacterial decay in hardwoods is more challenging because of their more complex anatomy,

Table 3. Species identification and level of decay for 13 samples extracted from four foundation sites in Venice.

No.	Samples code	Extraction depth (m)	Species	BD (g/cm$^{3)}$	RBD (%)	Decay level
1	A1-1	4.5–4.9	Elm (*Ulmus* sp.)			1 (light decay)
2	A1-2	5.0–5.6	Alder (*Alnus* sp.)			1 (light decay)
3	A1-3	6.4–7.0	Willow (*Salix* sp.)			3 (severe decay)
4	A6-1	4.5–4.9	Larch (*Larix decidua* Mill.)			2 (Moderate decay)
5	A6-2	5.0–5.3	Oak (*Quercus* sp.)			1 (light decay)
6	A6-3	5.6–6.0	Oak (*Quercus* sp.)			1 (light decay)
7	A8-1	5.9–6.0	Larch (*Larix decidua* Mill.)			2 (moderate decay)
8	A8-2	6.3–6.6	Alder (*Alnus* sp.)			1 (light decay)
9	A8-3	6.6–7.0	Alder (*Alnus* sp.)			1 (light decay)
10	A9-1	5.7–5.8	Larch (*Larix decidua* Mill.)			2 (moderate decay)
11	A9-2	5.8–6.3	Alder (*Alnus* sp.)			1 (light decay)
12	A9-3	6.3–7.0	Elm (*Ulmus* sp.)			1 (light decay)
13	A10-1	3.7–4.2	Oak (*Quercus* sp.)			1 (light decay)
14	RB1	1.6	Oak (*Quercus* sp.)	0.6	89	0 (no decay)
15	RB2	1.6	Oak (*Quercus* sp.)	0.6	86	1 (light decay)
16	RSG1	2.0	Larch (*Larix decidua* Mill.)	0.4	66	3 (severe decay)
17	RG1	1.8	Larch (*Larix decidua* Mill.)	0.4	70	2 (moderate decay)
18	RG2	1.8	Larch (*Larix decidua* Mill.)	0.4	70	2 (moderate decay)
19	RG3	1.8	Larch (*Larix decidua* Mill.)	0.4	70	2 (moderate decay)

which includes multiple wood cell types. This complexity increases the likelihood of bacterial decay patterns being overlooked in hardwoods.

5 . Discussion of the results

The amount of biological decay along the piles could be reliably assessed with the micro-drilling technique conducted on the piles from Amsterdam, where the measurements could be performed in multiple directions and specific areas on wooden piles. Micro-drilling can considerably improve the analysis of wood decay of the microscopy examination of drilled cores, providing a more comprehensive assessment of the decay distribution within the pile's cross section, without the need of laboratory testing. However, the analysis of drilled cores (See Section 1.2) has the advantage of determining

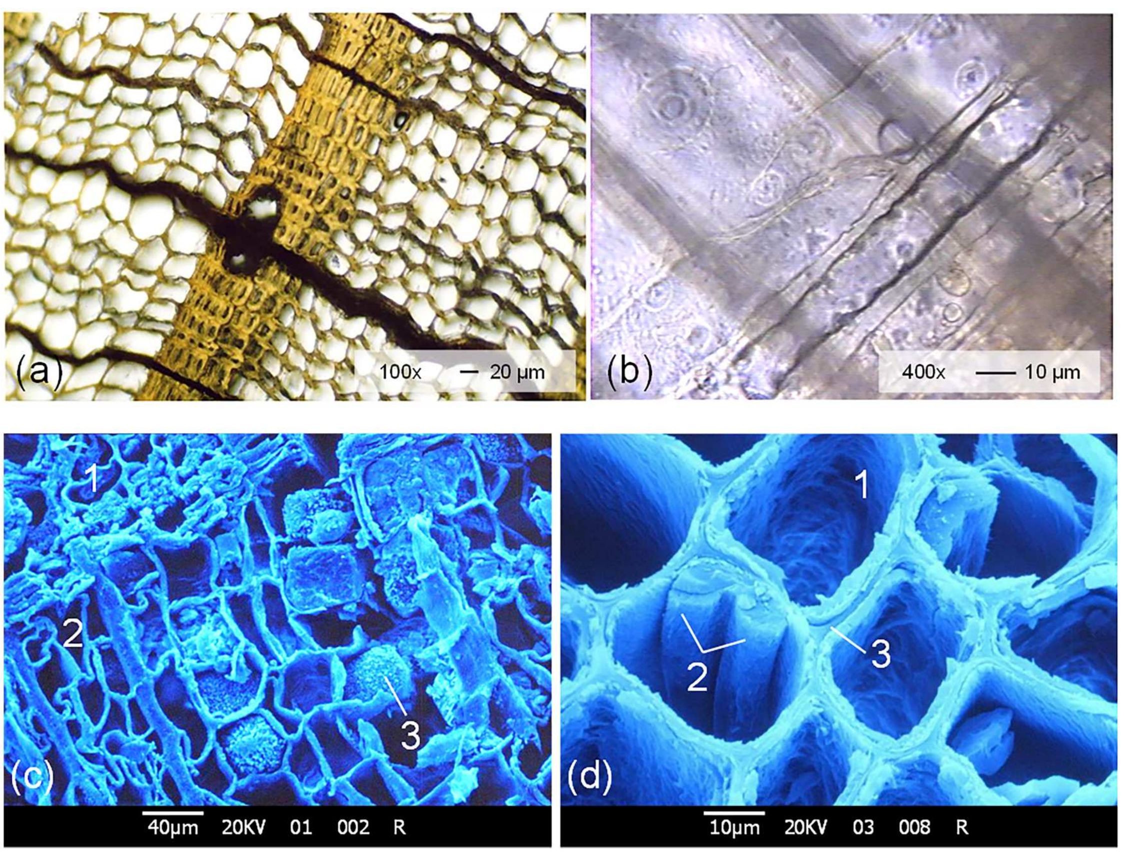


Figure 11. Example of species identification of Larch (*Larix decidua* Mill.): (a) cross section with abrupt transition between earlywood and latewood, (b) radial section with heterocellular rays and characteristic pits in marginal tracheids. (c), (d) SEM of larch pile RSG1, characterized by collapsed cells with thin walls in the (c1) latewood and (c2) earlywood, showing severe degradation, (c3) possible presence of what appear to be calcium carbonate crystals in the tracheids based on comparable literature pictures from University of Padova (However, this has not been verified with tests). (d1) signs of tunnelling in the cell, suggesting the attack of tunnelling bacteria, (d2) accumulation of silty and clayey material, and (d3) detachments of cell wall from the compound middle lamella, indicating the effect of erosion bacteria.

Table 4. Advantages and limitations of the analysis of drilled cores and micro-drilling measurements.

	Advantages	Limitations
Analysis of drilled cores	– Can determine the wood species. – Can assess the proportion of sapwood and heartwood.	– Localized analysis: it does not give a continuous representation of decay over the cross section of the pile. – Requires specific expertise and extensive laboratory investigations. Not suitable for pile sections that are embedded in the ground or for piles that are not visible.
Micro-drilling measurements	– Fast and accurate assessment. – No need of laboratory testing. – Direct prediction of the remaining compressive strength (Pagella et al. 2024b). – Independent of moisture content (Mirra *et al.* 2023)	– Cannot determine the wood species. – Dependent (in situ) on technician's and diver's expertise. – not applicable in pile portions embedded in the ground or in piles that are not visible.

the wood species and assessing the proportion of sapwood and heartwood within the pile. However, the accuracy of sapwood and heartwood distribution may be limited due to the localized nature of core extraction (Table 4).

The assessment of wooden foundation piles in Venice relies on the microscopy analysis of wood cores, based on laboratory testing to characterize their mechanical and physical properties (See Section 1.3). Similarly to the core extraction in Amsterdam (Klaassen *et al.* 2005), wooden samples in Venice are typically obtained from the core-drilling of piles using chisels, drilling tools, and borers.

The analysis conducted in this research identified various wood species of wooden piles across the four foundation sites of Venice, including alder, elm, oak, willow, and larch. Most of the wooden piles exhibited low levels of decay, with the exception of willow and larch, which showed severe and moderate decay, respectively. This is in line with the non-durable classification of larch (softwood), and hardwoods such as willow and elm (in contrast to oak) according to European standard EN 350. It is worth noting that heartwood is more resistant to bacterial decay under anoxic conditions compared to sapwood, as extensively demonstrated in the literature. However, the relatively low levels of decay observed in some hardwood piles might also be attributed to a shorter exposure period, which could have limited the extent of bacterial attack. Additionally, the localized extraction of samples, often not covering the entire cross-section of the pile, made it difficult to accurately estimate the decay depth. Thus, the analysis of the remaining sound cross-sectional area of the piles could not be performed – a useful information that may be used to assess the remaining strength of the piles. This limitation restricted the assessment to the overall condition of the pile, underscoring the cumbersome nature of the analysis of drill cores, as anticipated in Sections 1.2 and 1.3. The results in Venice support the broader findings of previous investigations (Section 1.3), which revealed a wide variety of wood species used for foundation piles and severe levels of degradation affecting different parts of the city. The degradation often resulted in significantly reduced mechanical properties of the piles. However, the current analysis of Venice's wooden foundation piles faces challenges due to a very limited database and difficulties in determining the construction time of the foundations. This highlights the importance of conducting further research to characterize the condition of wooden foundation piles in Venice. The future objective could be the expansion of the existing database and development of a standardized assessment method, potentially incorporating micro-drilling techniques similar to those successfully implemented in Amsterdam. The analysis of drilled cores and micro-drilling techniques can be used complementarily, combining the advantages and disadvantages of each method, as illustrated in Table 4. It should be noted that

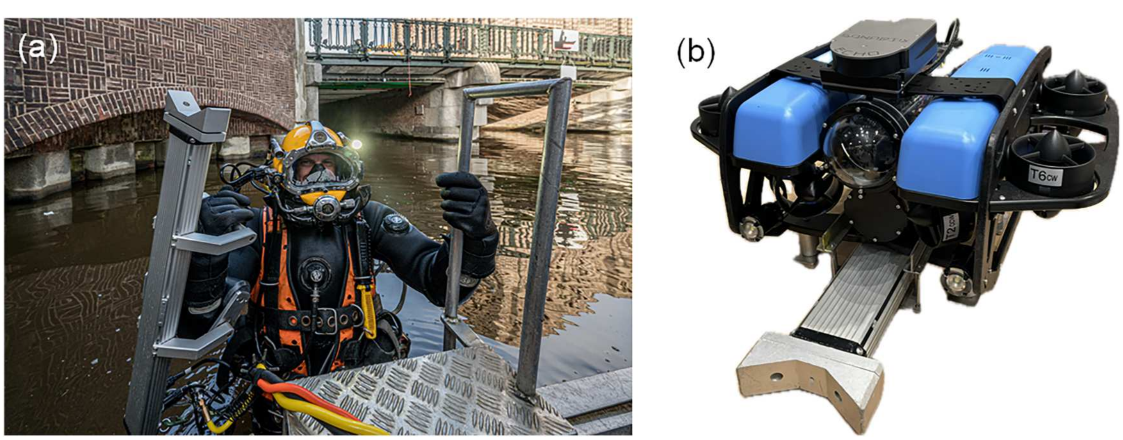


Figure 12. Micro-drilling conducted underwater on wooden piles by: (a) diver, and (b) prototype of ROV incorporating a micro-drilling tool developed by Baars-CIPRO (Baars-CIPRO 2024).

the applicability of micro-drilling in Venice may be limited due to the fact that the piles are concealed beneath the soil layer of the foundations of houses and bridges, as noted by Cavaggioni and Lionello (2009). Typically, the water in the canal is drained during periodic canal cleaning, using provisional dams installed between two consecutive points of the canal (Pizzo *et al*. 2016). This allows access to the foundations by carefully removing part of the soil covering the canal's side, enabling workers to examine the piles, extract wooden cores, and potentially perform micro-drilling measurements. An even more difficult challenge exists with houses in Amsterdam, where access to the foundation often necessitates removing the flooring of the house, facing the issues related with historical heritage of monumental buildings and troubles caused to residents. The scenario differs in Amsterdam for bridges and quay walls. In these cases, the upper part of the foundation (the heads of the piles) is accessible to divers underwater, since it is situated between the horizontal foundation and the canal's soil layer. It is important to note that micro-drilling may not be suitable for all Venetian or Dutch foundation piles due to the inaccessibility of piles that are either not visible or hard to reach, as well as the dense embedding of the piles in the ground.

6. Conclusions

The main objective of this work was to explore the currently most used assessment techniques to characterize the state of conservation of traditional wooden foundation piles in the cities of Amsterdam and Venice. These techniques were discussed in the light of their relevance and effectiveness in the contexts of the two cities, in assessing the impact of decay on the material properties of waterlogged wooden foundation piles that have been in service for centuries. The investigation techniques employed in Amsterdam currently rely on underwater micro-drilling measurements and the analysis of drilled cores from the wooden piles, whereas in Venice, only the analysis of drilled cores is used. In Amsterdam, micro-drilling was adopted on 60 wooden piles retrieved from two bridges in the city centre, built in 1727, 1886, and 1922. The micro-drilling technique allowed to accurately assess the impact of bacterial decay, by estimating the soft shell length and the remaining short-term compressive strength of the wooden piles. The micro-drilling signals retrieved from the piles are analysed using an algorithm developed by Delft University of Technology (NL), which estimates the "soft shell" of each pile: the degraded outer layer of the cross-section, to which zero strength is assigned.

The analysis of drilled cores in Amsterdam and Venice offers the advantages of a detailed decay investigation, allowing to determine the wood species and assessing the proportion of sapwood and heartwood within the pile. However, the accuracy of this technique may be limited due to the localized nature of core extraction.

The assessment techniques employed in Venice revealed varying levels of bacterial decay within the 19 samples extracted from wooden foundation piles at four different sites in Venice, ranging from no decay to severe decay in various hardwood and softwood species. This is in contrast with the results of previous assessments, where mostly severe decay levels were found, often related to a significant reduction of the mechanical properties of the piles.

However, no meaningful conclusions can be drawn regarding the overall state of conservation of the piles, as the analyses conducted in this study were localized to specific spots on the piles, and the available literature is based on a limited database.

Even though the different techniques for the assessment of the state of conservation of the wooden piles adopted in Amsterdam and Venice are complementary, micro-drilling offers the advantage of a non-destructive technique, and it allows a fast in-situ decay assessment and direct estimation of the remaining compressive strength of the wooden foundation piles.

The assessment technique based on micro-drilling is currently used on large scale in Amsterdam, where micro-drilling is conducted underwater by divers on timber foundation piles (Figure 12(a)), and by prototypes of remotely operated vehicle (ROV) incorporating micro-drilling tools (Figure 12(b)). The micro-drilling measurements allow inspections in different positions and directions, increased accuracy, faster in-situ testing, reducing costs and applicability. However, micro-drilling signals could be influenced by the accuracy and precision of the operator. It is always recommended to use at least two orthogonal micro-drilling measurements, to to increase the likelihood of achieving a more comprehensive and less localized assessment of decay. Micro-drilling represents a promising approach that could be adopted in Venice to improve the understanding of the state of conservation of the wooden foundations. Through micro-drilling, an extensive database of the state of conservation of the wooden piles can be collected and used in order to enable the planning of conservation and maintenance strategies, supporting the development of deterministic models and reliability-based design for assessing the remaining service life of wooden pile foundations.

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