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Structural assessment of centuries-old timber bridge foundations in Amsterdam’s historic centre

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Abstract

The majority of bridges in Amsterdam’s historic city centre are built on timber foundation piles, typically 12 to 15 meters in length, which function as end-bearing elements reaching the underlying stiff sand layer. Currently, many timber foundations have been in service for up to 300 years, raising concerns about their remaining load-bearing capacity and the overall safety of the bridges they support. The timber piles beneath the bridges remain fully submerged, where their outer cross-section is exposed to slow bacterial decay in anaerobic conditions, leading to a reduction in the sound load-bearing core of the piles. Despite decay, the piles maintain their structural capacity for many years, although their load-bearing capacity gradually decreases over time. The two primary risks are attributed to the applied loads exceeding the load-bearing capacity of the timber piles, and progressive damage accumulation over time due to sustained loading, ultimately leading to large settlements or failure. In this context, 201 pile segments were extracted from two bridges in Amsterdam and mechanically characterised, with respect to their amount of biological decay and service durations ranging from 100 to 300 years. Large-scale compression tests were carried out to determine the remaining saturated short-term compressive strength of the piles. Micro-drilling measurements were conducted to assess the amount of bacterial decay, validated with Computed Tomography (CT) scanning. On this basis, this study investigates the load history and current loads acting on the timber foundation of Bridge 30 (De Isa van Eeghenbrug) in Amsterdam, to assess the remaining load-bearing capacity of the historical piles, considering mechanical damage and decay as function of time.

Keywords: structural assessment; timber; biological decay; remaining load-bearing capacity; foundations;

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1. Introduction

1.1. Background

Many of the 100- to 300-year-old bridges in Amsterdam (NL) are supported by timber foundations (Klaassen et al. 2005). The foundation system typically consists of long vertical timber piles combined with horizontal cross- and longitudinal timber beams to support the masonry superstructure of the bridges (Gard et al. 2024, Pagella et al. 2025c). Traditionally, pine, spruce, and alder piles were used in Amsterdam, 10-12 m long and tapered. The piles were driven through the weak soil layers to reach the stable bearing sand layer, functioning as end bearing piles. Typical dimensions include diameters of 180-200 mm at the top and 120-140 mm at the tapered end (Klaassen et al. 2005). This foundation system is known as “the Amsterdam foundation” (in Dutch: *Amsterdamse fundering*).

Fig. 1. (a) batch of timber piles extracted from Bridge 30; (b) broken tapered end of the pile due to the effect of biological decay and compressive load; (c) part of horizontal foundation of Bridge 30.

1.2. Problem statement

The assessment of the state of conservation and remaining load-bearing capacity of timber foundation piles is important for ensuring their long-term durability and performance (Gard et al. 2024, Pagella and Urso 2025). When timber piles are in the ground below the water table, they can be subjected to biological decay, which may significantly reduce their load-bearing capacity, potentially leading to safety issues in the supported buildings (Pagella et al. 2024b). Biological decay in waterlogged soils can be caused by either soft rot fungi (in low-oxygen conditions), or bacteria even in anoxic conditions, as reported by Mirra et al. (2024). Bacterial biodegradation progresses more slowly over time compared to fungal decay, which cannot survive underwater in the absence of oxygen (Pagella et al 2024b). This allows the piles to perform their function for centuries before showing a substantial reduction of the load-bearing capacity. However, this poses a challenge in the engineering assessment of timber piles, exacerbated by the difficulty in inspecting the foundations hidden beneath the soil.

1.3. Scope

This study aims to assess the remaining load bearing capacity of historical timber foundation piles under Bridge 30 in Amsterdam. This is based on the approach of the reliable evaluation of bacterial decay with micro-drilling measurements (Pagella et al. 2024a) and the prediction of the residual load bearing capacity of the piles based on experimental data of the large testing campaign conducted in Pagella et al. 2024b.

2. Materials

The materials comprised 28 spruce piles that were retrieved from Bridge 30 (De Isa van Eeghenbrug) in Figures 2 and 3. The timber foundation piles were dated back to 1727, 1886, and 1922. The full-length specimens ranged from 9.5 m to 13.5 m, with an average head diameter of 230 mm and average tapered end (tip) diameter of 145 mm.

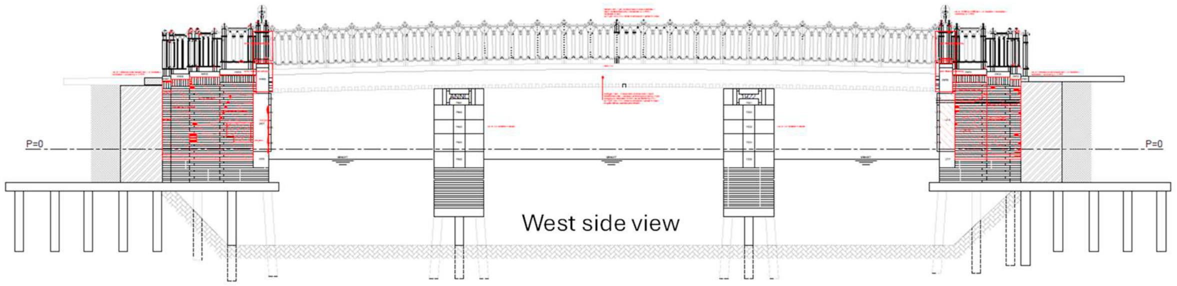


Fig. 2. West side view of the Bridge 30 in Amsterdam. Image courtesy of the municipality of Amsterdam.

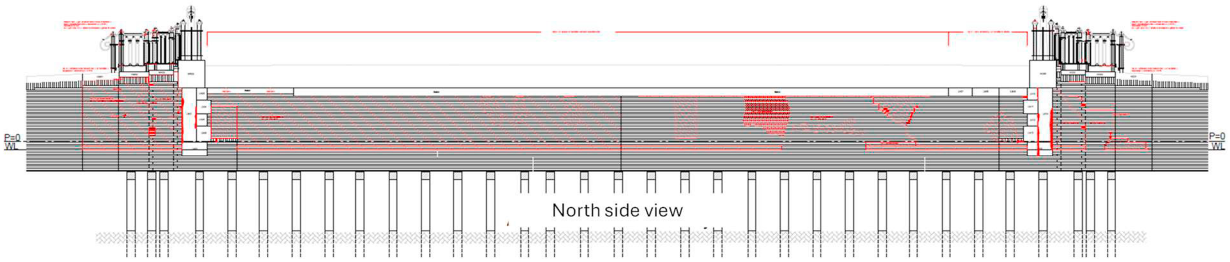


Fig. 3. North side view of the Bridge 30 in Amsterdam. Image courtesy of the municipality of Amsterdam.

3. Methodology

In this work, spruce (*Picea abies*) foundation piles were considered. Spruce piles represent the majority of the foundation piles used in Amsterdam (Pagella et al. 2025c), with a time in service (with reference to 2021) of 55 years up to 396 years. This is based on the analysis of 3713 drill cores taken from piles of bridges in Amsterdam where 68.4 % were made of spruce. However, a large part (28%) of pine (*Pinus sylvestris*) piles were also found.

The methodology for the assessment of the load bearing capacity of the piles under Bridge 30 was based on two large mechanical testing campaign:

- Characterisation of the mechanical properties by means of large-scale mechanical testing of 55 spruce (*Picea abies*) historic piles that have been in service for 100, 135, and 295 years (Pagella et al. 2024b). The piles were retrieved from two bridges in Amsterdam.
- The assessment and analysis of biological decay along 55 old spruce piles with the innovative utilization of micro-drilling measurements in Pagella et al. (2024a). The extent of decay within the piles' cross section was analysed by estimating the portion of sapwood with empirical models from literature, which were successfully validated with computed tomography (CT) scanning of 49 discs extracted from the piles. The decay rate of the pile is assumed to be constant over the years, until it reaches the sapwood-heartwood boundary. This is based on the analysis of historic piles in Amsterdam which showed that decay significantly slowed down or stopped upon reaching the heartwood.

These studies allowed to estimate the equivalent sound compressive strength assigned to sound core area (A_{sound}) of the tested piles for 300 years, giving useful information about the remaining mechanical properties, and the mechanical damage throughout the years of the sound core of the piles. The equivalent sound compressive strength of A_{sound} of piles from 1727 was lower than those from 1922 and 1886, due to a larger decayed portion of sapwood. This was associated with the intrinsic lower compressive strength of sound heartwood and juvenile wood and the effect of long term loading. The mechanical properties of timber decrease over time when subjected to a constant load. The 'duration of load' (DOL) effect describes the dependency of material strength on both the magnitude and the duration of loads (Svensson 2009). Phenomenological models, validated through extensive experimental studies (van de Kuilen and Gard 2012) were used by introducing a damage accumulation coefficient α that develops over time. The extent of 'damage' can be measured, facilitating the prediction of time to failure for specific material-load combinations (Yang et al. 2025).

To evaluate the long-term damage loss of timber piles under sustained loading, reference values were established using sound core piles dated 100 and 150 years old (from the experimental campaign in Pagella et al. 2024b). These piles showed no signs of degradation and were used to assess strength loss over time. Additionally, piles from the year 1727 were analysed. In the latter, the decayed portions of the cross-section were removed, and only the remaining sound core was considered in the strength evaluation. This approach enabled the reconstruction of a damage profile spanning up to approximately 300 years. For the baseline (0 years), the compressive strength of new spruce piles was used, based on data from the characterisation of 38 new spruce (*Picea abies*) piles presented in Pagella et al. 2025a. Two damage functions were taken into account (Figure 4): one for the head and middle sections of the pile (Fig. 4a), which exhibited similar strength characteristics, and another for the tapered tip (Fig. 4b), which differed from the other two sections by exhibiting lower strength. The two linear damage functions describe a strength decrease over time due to DOL effect, which is based on the large experimental campaign conducted on historical piles in Pagella et al. 2024b.

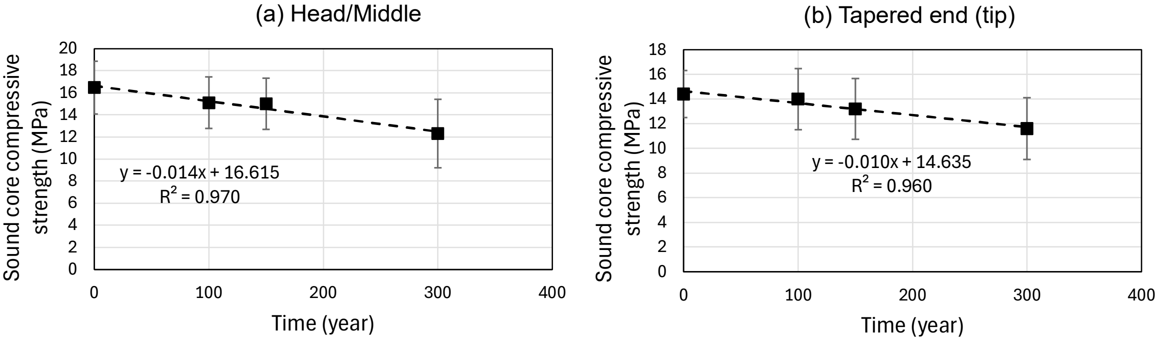


Fig. 4: Sound core compressive strength of (a) head and middle part and (b) tip of timber piles tested in 4 different time periods. The vertical bars represent the standard deviation.

The decay rate is assumed to follow a linear trend over time. This assumption is supported by micro-drilling measurements conducted during spruce pile condition assessment in Pagella et al. (2024a), as well as the analysis of a database of spruce drill cores from Pagella et al. (2025c). In these latter data, decay exhibits a generally linear increase over time until reaching a plateau (Fig. 5), which is likely associated with the sapwood–heartwood boundary. No data was available between 0-50 years. It is important to note that the data show considerable scatter, indicating variability in decay behaviour across different piles and conditions. For the bridges in Amsterdam, the decay assessment is based on micro-drilling measurements performed on the accessible portion of the pile, typically at the pile head located underwater. This method allows for the calculation of the average soft shell caused by decay as extensively reported in Pagella et al. (2024a). Based on micro-drilling measurements, the decay rate is calculated as the average depth of the decayed outer soft shell divided by the known age of the pile at the time of testing. The soft shell (the decayed outer part of the pile) measured at the pile head is assumed to be equivalent to the soft shell along the rest of the pile, more specifically in middle-part and tip (see Figure 6), according to the results of the analysis of historic spruce piles reported in Pagella et al. (2024b) and Mirra et al. (2024).

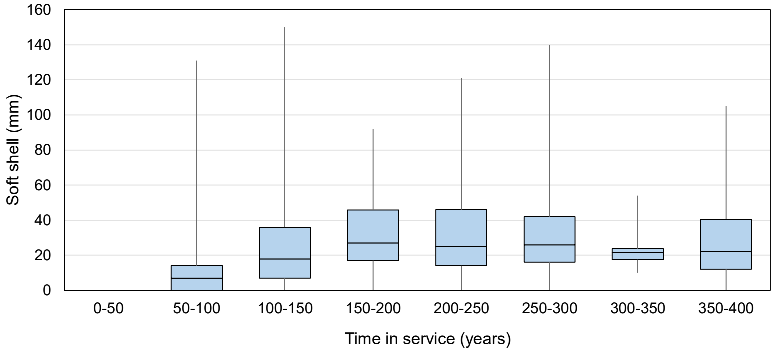
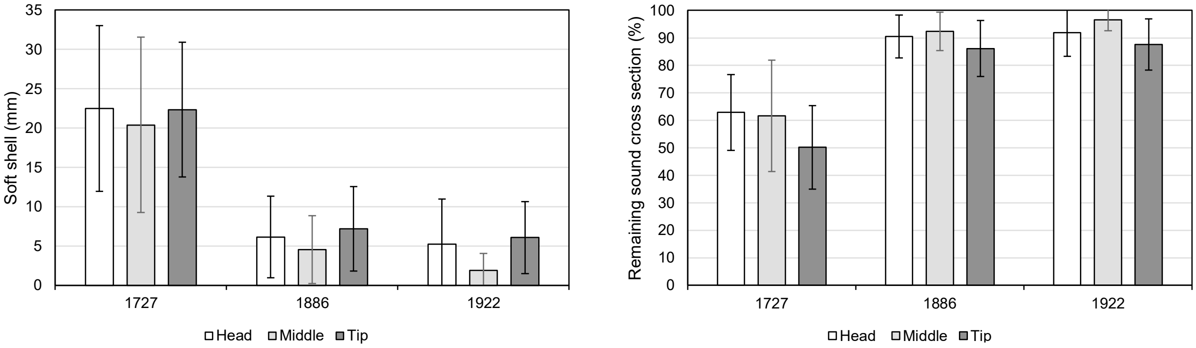


Fig. 5. Decay distribution (soft shell) for spruce piles between 0-400 years in Amsterdam based on the analysis of 2540 drill cores.



(a) (b)

Fig. 6. Visual comparison of the soft shell (a) and remaining sound cross section (b) along the piles' length obtained from micro-drilling measurements conducted on 60 piles from 1922, 1886, and 1727 in Pagella et al. 2024b.

The cross-sectional area of timber piles decreases over time as a result of decay, which gradually reduces the effective load-bearing section. This degradation continues until the decay front reaches the heartwood, at which point no further reduction in cross-sectional area is assumed. The area function follows a parabolic trend as function of the time as in Equation 1:

$$A_{sound}\ (t) = \pi\left(R - decay\ (t)\right)^2 \tag{1}$$

where R is the original pile radius at t_0, and *decay (t)* is the decay depth over time, calculated at time t_{end} and assumed as linear as previously explained. The forces acting on the timber foundation piles were subdivided into 7 distinct time intervals in Table 1 (up to 2020), selected as critical intervals during which notable variations in loading of the bridge were observed. For each interval, both the highest permanent load and a live load were estimated. These data were provided by the Municipality of Amsterdam, based on an analysis of the historical load progression for Bridge 30 (Fig. 7). Only the piles from 1727 were analysed in this paper, due to their longer service life and higher decay.

Table 1. Loads acting on piles from 1727 of Bridge 30 in Amsterdam.

Time intervals (year)	Correspondent timeframe in building years	Permanent load (kN)	Live load (kN)
0-159	1727-1886	24.4	10.9
159-173	1886-1900	20.6	2.7
173-195	1900-1922	20.6	2.7
195-206	1922-1933	26.9	3.3
206-236	1933-1963	26.9	3.7
236-285	1963-2012	26.7	2.7
285-293	2012-2020	26.7	2.8

To assess the mechanical response of the piles, the stress acting on each pile was computed for every time interval using the following Equation 2:

$$Stress\ (t) = \frac{F(t)}{A_{sound}\ (t)} \tag{2}$$

Where: $F(t)$ represents the total load (permanent and live load) at time t, and $A_{sound}\ (t)$ denotes the effective cross-sectional area of the pile at that time. The area is updated annually to account for reductions due to material decay, which gradually reduces the structural capacity of the timber.

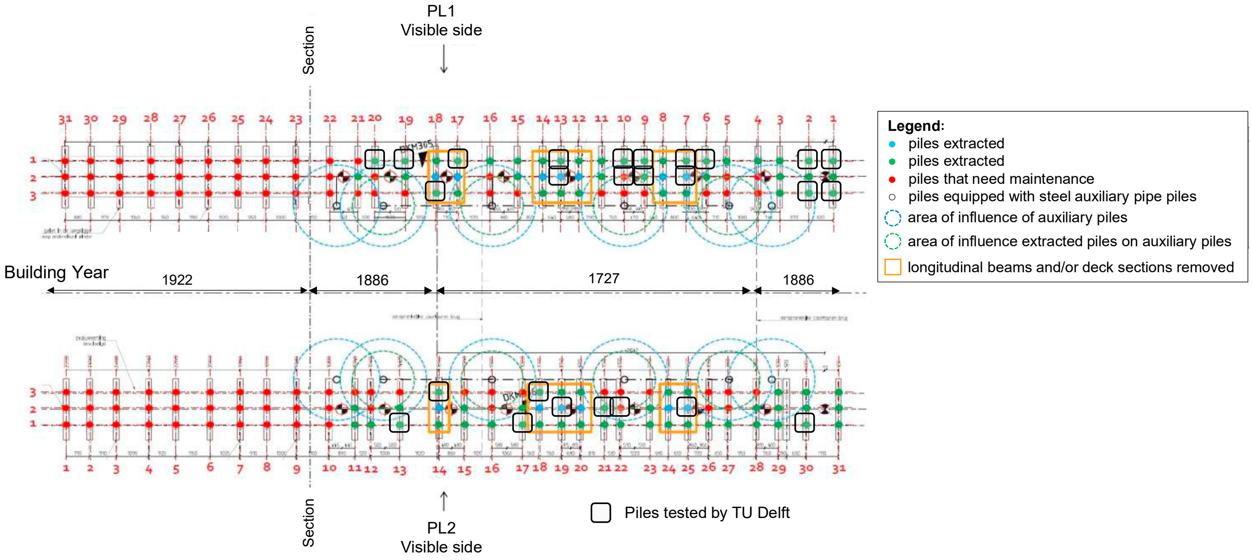


Fig. 7. Plan of piles layout of Bridge 30 in Amsterdam. Image courtesy of the municipality of Amsterdam.

4. Results

The results are based on empirical data from spruce foundation piles in Amsterdam and integrate decay progression, cross-sectional area loss due to decay, long-term strength degradation (due to duration of load), and time-dependent stress calculations. The analysis was conducted on a single pile tip (tapered end of the pile) from 1727 (row 1, column 6 in PL1 of Fig.7 – named P1.6), which was subjected to higher loads and exhibited a decay rate of 0.066 mm/year, according to micro-drilling measurements taken in 2020 (at t = 293 years). The pile tip had a diameter of 186 mm, and a heartwood-sapwood boundary depth of 47.9 mm measured from the outer cross section. This part was chosen since it corresponds to the critical section of the pile featuring the lowest mechanical properties, and depending on soil conditions, it could be subjected to high stresses during service due to its smaller cross section.

The reduction in cross-sectional area follows a parabolic trend as shown in Figure 8, and directly influences the load-bearing capacity over time. A year-by-year assessment of the remaining load-bearing capacity (LBC) of the timber pile is presented in Figure 9. Mechanical strength loss is integrated into the LBC calculations, using experimentally derived damage functions from 100- to 300-year-old spruce piles. Historical loading scenarios are also considered in Figure 9 to simulate stress evolution over time, based on the loading conditions described in Table 1. The plots indicate that after 293 years, the pile retains a sound cross section of 63% and a remaining LBC of 7.4 MPa. The applied stress on the pile at t = 293 years is 1.73 MPa, which remains well below the LBC. These findings suggest that, even after nearly 300 years in service, the oldest piles of the bridge are still capable of safely supporting the applied loads, which have been considerably lower than the LBC over the entire the service life of the pile.

In this study, only vertical loads were considered, comprising a combination of permanent loads and live actions. However, it is important to note that horizontal loads (not included in the current analysis) can also have a significant impact on the structural performance of timber foundation piles. The lateral forces can originate from wind loading, soil movement, differential settlement, and, notably, seismic activity. Especially in the Netherlands, regions like Groningen have experienced seismic activity in the past decades due to induced earthquakes from gas extraction (Mirra et al. 2021). Additional lateral stresses on foundation piles, already weakened by biological decay and DOL effects, could lead to structural instability.

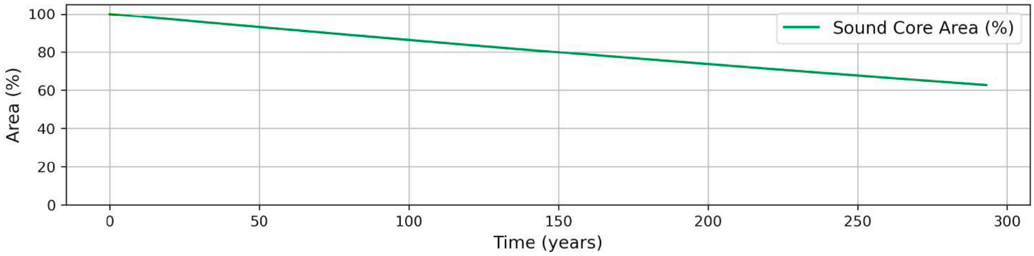


Fig. 8. Evolution of cross-sectional area as function of decay over time calculated for one pile (PL1, row 1, column 6) from 1727 in Bridge 30.

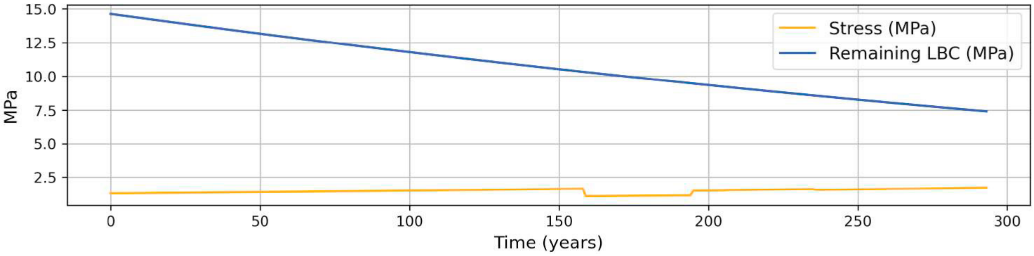


Fig. 9. Stress and load-bearing capacity (LBC) calculated for one pile (PL1, row 1, column 6) from 1727 in Bridge 30.

5. Conclusions

This study presents a detailed, year-by-year assessment of the structural integrity of the timber foundation piles of Bridge 30 in Amsterdam. The evaluation focuses on three key parameters: the sound core area of the timber as a function of time and decay development, the internal stress distribution, and the remaining load-bearing capacity over time. By integrating structural analysis with time-dependent deterioration data, the study introduces a consistent methodology for predicting the remaining service life of the foundation piles and identifying the timeframe during which structural failure may occur.

Decay progression was assessed using micro-drilling resistance measurements, a non-destructive technique that enables in-situ assessment of the cross-sectional decay at pile heads. These measurements are analysed to estimate the remaining sound cross-sectional area, under the assumption of uniform decay along the length of the pile, particularly between the head, middle, and tip. This assumption is critical, as the pile tip is generally the most vulnerable section: it has the smallest cross-section, exhibits the poorest mechanical properties, and – depending on soil conditions – often endures the highest service loads. As such, decay and higher stresses have the greatest potential to compromise the overall structural performance of the pile.

Despite being nearly 300 years old, the investigated pile P1.6, selected for its critical position within the foundation pier of Bridge 30, had sufficient load-bearing capacity to continue supporting the bridge. This highlights the inherent durability of well-preserved timber piles, particularly in anaerobic soil environments.

Although only one pile was analysed in this initial assessment, the methodology provides a solid basis for broader application. The approach was calibrate on the mechanical tests of spruce piles, which represent the majority of timber piles in Amsterdam. Future models can expand on this work to incorporate probabilistic decay rates, load histories, and soil-pile interaction effects across multiple piles. Such models will allow for more comprehensive predictions of remaining load-bearing capacity, helping to predict critical years when structural failure might occur due to progressive decay, increased loading, or a combination of these factors. In addition, the models can incorporate horizontal load components, including dynamic seismic loading, to evaluate the resilience of timber pile foundations under multi-axial stress conditions. This would enable a more comprehensive assessment of the structural reliability historic bridges in the Netherlands, particularly in the regions in the north of the country with known seismic vulnerability. Finally, this research contributes to the development of maintenance and rehabilitation strategies for aging timber foundations in historic infrastructure.

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