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Bacterial decay in wooden foundation piles—Patterns and causes: A study of historical pile foundations in the Netherlands

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Abstract

Many wooden foundations under historical buildings in the Netherlands are affected or threatened by bacterial degradation. This study provides some fundamental information for: (1) classification of the degree of degradation in relevant hardwood and softwood species by evaluating wood anatomical characteristics; (2) assessment of the degree of bacterial degradation in wooden foundation piles across pile diameters, and vertically, along the piles for an inventory; and (3) determination of the effect of the degree of bacterial degradation and specific wood technological parameters on the wood piles. The aim is to get a better understanding of those parameters that affect the degree of degradation. Based on observations from more than 2000 piles, different patterns of degradation across and along the piles are studied, and a simple model is presented to predict compression strength from the moisture content of increment cores taken from the pile head. With this model, it became possible to calculate whether a pile foundation in service is stable enough to remain in place and function as a support. A hypothesis is presented on water movement in the piles, which is identified as a key factor that stimulates bacterial wood degradation.

Keywords: Foundation piles; Bacterial decay; Pine; Spruce; Fir; Oak

1. Introduction

The northwestern part of the Netherlands is a delta formed from sediments deposited as the rivers Rhine and Meuse flow into the North Sea. The dynamics of and depositions from these rivers caused the formation of massive peat and clay layers on top of Pleistocene sand. The thickness of the clay and/or peat layer varies from less than 6 m, in the city of Haarlem, to a maximum of 16 m in Rotterdam. Due to the unstable nature of these top layers, most buildings were constructed on long wooden foundation piles, extending deep into the Pleistocene sand layer, until approximately 1950, when concrete piles were introduced. These wooden piles can be subjected to bacterial degradative processes under waterlogged conditions, endangering the supported buildings. In this paper, the different stages of bacterial degradation are defined, the factors that influence the degradation process are described and modelled to predict the compression strength of piles, and a hypothesis is proposed concerning the importance of water flow in the degradation process.

1.1. History of wooden foundation piles

The use of pile foundations started as early as the 15th century, when short stakes from different wood species were employed to support the erection of stone walls in Amsterdam (Gawronski and Veerkamp, 2003). From the 15th century on, longer, closely spaced piles were used to compress the soil and improve the foundations' supporting strength. During the 17th century, the inclusion of pile foundations, mainly from pine, spruce, and alder, became common practice; these piles were widely spaced and deeply driven into the stable sand layer. The construction of pile foundations needed skilled workers, and special guilds were founded where craftsmen could be organised (Wennekes and Grijp, 2002). The methods involved in foundation construction changed little during the 18th, 19th, and 20th centuries until the large-scale introduction of concrete foundation piles after World War II. During

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the past 50 years, wooden foundations have been used only for small buildings such as sewer systems, greenhouses, and sheds, where piles made of larch, spruce, fir, and Douglas fir were applied. The majority of buildings that were constructed on wooden pile foundations date to the beginning of the 20th century, when many Dutch cities expanded. Rough estimates suggest that more than 12 million wooden piles are in place, sometimes acting dysfunctionally, under Dutch (historical) buildings. Furthermore, this number is even higher if piles under quay walls and bridgeheads are included. Nearly all of the buildings in Amsterdam are founded on wooden piles, including the famous Royal Palace (1640), which rests on 13,659 wooden piles.

1.2. Degradation of wooden foundation piles

To guarantee the stability of wooden pile construction, and to prevent soft-rot decay (Savory, 1954), the upper level of a wooden foundation should always be positioned below the lowest expected groundwater height. Varossieau (1949) was one of the first to describe a specific pattern of degradation that occurred in wooden piles located permanently *under* ground water. This pattern occurred in 30- to 600-year-old spruce, pine, and fir foundation piles from the city of Rotterdam, but at that time, the type and cause of the degradation was unknown. It was later suggested that this type of degradation, i.e., degradation under (almost) anoxic conditions, was caused by bacteria. As a consequence, in the 1970s, pine was excluded as a foundation wood because of its susceptibility to degradation beneath the groundwater level (NNI, 1983; SKH, 1997; van Wijnpersse, 1931; Buiten, 1997).

Nilsson and his co-workers deserve credit for their work on the description of general patterns of bacterial wood degradation and the isolation of these bacteria (Daniel and Nilsson, 1986, 1997; Blanchette et al., 1990; Singh et al., 1990; Björdal et al., 1999). However, up to now only a few studies were made on the pattern of bacterial degradation throughout the whole length of a foundation pile (Boutelje and Bravery, 1968; Boutelje and Göransson, 1975; Van Bueren, 1987; Grinda, 1997; Björdal et al., 2000; and some internal reports of Dutch foundations). One aspect of this study is an effort to fill this gap by describing (macroscopic) degradation patterns in relation to timber species, soil type, and site hydrology and environment.

1.3. Wood-degrading bacteria

Wood-degrading bacteria comprise erosion bacteria and tunnelling bacteria. Erosion bacteria are rod or spherical in shape, 1–4 μm long, 0.5–1 μm thick, Gram-negative cells that lack flagella, but have a thick slime layer and are motile via gliding. A slime layer surrounds bacteria attached to the cell wall and only those attached in this way are able to degrade wood. Landy et al. (2007) described wood-degrading bacteria as specialised species, most likely belonging to the group of *Cytophagaceae* (gliding bacteria), that are able to deeply penetrate into the wood matrix, destroying cellulose and hemicelluloses. Bacterial degradation by erosion bacteria is mostly concentrated in the cellulose-rich S_2 layer, whereas tunnelling bacteria destroy all of the cell-wall layers. Severe degradation by erosion bacteria leave the S_3 and the compound middle lamella intact. These two remaining layers, however, are often strong enough to keep waterlogged wood in its original shape and even preserve traces of its manufacture on archaeological finds (Huisman et al., 2007). Nilsson and Björdal (2007) found that erosion bacteria are nearly always present in aquatic environments. Moreover, it has become clear from microcosm experiments that erosion bacteria can be active under anoxic conditions and are not stimulated by higher nutrient supply (Kretschmar et al., 2007). This last observation is in conflict with results from Boutelje and Göransson (1975), who described a positive relationship between nutrient availability and the degree of decay in foundation piles in Sweden.

1.4. Motivation and objectives of the research

During the 1980s, many approximately 100-year-old houses in the Dutch city of Haarlem showed cracks or became unstable. Although the groundwater was kept at a high level throughout this time, wooden foundation piles were severely degraded. Similar problems occurred in other Dutch cities as well. There was, therefore, an urgent need to make an inventory of the Dutch situation regarding the stability of wooden foundations and to produce systematic studies on the patterns, causes, and processes behind their degradation.

This article provides a survey of current research into bacterial degradation of waterlogged wooden piles in the Netherlands. It is comprised of the following study areas:

(1) A *classification of bacterial degradation* is presented based on wood anatomical characteristics for different species that are used in wooden foundations—namely pine, fir, spruce, and oak.
(2) A *macroscopic assessment of the degree of bacterial degradation* in wooden foundation piles is made whereby gradients both radial—i.e., across pile diameters—and vertical—along the piles—are presented.
(3) The *impact of (the intensity) of bacterial degradation on wood technological properties* is studied in order to predict the compression strength of wooden piles. A model is presented whereby moisture content and wood density are used as indicators/predictors of compression strength.
(4) From the information detailed in study areas (2) and (3), a model is presented to explain (i) the differences in susceptibility of different timber species to bacterial degradation and (ii) the relation between the degree of degradation of the piles and the surrounding (hydrological) environment.

2. Material and methods

2.1. Increment cores from the inventory of wooden foundations in the Netherlands

From 1995 to 2005, a total of approximately 2000 foundation piles were sampled and assessed according to a national standard that was defined for the inspection of wooden pile constructions (VROM, 2003). Most samples originated from the foundations of approximately 100-year-old historical buildings, mainly from Amsterdam but also from other Dutch cities. With a hand-driven increment borer (Ø10 mm), cores were taken from each pile at 50 cm below the pile head in a radial direction from the outside toward the centre of the pile. Each core was sealed, together with some groundwater, in a plastic tube and sent to the laboratory.

2.2. Stem disks from pile heads and whole extracted piles

In order to study the degradation pattern across and along the piles, extensive wood anatomical and wood technological investigations were conducted on stem disks (thickness ca. 20 cm) originating from pile heads, and on whole extracted foundation piles.

In total, 41 pile heads were taken from foundations of approximately 100-year-old buildings from Haarlem (12 pine), Dordrecht (11 spruce, 1 pine), and Amsterdam (7 pine, 2 spruce).

Twenty-seven piles with a maximum length of 14.5 m were extracted as a whole from six historical and two archaeological sites in the Netherlands, Germany, and Sweden (Table 1).

2.3. Reference material

Reference material was collected from a forest in the central part of the Netherlands. Stems were cut with a mean diameter of about 25 cm from five samples of pine, spruce, and oak. This material was used to evaluate the impact of bacterial degradation on the anatomical and technological properties, and moisture content, of piles excavated from the sample sites.

2.4. Wood anatomical structure and degradation patterns

Blocks (10 mm × 10 mm × 15 mm) were cut from the increment cores and over four radials of each stem disk prepared from the pile heads and extracted piles (sampled at 1-m intervals). Thin sections (20 μm) were prepared from the cross section and radial section of each of the consecutive blocks so that the anatomical features and degradation patterns across the whole radius of each sample could be evaluated. When cases of heavy degradation occurred, the thickness of the thin sections was increased to 50 μm.

Softwood was stained with Picrine Aniline Blue for 0.5–5 min; during staining the section was boiled for 1–5 s. Picrine Aniline Blue stains undamaged softwood green to yellow and heavily degraded wood dark blue. This stain will also penetrate fungal mycelium present in wood samples; colourless hyphae appear blue whereas the brown hyphae of blue-stain fungi retain their original colour.

Hardwood was treated for several minutes with safranin/astrablue, which stains wood deep red normally except for heavily degraded wood, which is coloured blue after staining. Black-coloured archaeological wood was bleached with chlorine for several minutes before staining. All sections were imbedded in glycerine for temporary storage.

The wood structure and the pattern of degradation were studied with a light microscope and under polarised light using final magnifications of 100, 200, 400, and 630. Sound wood shows strong birefringence, indicating the presence of intact crystalline cellulose, which diminishes with increasing cellulose degradation. Thin sections greater than 20 μm in thickness generally showed a higher intensity of birefringence than do thinner ones. Based on these wood anatomical observations, a species-specific classification detailing the degree of bacterial degradation was made. Samples exhibiting soft-rot degradation were excluded.

2.5. Wood technological properties

Wood technological properties were determined for each sample block in order to assess changes along the radius (cores and pile heads) and vertical axes of the extracted piles. The following properties were measured: specific gravity (wet volume/dry mass (kg/m^3)); density (dry volume/dry mass (kg/m^3)); and moisture content (wet mass−dry mass)/dry mass (w/w, %).

Volume determination was achieved using a modified method described by Panshin and De Zeeuw (1980): each sample block was fixed to a preparation needle, and placed under water for at a minimum of 10 s until it was water-saturated; the excess water was shaken from the sample, which was then submerged just beneath the water surface in a beaker placed on a scale. The force needed to submerge the sample is reflected as the increase in weight of the beaker-water-sample complex. When the increased weight stabilised for a period of 5 s, the additional weight was recorded and taken to be the equivalent of the weight/volume of the water that had been displaced by the sample. Dry mass was determined after drying for 25 h at 103 °C. A comparison between density and specific gravity showed that specific gravity is approximately 20% lower than density. However, because density values vary extremely in heavily degraded wood, specific gravity is a more reliable wood technological measurement.

The amount of sapwood in each pine and oak sample was determined. The sapwood–heartwood boundary in pine was detected by using anisidin (1 g *o*-anisidin, 2 ml HCl [90%] 98 ml demineralised water 1:1 mixture with 10% sodium nitrite solution in water) as staining reaction, whereas for oak the presence of tyloses in combination with the colour was used to indicate heartwood. Alder, fir, and spruce are regarded as timber species without visible sapwood.

Compression strength was measured on stems disks of pile heads and extracted piles. Two radial samples were taken perpendicular to each

Table 1
Origin, species, and site of the extracted piles

Origin	No. of piles	Diameter (cm)	Length (m)	Building period
Amsterdam (NL)	4 (2 pine, 2 spruce)	23	11	1926
Borselle (NL)	2 (oak)	18	2	1st century
Haarlem I (NL)	3 (poplar)	13.5	4	1895
Haarlem II (NL)	6 (pine)	12	1	1900
Rotterdam (NL)	3 (1 fir, 2 spruce)	25	14.5	1903
Zaandam (NL)	3 (pine)	11	7	1937
Stockholm (S)	2 (pine)	25	6	1895
Travenhorst (D)	3 (oak)	27	1.5	Late medieval

The building period of the object from which the piles where extracted is also given.

other, with one of them located in the vicinity of the sample used for the wood anatomical study. The two radials were separated into a series of small test blocks (20 mm × 20 mm × 30 mm). Occasionally the small size of some stem disks did not allow the preparation of standard test samples (20 mm × 20 mm × 60 mm; ISO 3131, 1975). To check whether the resulting reduced sample size influenced the determination of the compression strength, 30-mm- and 60-mm-long blocks from the same pine, oak, and spruce trees were tested. The results showed that the influence of the block length on the compression strength was smaller than the variation of the strength properties within the wood. The compression strength of each block was determined on a test bank, and the maximum load was achieved in 1–2 min. Subsequently, the specific gravity and moisture content of each block were determined.

To check whether the compression strength of sound ca. 100-year-old foundation piles changed with time, a comparison was made with freshly felled timber (reference material). The compression strength of testing blocks ($\approx 12\,\text{cm}^3$) without degradation originating from foundation piles which were at least 80 years in service were compared with blocks taken from freshly sawn stems. No oak or alder material that was free of degradation was available for study.

The mutual relationship between compression strength, moisture contents, specific gravity, and degree of degradation was used to construct a model, which predicts compression strength of foundation piles from moisture content, specific gravity, and degree of degradation.

3. Results and discussion

3.1. Classification of bacterial degradation

Five categories were defined for classifying the degree of degradation due to erosion bacteria in pine, spruce and fir, and oak and alder (Table 2). In conifer diagnostics changes in wood anatomy resulting from bacterial degradation are best visualised in the radial/longitudinal sections (RS in Figs. 1 and 2), whereas degradation patterns in oak wood can be best evaluated by screening the cross section (CS in Fig. 3). Samples with other types of decay were omitted from this description.

Although the patterns of degradation caused by erosion bacteria have been described previously, the definitions of different stages of degradation, as classified in this study, are novel. Before discussing the results of this study, it has to be mentioned that it became more difficult to distinguish between the degradation caused by erosion and tunnelling bacteria, or even that caused by fungi, with increasing levels of degradation. The general patterns of degradation that were observed in the softwood species agreed with those described by Blanchette et al. (1990) as caused by erosion bacteria. Typical features that can be observed in cross section are single degraded tracheids within a matrix of sound cells. Along the radial longitudinal section, the groove-like erosion pattern in the EW tracheid walls follows, more or less, the microfibril angle, and "V" notches occur in the latest LW tracheid cell walls. Moreover, a sharp demarcation between eroded and sound cell-wall material is obvious. In oak and alder, the pattern of erosion bacterial degradation is more difficult to recognise: here, the presence of single degraded fibres within a matrix of solid cell tissue, viewed in cross section, and the absence of fungal hyphae or fungal degradation patterns is typical. In longitudinal sections, eroded cell walls are difficult to recognise. However, differences in staining intensity and the presence of a groove-like pattern are typically observed in degraded areas.

Only a limited number of studies on the pattern of bacterial degradation in oak and other temperate hardwood species have been published (Hoffman et al., 1986: *Quercus*; Schmitt and Hoffmann, 1998: *Quercus*; Blanchette et al., 1991: *Castanea*, *Fraxinus*, *Torreya*; Schmidt, 1980: *Fagus*; Blanchette and Hoffmann, 1993: *Quercus*, *Ulmus*, *Alnus*). All of them confirm the general patterns found in this study.

The classification of the degree of degradation was used to assess gradients across cross sections of pile heads and whole piles and to link them to technological properties.

3.2. Degree of bacterial degradation along whole extracted piles

All 27 extracted piles were degraded along the whole pile length, and the degree of degradation along the pile did not change for most of them. Only some showed a slight increase in degree of degradation with increasing depth. In three 14.5-m-long piles from Rotterdam (two spruce, one fir) wood degradation was restricted to the outermost 1–2 mm, whereas two 11-m-long spruce piles from Amsterdam showed a gradient from severe to weak degradation in the outermost 25 mm. Two extracted pine piles, from the same Amsterdam site, exhibited severe degradation of the whole sapwood area, comprising the outermost 45 mm of the radius. This pattern was also observed for almost all of the other extracted pine piles from Haarlem, Zaanstad, and Stockholm (Table 1); the sapwood of these piles was severely degraded mainly over the whole pile length. Heartwood degradation was the exception in all of these samples that were tested.

The three short poplar piles from Haarlem were severely degraded across the whole diameter and length. The five extracted oak piles from Travenhorst and Borselle (Table 1) originated from an archaeological site and were much older than the other piles, with the oldest being around 2000 years old. These oak piles showed a gradient from severe to weak bacterial degradation across the entire radius and length of the pile. The oak sapwood was always severely or even totally degraded, whereas in the heartwood the degree of degradation was moderate and decreased toward the pith of the pile.

In summary, it can be said that all the extracted piles were degraded by bacteria over their full length with no observable gradient across pile length, if the conical stem form is taken into consideration. However, based on the limited amount of samples studied, local higher degradation intensities across the pile length cannot be excluded. The results presented in this paper suggest that the status of the pile head, in terms of degradation assessment, can be regarded as representative of the whole pile. This is important because, when inventories are taken, for

Table 2
Classification of degree of bacterial degradation in pine, spruce, fir, alder, and oak

Degradation	Changes in wood anatomy of pine
Absent	All cell walls smooth, clear intensive birefringence under polarised light.
Weak	Ray cell walls and parts of isolated late wood (LW) tracheids cell walls degraded (Fig. 1a) in longitudinal sections "V" shaped notches of eroded cell-wall material (Fig. 1b), along with smaller "V" shaped notches in the S_1 layer and larger notches reaching with the pointed side of the "V" in the S_1 layer; notches concentrated near tracheid-ray connections; in some early wood (EW) tracheids cell wall with small eroded grooves (Fig. 1c).
Moderate	Isolated degraded cells in a matrix of sound cells with a higher intensity round the rays, larger notches in more (adjacent) LW tracheids; notches further away from the tracheid-ray connection, coalescent (Fig. 1d); within a tracheid demarcation between sound and degraded cell-wall parts sharp, at an angle of about 45° to cell axis; in more EW tracheids eroded areas in a grooved-like (Fig. 1e).
Severe	Isolated sound cells in a matrix of degraded cells, diffuse (Fig. 2f) almost all tracheid cell walls fully eroded and filled with amorphous residue material; EW tracheid cell wall fully eroded in grooved-like pattern following more or less the micro-fibrilaire angle (Fig. 2d); in some tracheids small areas with intact cell wall, sharply separated from completely degraded cell-wall areas with the separating line orientated at angle of 45° to cell axis (Fig. 1f, g).
Total disintegration	Although different cell types still be recognised, all cell walls completely eroded except for the compound middle lamella and some parts of the S_3; all former cell layers substituted by an amorphous residue material; no birefringence and no clear pattern of degradation visible.
Degradation	**Changes in wood anatomy of spruce and fir**
Absent	All cell walls smooth, clear intensive birefringence under polarised light.
Weak	Isolated EW tracheid cell walls degraded; although small areas with grooved-like cell-wall erosion present, not necessarily associated with ray cells (Fig. 2a). LW tracheids (almost) free of degradation.
Moderate	Isolated degraded tracheids in a matrix of sound cells, diffuse (Fig. 2c); in most EW tracheids eroded areas, grooved-like following the microfibril angle, these areas sharply separated from sound cell walls; adjacent LW tracheids with small "V" shaped notches, not related to tracheid-ray connections (Fig. 2b).
Severe	Isolated sound cells in a matrix of degraded cells, diffuse (Fig. 2f), most all tracheid cell walls fully eroded and filled with amorphous residue material; erosion in EW tracheid cell wall grooved-like, following more or less the micro-fibril angle (Fig. 2d); in some tracheids small areas with sound cell wall sharply demarcated from the degraded area at an angle of 45° to cell axis (Fig. 2e).
Total disintegration	Although different cell types still be recognised, all cell walls completely eroded except the compound middle lamella and sometimes parts of the S_3; all former cell layers substituted by an amorphous residue material. No birefringence and no clear pattern of degradation visible.
Degradation	**Changes in wood anatomy of oak and alder**
Absent	All cell walls smooth, clear and intensive birefringence under polarised light.
Weak	Walls of single cells of the tracheary tissue around the vessels (partly) eroded; accumulation of amorphous residue material in cell lumen (Fig. 3a, b), adjacent fibres with swollen cell walls (Fig. 3c).
Moderate	Walls of most cells of tracheary tissue eroded and filled with residue material, with a reduction of birefringence; many fibre cell walls swollen, with erosion starting from lumen onwards. Increasing degradation intensity of fibre walls indicated by changes in staining (safranine/astrablue) from red via light red to blue; birefringence intense for most fibre cell walls, under polarised light and they appear as light-reflecting "islands" in a matrix of degraded tracheary tissue (Fig. 3d–f). Degradation of ray cells follows the pattern of the fibres but often starts in a later stage.
Severe	Cell walls of many fibres completely eroded and filled with an amorphous material; no birefringence. Single sound fibres imbedded in a matrix of degraded fibres (Fig. 3g–i). Degradation pattern and intensity of the affected tissue not related to location of the rays. Some of ray cells degraded (Fig. 3j).
Total disintegration	Although different cell types still be recognised, all cell walls completely eroded and all former cell layers except the compound middle lamella and sometimes parts of the S_3 are substituted by amorphous residue material. Most cells lost their birefringence with the exception of the cell walls of the (EW) vessels, indicating that cell walls of vessels have a high resistance against bacterial degradation (Fig. 3k–m).

RS: radial section; CS: cross section; EW: early wood; LW: late wood; EB: erosion bacterial decay.

practical reasons the degree of degradation is assessed by studying pile heads only.

3.3. Degree of degradation in pile heads

Based on more than 2000 pile-head samples (cores and disks), the mean degree of degradation for most intensively sampled Dutch cities was determined and summarised in Table 3. For each city, the mean degradation depth was calculated for the classes severe, moderate, and weak. The degree of degradation decreases in all piles from the outside to the pith onwards. In Fig. 1, an estimation of the pile-head dimension per city is given. Amsterdam is the most intensively studied site because the city government will not permit building construction or the selling of property without an insurance statement on the quality of foundations. In other cities, samples were taken only when problems appeared with the stability of the building. In general, the timber species used for foundation piles is city-specific and seem to be related to the length of the piles

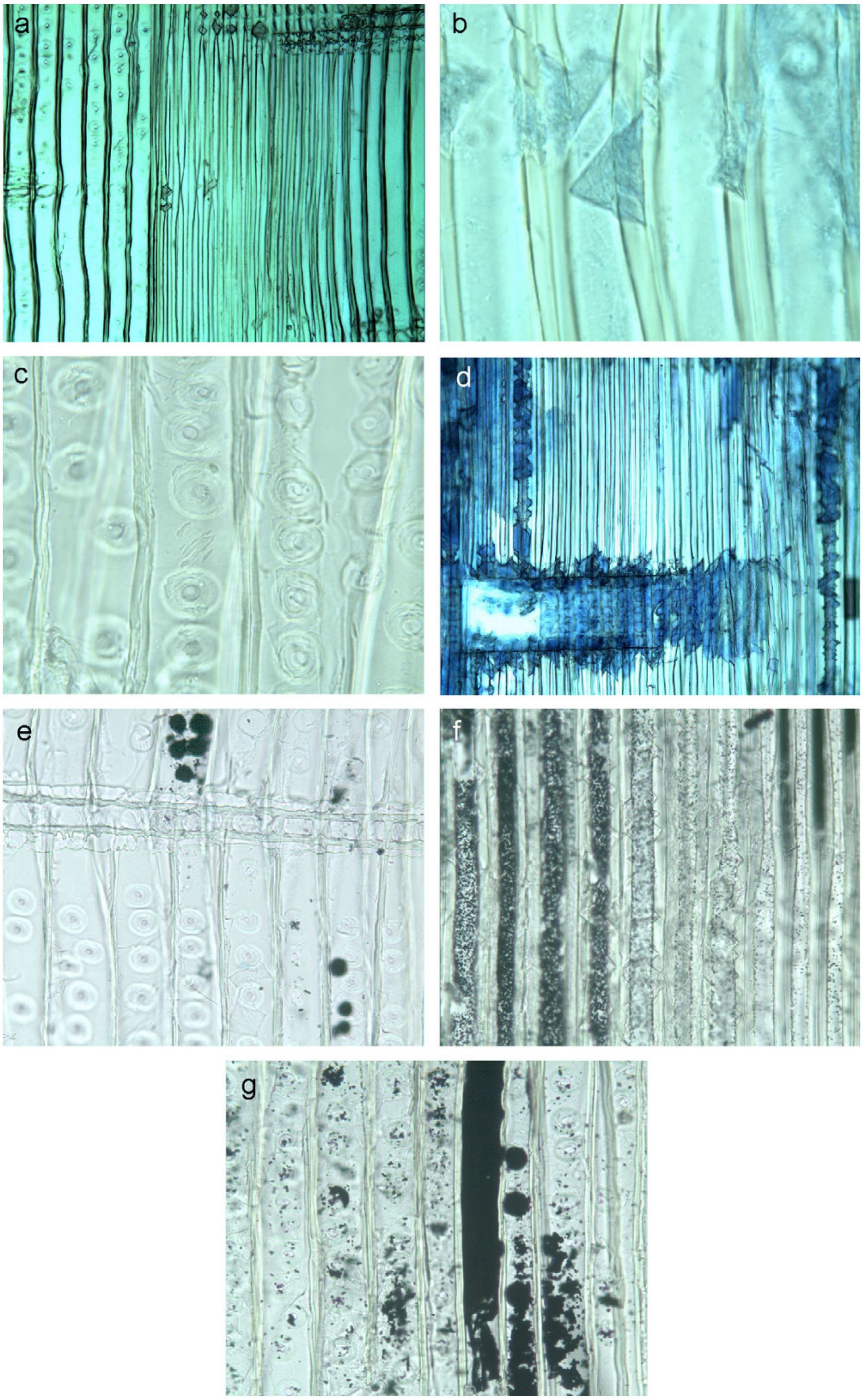

Fig. 1. (a) RS, pine, weak EB in LW tracheids, especially adjacent to the rays (100 ×). (b) RS, pine, weak EB in LW tracheids, locally degraded cell-wall areas, "V" shape notches of eroded (granular, blue-stained) cell wall area (630 ×). (c) RS, pine, weak EB, groove-like erosion local in EW cell wall (630 ×). (d) RS, pine, moderate EB, LW tracheids over the whole length degraded, "V" shape notches coalescent and differing in intensity per cell. Extensive degradation in LW next to ray (200 ×). (e) RS, pine, moderate EB, EW tracheids cell walls locally degraded with sharp boundary to sound cell wall area, pyrite in cell lumen especially around the pits (400 ×). (f) RS, pine, severe EB in all LW tracheids over whole length in high intensity, lumen filled with pyrite (200 ×). (g) RS, pine, severe EB, EW tracheid, almost fully degraded cell wall, high pyrite concentration in cell lumen especially around the pits (400 ×).

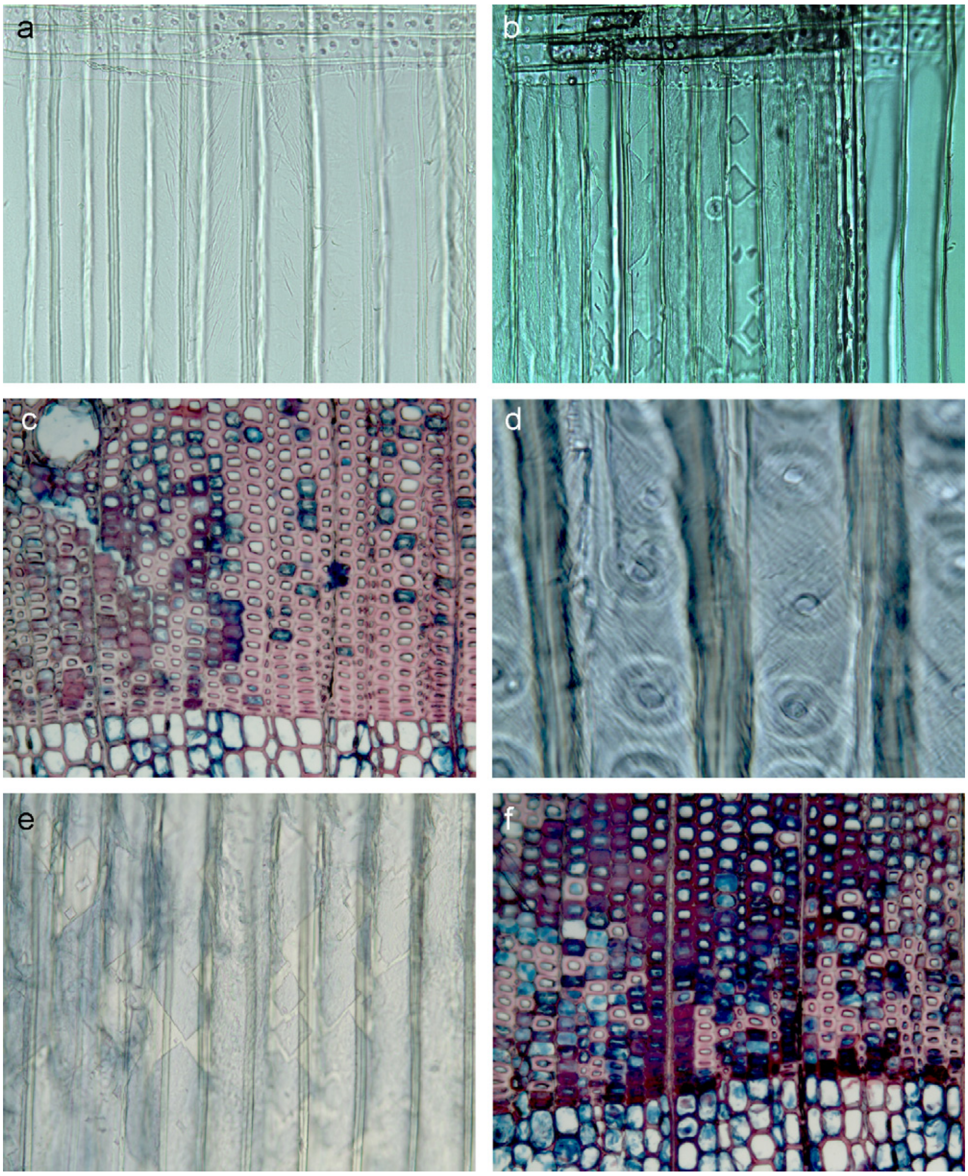

Fig. 2. (a) RS, spruce, weak EB, EW tracheids with groove-like erosion (200 ×). (b) RS, spruce, moderate EB, mainly in EW tracheids, coalescence of degraded cell wall areas, not related to rays (100 ×). (c) CS, spruce, moderate EB, single degraded cells within a matrix of sound cells (blue-purple cells are severely degraded) (100 ×). (d) RS, spruce, severe EB, EW tracheids, whole cell wall areas groove-like erosion (630 ×). (e) RS, spruce, severe EB, LW tracheids fully degraded, some remaining sound cell wall between coalescing of V-shaped notches (200 ×). (f) CS, spruce, severe EB, single non-degraded cells within a matrix of degraded cells (blue-purple cells are severely degraded) (100 ×).

needed in order to reach a stable sandy soil layer. In Haarlem, Den Hague, and Zaandam primarily short pine piles were used, whereas in Rotterdam, Dordrecht, and Wilnis mainly long spruce piles were employed. In Amsterdam both species were used, as well as alder—a species that was in use before 1850—in foundations older than 150 years. Another species occasionally used was fir, which is often intermixed with spruce piles.

Fig. 4 illustrates the general degree of bacterial degradation in combination with the mean sapwood width, only for those cities where at least 40 piles were studied as well as for oak from three archaeological sites. Fig. 4 shows the differences in degree of degradation in relation to species and location.

Although there is great variation in the degree of degradation among piles of the same species from a city site (Table 3), clear trends were observed related to the different species, their location, and age. In each city, pine is more heavily degraded than spruce. Fir shows characteristics similar to spruce in degradation. Alder, which is only found in Amsterdam, is almost completely degraded. In most pine piles, the whole sapwood layer is moderately to severely degraded, whereas almost all heartwood is sound (Fig. 4). This almost exclusive restriction of erosion bacterial degradation to sapwood explains the direct relationship between the amount of sapwood and the degree of degradation in ca. 100-year-old pine.

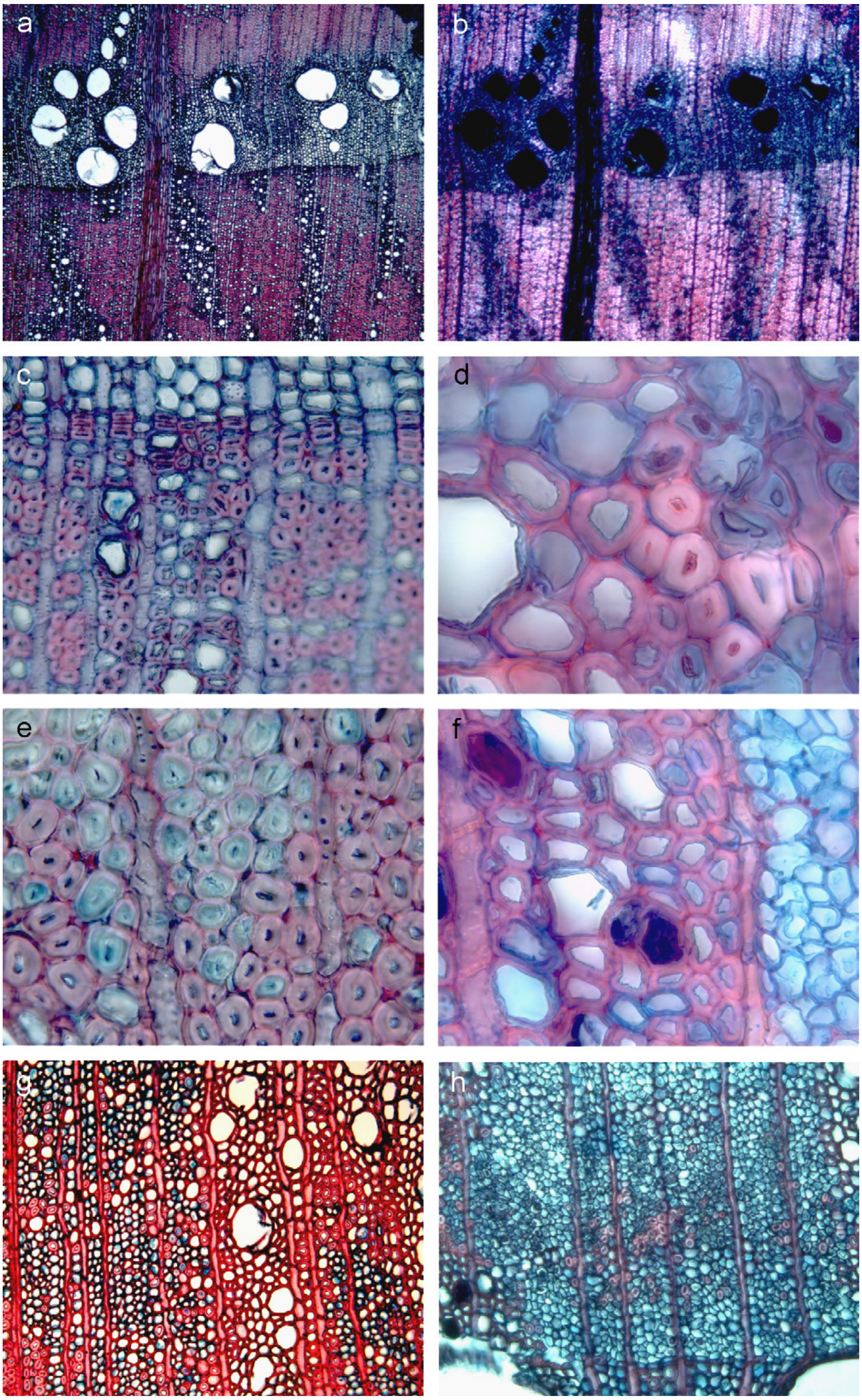

Fig. 3. (a) CS, oak, weak EB, only in tracheary cells (40 ×). (b) CS, oak, as (a) but the image was taken under polarised light (40 ×). (c) CS, oak, weak EB, swollen cell walls visible through wrinkly S_3 layer (200 ×). (d) CS, oak, moderate EB, fibre cells with sound walls (red); with increasing degradation: swollen walls (S_3 is crumbled); dark reddish S_3; finally blue cell walls (400 ×). (e) CS, oak, moderate EB, erosion from lumen onwards, visible by blue staining (400 ×). (f) CS, oak, moderate (left) and severe EB (right) separated by a ray. In the moderately degraded part swollen and degraded cell walls are intermixed; in the severely degraded part only compound middle lamella is left, and the cell shape is disrupted (400 ×). (g) CS, oak, severe EB, isolated less degraded or sound cells in matrix of degraded fibres, tracheary tissue with severe EB (100 ×). (h) CS, oak, severe EB, some sound fibres in matrix of degraded fibres, in most degraded cell S_3 layer present and filled with residue material (100 ×). (i) CS, oak, severe EB, only compound middle lamella left, sometimes with the S_3 layer and residue material (400 ×). (j) TS, oak, severe EB, heavy degradation in ray cells (200 ×). (k) CS, alder, severe EB, some less degraded isolated cells in a matrix of fully degraded cells filled with residue material or empty; only compound middle lamella left (200 ×). (l) CS, alder, total disintegration, all cells degraded, most cells filled with residue material, most cells empty and consisting only of compound middle lamella (200 ×). (m) CS, alder, total disintegration, all cells degraded, empty, only eroded compound middle lamella left, disruption of the cell shape (200 ×).

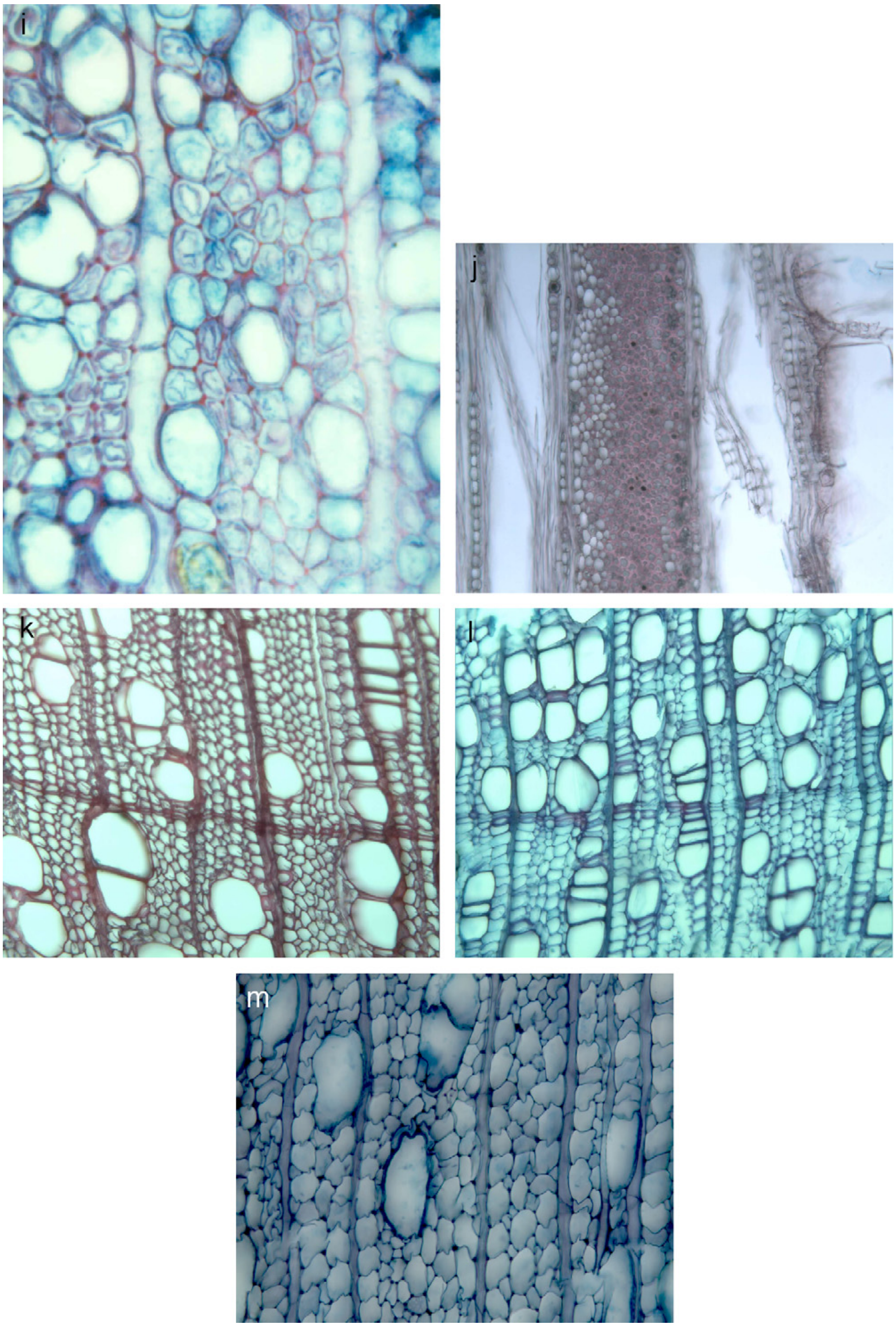

Fig. 3. (*Continued*)

Although the sample material of fir is limited, it seems that the sensitivity of this species for bacterial degradation is more comparable to that of spruce than to that of pine. In addition to the softwood species and oak, occasionally alder (Amsterdam) and even poplar piles (extracted in Haarlem) were found, and both these sapwood species are regarded as more sensitive to bacterial decay than that of pine.

In logs and stocks of equal size (diameter, length), which form foundation piles, the amount of sapwood per pile can vary tremendously. As the amount of sapwood in pine is related to age (Gjerdrum, 2003), trees of different origins with different growth rates, but the same diameter, have varying amounts of sapwood. The generally fast-grown pines from plantations in the Netherlands have relatively more sapwood than the slow-growing pines from

Table 3
Mean degree of degradation in foundation piles 50 cm below the pile head for most of the studied Dutch cities

Species	Sample size	Mean depth (mm) of degradation from bark onwards					
		Severe		Moderate		Weak	
		Mean	Std	Mean	Std	Mean	Std
Amsterdam ($n = 1692$)							
Pine	827	36	24	17	19	10	15
Spruce	826	21	20	9	14	5	10
Fir	12	3	9	19	30	27	20
Alder	27	81	38	11	28	1	7
The Hague ($n = 9$)							
Pine	8	7	16	45	18	10	15
Spruce	1	0	19	30	13	5	10
Dordrecht ($n = 56$)							
Pine	13	32	11	11	13	11	14
Spruce	38	11	10	9	10	4	7
Fir	5	7	7	7	7	4	3
Haarlem ($n = 77$)							
Pine	59	25	19	17	16	7	10
Spruce	18	14	11	16	7	3	6
Rotterdam ($n = 44$)							
Pine	5	15	3	2	5	7	16
Spruce	39	8	11	4	6	6	9
Wilnis ($n = 22$)							
Pine	1	5		5		20	
Spruce	21	5	11	9	10	7	11
Zaandam ($n = 76$)							
Pine	57	27	19	19	20	8	16
Spruce	19	7	12	6	6	3	7

Most of these showed heavy degradation at the bark side which decreased inwards towards sound wood near the pith.

Scandinavia or middle Europe. This, together with preferential degradation of softwood by bacteria, could explain why some pine foundation piles collapse while others, under the some environmental conditions, remain strong enough to provide building support.

The faster-growing pines from the Netherlands produce short piles of 6–7 m in length only, which is not long enough to reach the stable soil layer in some parts of the Netherlands. Cities, such as Haarlem and Zaandam, where the stable soil is found at a shallow depth can use the cheaper short foundation piles of Dutch origin; while other cities, where the stable layer is deeper, have to use the more expensive imported pine, fir, or spruce to construct longer piles. It is believed that these longer softwood piles originated from wood that came from middle and northern Europe, as spruce and fir did not appear in Dutch forests during the 19th and 20th centuries. Tree ring analysis, performed by Sass-Klaassen et al. (2007) to estimate the age and provenance of piles, confirmed that many of the larger spruce and pine piles did originate in Scandinavia, while some of the shorter pine piles came from the Netherlands. Furthermore, in another study (unpublished report), it was shown that the large 350-year-old spruce and pine piles under the "Scheepsvaartmuseum" in Amsterdam originated from the Oslo fjord in southern Norway.

In oak, just as in pine and spruce, the sapwood is more vulnerable to bacterial decay than is the heartwood. This results in an acute decrease in the degree of decay at the sapwood–heartwood boundary. Nevertheless, given time, the heartwood of oak can become heavily degraded over its full width. Such degradation was only observed in piles of approximately 2000 years of age in this study.

From Fig. 4, it is obvious that the degree of bacterial degradation varies with location. In pine, the degree of degradation is similar in Amsterdam, Dordrecht, Haarlem, and Zaandam, but there is less degradation in Rotterdam, where even intact sapwood was found. The reason for this might be that the activity of the wood-degrading bacteria is very low at this location. Varossieau (1949) found a slow increase of degradation in 30-, 75-, and approximately 300-year-old pine piles from Rotterdam, which is in agreement with this study. It is possible that the soil type found in Rotterdam influences bacterial activity. In contrast to the other Dutch cities, the Rotterdam piles are almost exclusively enclosed by clay, whereas in most other places the soils contain thick layers of peat or a mixture of clay and peat.

As with pine, the bacterial degradation in the Rotterdam spruce piles is one of the lowest recorded, but differences in degree of degradation of spruce do exist for piles from other cities. In Amsterdam, the degree of degradation is greatest and it decreases from Haarlem toward Dordrecht and Zaandam. As differences in heartwood and softwood in spruce are characterised by pith closure more than by the deposit of extractives, no chemical barrier exists for wood-degrading bacteria at the sapwood—heartwood boundary (Taylor et al., 2002). Another aspect to be considered here is water movement; the closed pit structure found in spruce could increase water flow resistance, compared to that in pine sapwood, and this will slow the rate at which bacteria colonise different areas of the wood. Water movement in spruce heartwood, however, experiences less resistance than it does in pine .The cross field pits are small (piceoid) in spruce and do not act as a bypass in each axial tracheid connection, as the wide (pionoid) cross-field pits do in pine. It is assumed that rate of water movement in the pile is related to wood-degrading bacterial activity. As there is no difference in the water-transporting capacity observed in foundation piles between spruce sap- and heartwood and there is no strong chemical barrier, the velocity of bacterial degradation is less in spruce and is not affected by the sapwood—heartwood boundary. Time is another factor that has to be taken into consideration to explain the lower degradation rate found in the relative young (<70 years) Zaandam spruce piles compared to those of older ones (>100 years) in other cities.

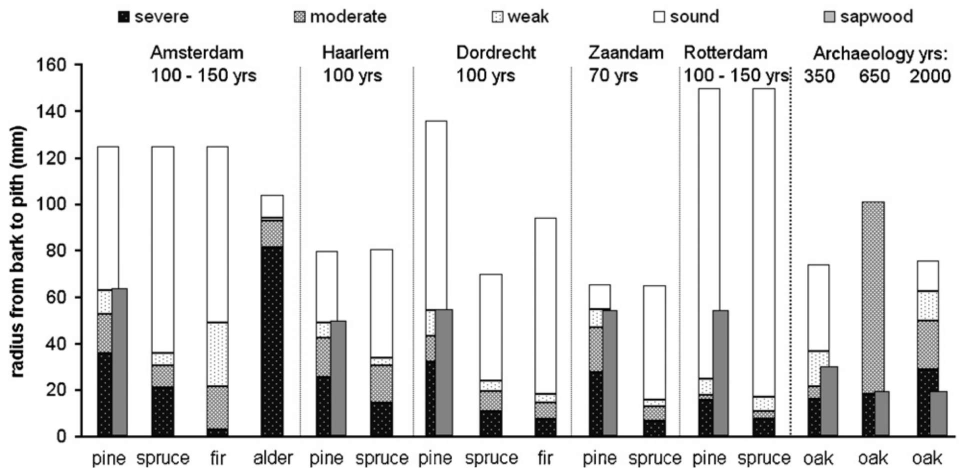

Fig. 4. Mean degree of degradation in pile heads from five Dutch cities (Amsterdam, Rotterdam, 100–150 years; Dordrecht and Haarlem, ca. 100 years; Zaandam, ca. 70 years) and oak from archaeological sites of 350, 650, and 2000 years old. The amount of sapwood is only given for oak and pine. The dimension of the radius is an estimation based on measurements of the pile circumference.

It is hypothesised that local hydrology can be responsible for the observed differences between cities by affecting the water movement in the wood. In Rotterdam, it is believed that the groundwater hydrology is very stable, whereas in other cities it is more dynamic.

Considering these results, one can understand why many buildings in Haarlem and Zaandam that were built on short foundation piles out of pine are strongly endangered or have already collapsed. Although the bacterial activity in Haarlem and Zaandam is almost equal to that in Amsterdam, the larger Amsterdam piles contain enough sound wood to maintain their supporting function.

3.4. Degree of bacterial degradation in relation to moisture content and specific gravity

In this section, the relation between the degree of bacterial wood degradation and structural and technological properties will be discussed. Fig. 5 shows the relationship between moisture content (ω), specific gravity (ρ), and degree of degradation for those four timber species (pine, spruce, alder, and oak) where more than 100 sub-samples were available covering the whole range of degradation. The data originated from the radial profile of consecutive small sub-samples ($\approx 1\,cm^3$) of all the sampled piles.

A strong and similar relationship between moisture content and specific gravity was found for all four species. From 200% moisture content upwards (when moderate, severe, and total disruption occurs), all data points follow the same equation ($\rho = 602{,}22 \times \omega^{-0.745}$) almost exactly. Deviations from this equation occur for weak or non-degraded spruce and pine specimens between ca. 50% and 150% moisture content, where varying amounts of air present in the wood result in a lower than expected moisture content. Many pit membranes were observed to be destroyed in some samples that had suffered the initial stages of bacterial decay, where formerly air-filled areas had become water-saturated. In oak and alder originating from archaeological sites, this phenomenon was not observed because even the sound wood was completely water-saturated due to the time (up to 2000 years) that it had been preserved under waterlogged soil conditions.

Fig. 6 illustrates the relationship between compression strength, moisture content, and specific gravity together with the degree of degradation for pine and oak. Only the sample set of these two species comprised more than 100 sub-samples, covering the entire range of degradation. The data are derived from the compression experiments on large testing blocks ($\approx 12\,cm^3$), which were available from disks and extracted piles. For alder specimens there were insufficient testing blocks for analysis, and the fir and spruce samples lacked testing blocks with moderate or strong degradation, so they had to be excluded.

Examining the relationship of compression strength with both specific gravity and moisture content revealed some interesting differences between pine and oak. In oak, a strong negative effect of moisture content on compression strength is present, especially between 100% and 150%, with small changes in moisture content having an impact on compression strength; from 200% onwards, this relationship diminishes. In pine, there is a broader relation, almost linear, between compression strength and moisture content until 200%. The relationship between specific gravity and compression strength is tighter in pine than in oak, with higher values in specific gravity yielding a greater compression strength. Oak shows a considerable variation in the relationship between compression strength and specific gravity, especially at ρ-values of $400\,kg/m^3$ and higher. This variation in specific gravity is caused by the presence or absence of soil particles that were washed into the wood. With the presence of these soil particles, i.e., silicates, the specific gravity becomes greater. In the oak archaeological samples, this process is more prominent

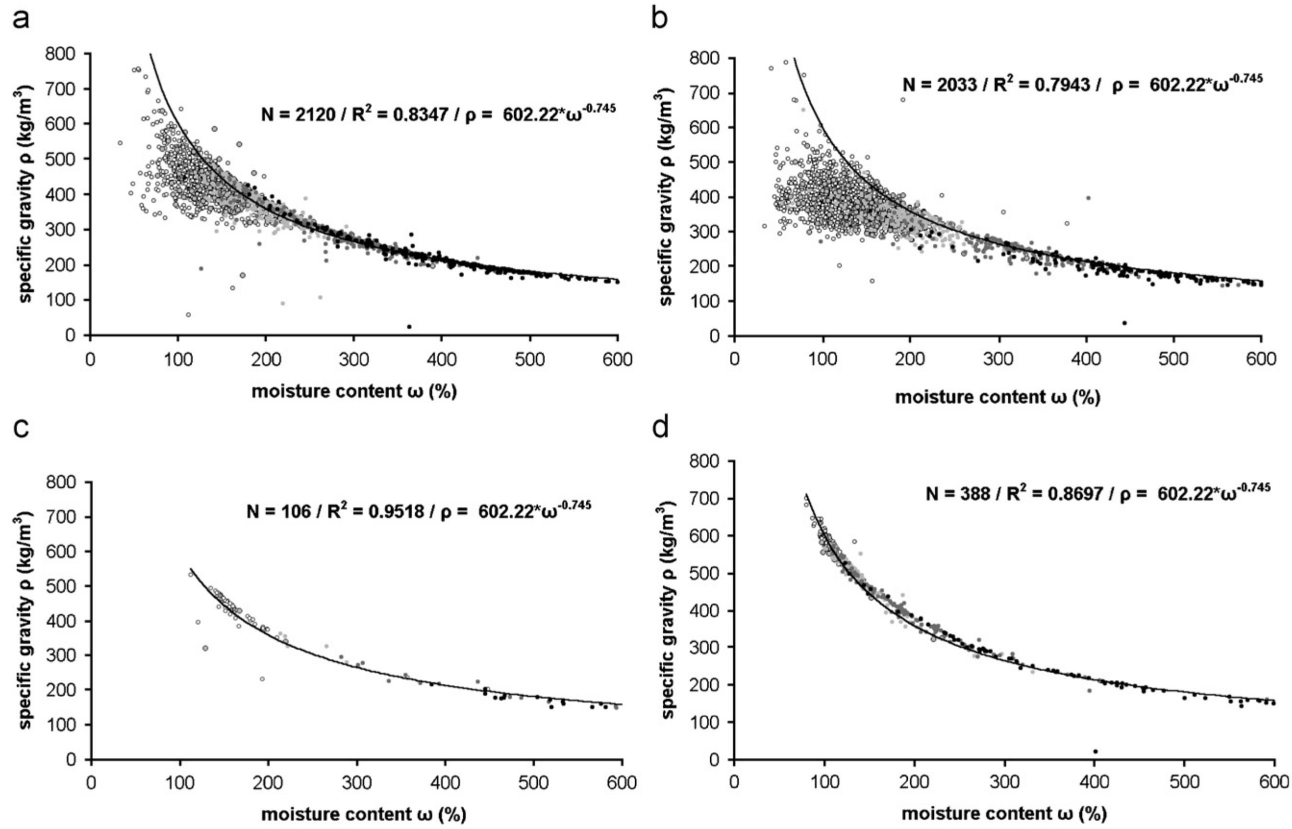

Fig. 5. Relationship between moisture content (ω), specific gravity (ρ), and degree of degradation: (a) pine, (b) spruce, (c) alder and (d) oak: (O) sound, (O) weak, (●) moderate, (●) severe, (●) total disruption of wood structure.

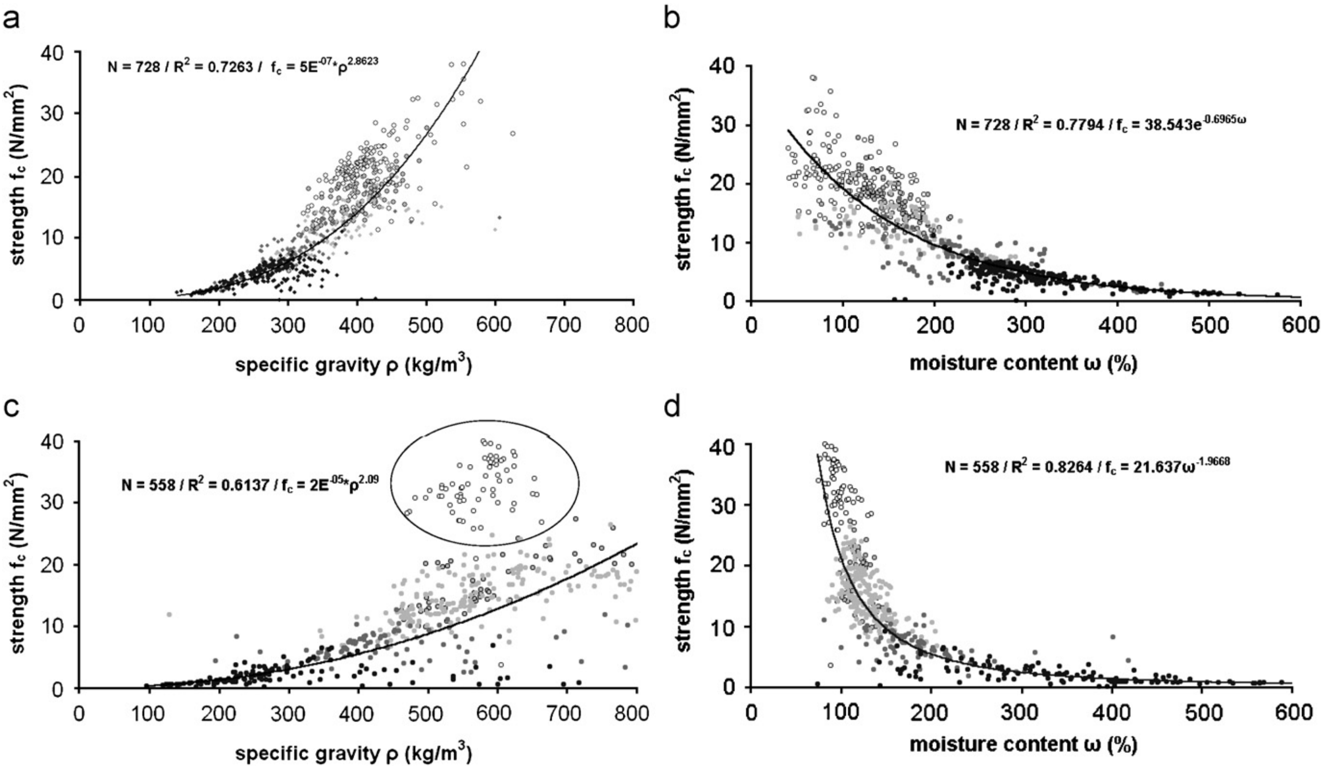

Fig. 6. Relationship between compression strength and specific gravity, moisture content, and degree of degradation: (a and b) pine and (c and d) oak; in (c) fresh material is marked: (O) sound, (O) weak, (●) moderate, (●) severe, (●) total disrupted wood structure.

than in the relatively younger pine samples. Chemical wood analysis of these oak samples showed that the ash content can be extremely high compared to that in fresh wood, which can be explained by the amount of included soil material (Passialis, 1997; Giachi et al., 2003; Huisman and Klaassen, 2005).

All sound samples of oak originated from fresh material (marked group in Fig. 6c) and showed a high compression strength at ρ-values between 500 and 650 kg/m^3. Oak archaeological samples with the same range of specific gravity (500–650 kg/m^3), and with mainly a moderate degradation status, yielded much lower values of compression strength. It can be concluded that the wood of these old oak samples contained many soil particles, which lead to its increased specific gravity, and this obscured the relationship between the specific gravity of the wood and compression strength. It remains unclear whether the adsorption of these soil particles is time-dependent or if it reflects a greater ability of oak wood to absorb them.

3.5. The effect of pile foundation service age on wood compression strength

The time that a pile is in service as a foundation support could compromise its compressor strength. To address this possibility, a comparison was made of specific gravity and compressor strength measurements for foundation piles that have been in service for at least 80 years, suffering no bacterial degradation, with wood samples from freshly sawn timbers.

Fig. 7 shows the effect that time has on foundation piles in use, regarding the relationship between specific gravity and compression strength for pine and spruce. Although the compression strength of samples with the same specific gravity varied considerably, no significant differences could be found for either pine or spruce between sound wood that had been in use for more than 80 years and freshly sawn timber. Mean compression strength for fresh and old spruce was both 18 N/mm^2 ($N = 427$ and 115; Std = 4 and 3 N/mm^2, respectively). Mean compression strength for fresh and old pine was valued at 23 and 19 N/mm^2 ($N = 74$ and 96; Std = 6 and 4 N/mm^2), respectively. The slight difference in the results for pine between both collections can be attributed to the relatively greater amount of juvenile wood, with a lower compression strength, in the >80-year-old pine samples. This is due to the fact that sound samples in foundation piles of pine are taken almost exclusively from the inner heartwood portion, which comprises mainly juvenile wood.

The results presented here suggest that there is no reason to expect a loss in compression strength in sound wood that has been under a permanent load for at least 80 years and exposed consistently to wet soil conditions.

3.6. A simple model to predict compression strength

Compression strength is a key measurement in the evaluation of foundation pile stability. Its assessment, however, cannot be easily made for piles in service. The development of a model that can be used to predict the compression strength of a pile from cores that are convenient to sample, such as the pile head, would benefit the construction industry. A strong mutual relationship exists between specific gravity, moisture content, and the degree of degradation (Figs. 5 and 6), all of which have an effect on compression strength. These variables were used to test whether it was possible to predict compression strength from cores taken at the pile head. From the three variables, the degree of degradation was regarded as too subjective and inconsistent (Fig. 6) to accurately predict the compression strength of the wood. Moisture content, however, proved to be the variable closely related to compression strength (Fig. 6), clearly reflecting changes in specific gravity in response to the degree of bacterial degradation (Fig. 5). For this reason, a simple model was as calculated from Fig. 6 and used to predict compression strength from moisture content. Fig. 8 shows the similarity between determined (measured) and predicted (based on the equations from Fig. 6) values for oak and pine. In both models, the prediction of the compression strength is accurate for values <15 N/mm^2; with increasing compression strength, i.e., >15 N/mm^2, the reliability of both

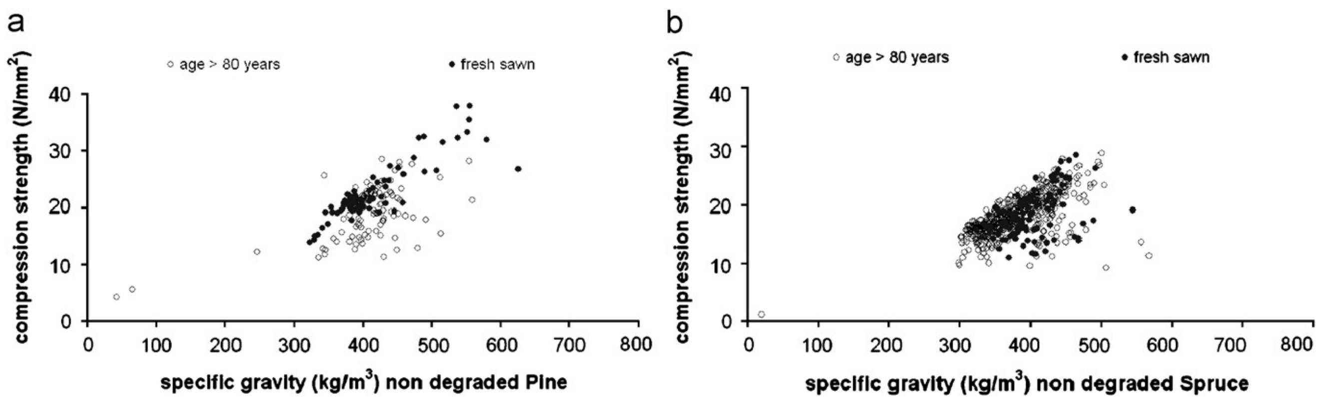

Fig. 7. Comparison of relationship between compression strength and specific gravity in piles that are >80 years in service and freshly sawn material for pine (left) and spruce (right).

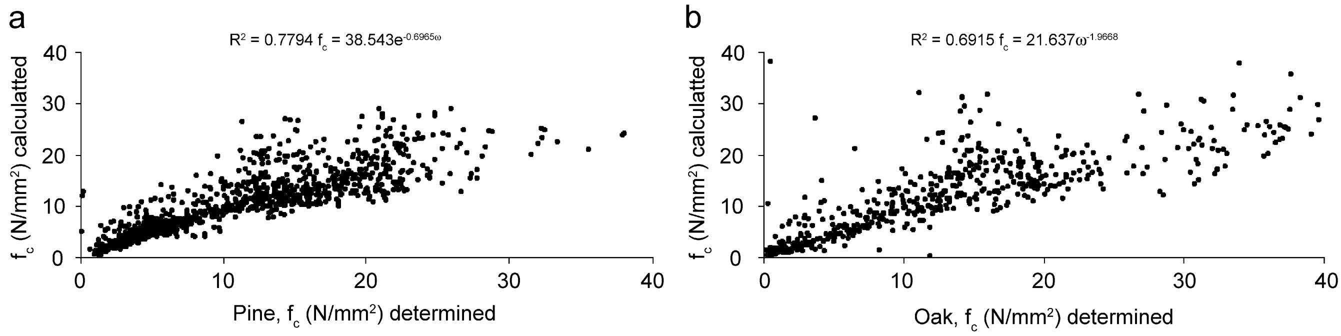

Fig. 8. Model to predict compression strength (f_c) from moisture content (ω) in pine (left) and oak (right).

models declines due to an underestimation of the real compression strength. However, as most of the foundation piles used in this study were characterised by a compression strength $<20\,N/mm^2$, the presented models can be an efficient tool to predict the compression strength and thus the safety of a construction with a reasonable precision.

3.7. A water-flow hypothesis for bacterial degradation of wooden pile foundations

The importance of timber species, time in service, and location of foundation piles as factors that influence the degree of bacterial degradation has been discussed in previous sections.

The bacterial degradation of waterlogged piles is likely to be caused by several groups of bacteria working in consortia that behave differently according to these factors (Nilsson and Björdal, 2007). Given these circumstances, a prerequisite for an active degradation process would be a continuous circulation of different wood-degrading bacteria species through the pile. Although some wood-degrading bacteria appear to be motile, there is still a need for them to be transported inside the wood by an additional force or forces. A mechanism that could provide such a force for bacterial circulation is water movement within the submerged piles. Klaassen (2007) showed that a water-transporting capacity of the axial and radial wood-cell matrix in submerged piles is present, and that the water-stream velocity depends on the timber species and the pressure differences between the bottom and the top of the piles. As the water pressure can differ between different types of soil layers around the pile, soil type and soil hydrology could play an important role in the rate of bacterial degradation. If a consortium of wood-degrading bacteria colonise the pile, the cells will enter this water-transporting system and be spread via the water stream. In pine, the easiest pathway is the tracheid–ray–tracheid connection, whereas in spruce the rays are less important. In oak, the likeliest pathway is the latewood-tracheary system, because all early wood vessels in the heartwood, and also in the older parts of the sapwood, are blocked with tylosis (Tyree and Zimmerman, 2002). The early stages of decay, in this scenario, would have the infection being restricted to those cells that are directly involved in the water-transport pathways. Because in pine the rays are important gateways, decay is most prominent here, whereas in oak it starts to spread around the tracheary-latewood tissue. In general, timber species with an open structure, where water transport is easy, would be more susceptible to bacterial wood decay. Sapwood of pine and oak, as well as the wood of alder, poplar, and especially beech (Gawronski, 2002) are therefore susceptible to bacterial degradation, whereas spruce and fir are more resistant, with the heartwoods of oak and pine being the most durable.

This water-flow hypothesis not only explains differences in degree of degradation, but also provides an explanation for the frequent observation that pyrite accumulates inside degraded wood areas. Pyrite is a mineral that is formed under anoxic conditions from iron and sulphur. The presence of pyrite inside the wood structure indicates that the reaction of both elements has occurred in the wood. These elements, however, originate from different soil areas and need transporting inside the wood, which could be mediated by the water flow system of the timber (Huisman et al., 2007).

4. Conclusions

Light microscope observations are sufficient to distinguish erosion bacterial attack from other types of wood degradation for softwood species. However, the patterns of degradation caused by erosion bacteria are less specific in hardwoods, and it is advisable to scan the wood structure for the presence, or absence, of specific decay patterns in the woody cell wall.

The loss of compression strength of a degraded wooden foundation pile can be predicted with reasonable precision from the moisture content measured on sub-samples from an increment core with a diameter of 10 mm. However, additional information on specific gravity and the degree of degradation is required to properly evaluate the strength of the wooden pile construction, and to provide insights about the progression of any decay. Furthermore, the compression strength of pine and spruce does not seem to be correlated to the length of foundation pile service. Piles in service longer than 80 years had strengths comparable to those of fresh timbers, suggesting that piles under a permanent load for long periods do not experience a reduction in strength in wet soil environments.

In all vertically oriented piles older than 50 years, bacterial degradation was present in the outer layers at least. When the whole length of the extracted piles was examined, the intensity of degradation did not change from the bottom to the top of the structure. Consequently oxygen, which could be available in soil layers at the top of the pile and is absent around the tip of the foundation piles at 6–15 m below the groundwater level, can be excluded as a main trigger for bacterial degradation. Instead, it is proposed that water movement through the wood is the driving process for bacterial wood degradation. With this hypothesis, it is possible to explain variations in degree of degradation found in foundation piles in terms of wood structure (related to timber species), soil type, and site hydrology.

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