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Factors that influence the speed of bacterial wood degradation

René K.W.M. Klaassen[a,*], Berdien S. van Overeem[b]

[a] SHR Timber Research, PO box 497, 6700 AL Wageningen, The Netherlands
[b] Wageningen UR forest ecology and forest management, PO box 47, 6700 AA Wageningen, The Netherlands

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ABSTRACT

Bacterial wood decay is a serious threat to the many wooden foundation piles in the Netherlands. In order to learn more about the factors that influence the process of decay, approx. 2000 wood samples taken from Amsterdam piles heads were analysed on type and degree of decay and for 59 extracted piles originated from eight different locations the decay gradient of the pile length was determined. Although large differences in soil constitution (between cities) affect the process of wood decay, on microscale (within Amsterdam), no influence was found that explains the variety in degree of decay at the pile head. Wood quality (growth rate, origin, process of harvesting) is regarded as more important in causing the variety in degree of degradation in pile heads at a similar location. The gradient of bacterial decay over the pile length is mostly decreasing towards the tip and a correlation with soil parameters is suggested.

1. Research aim

For service life prediction of wooden foundation constructions, it is important to know the factors that influence the spread of bacterial decay over the diameter and length of piles in the ground under the groundwater table. The study is focused on the interaction of soil conditions and bacterial wood decay and to quantify the gradient of the pile length.

2. Introduction

As a consequence of the wet and unstable soil conditions in the Netherlands, many houses are standing on foundation piles. Although the concrete pile replaced the wooden pile rapidly after Second World War, it is estimated that 25 million wooden piles are still in use. Half of these piles are carrying buildings and the other half carry water constructions (e.g. quay walls, bridge headings). From the old days onwards, it was required that the wooden pile head should always be below ground water level, because it was believed that no degradation could occur below the ground water level. As discovered in the last decades, wood degradation does occur below ground water level, this is however exclusively caused by erosion bacteria [1].

Most historic buildings in cities in the western part of the Netherlands are standing on wooden foundation piles with many of them exceeding 300 years of age. However, the majority of the wooden piles originated from 70 to 150 years ago. Around 1875, during the industrialisation period, a rapid expansion of most cities started, with the consequence that until ca. 1950 large volumes of wooden piles were used.

Two decades ago, large-scale problems appeared with the stability of foundations under family houses. At the moment, these problems are known for approx. 200,000 houses divided over 150 cities including Amsterdam, Dordrecht, Gouda, Haarlem, Rotterdam and Zaandam. The main part of the problem is caused by bacterial decay but another significant part is caused by a too low ground water table. The mean costs of foundation repair are €60,000 and can cause severe financial problems for the house owners [2]. Nevertheless, the Dutch government does not give any support in solving this problem. Probably because of the huge financial implications (estimation of the cost on national level > €10 billions) and the fact that foundation repair is a non-visual issue. Today, in several Dutch cities, knowledge on the state of the foundation is required when houses are under construction in order to avoid collapse of houses, but also when houses are sold. Inspections are then carried out, but these are unfortunately not done automatically, sometimes resulting in unexpected high financial costs to be accounted for the last house owner. During the foundation inspections, wood samples are taken with an increment borer and inside the laboratory, the degree and pattern of decay is determined. The result of an inspection is an estimation of the actual quality and a forecast of the quality of the foundation during the next 25 years.

During the last 15 years, sample information has been collected on the condition of more than 5000 foundation piles originating from different locations in the western part of the Netherlands. Together with laboratory experiments, this

* Corresponding author.
E-mail addresses: r.klaassen@shr.nl (R.K.W.M. Klaassen), berdien@avih.nl (B.S. van Overeem).

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comprehensive database was used for a better understanding of the process of bacterial decay. Earlier studies show that spruce and pine are beside alder, fir, poplar and oak the most common species used in the Netherlands. It appeared that all piles, older than 5 years, are degraded by erosion bacteria at least in the outer most wood layer. The velocity of bacterial degradation is highly variable and ranges between 0– > 1 mm/year [3,4]. Variation in decay velocities can only partly be explained by the timber species used: poplar, alder, and pine sapwood are more susceptible to bacterial degradation than heartwood of oak, pine, douglas fir and larch [5]. An interaction between the wood permeability and soil hydrology was suggested which could explain the variation in bacterial decay velocity to a better degree [6]. This suggestion is supported in the fact that the bacterial decay in piles from Rotterdam is less active compared to the piles of many other cities (e.g. Amsterdam), which could be related to the soil hydrology (Rotterdam with a thick homogeneous clay soil layer and low difference of water pressure between pile tip and top, vs Amsterdam with a mixture of clay, peat and sand layers and higher difference of water pressure between pile top and tip [4]). Yet, although soil hydrology may explain variations in bacterial decay on a large scale, within cities variation in velocity of decay can be large and has not been explained yet. This study was performed to gain insight in the patterns of bacterial degradation within cities. Two thousand records from the database originating from Amsterdam are used to analyse the differences in activity of bacterial wood decay over the city. The relation between bacterial degradation, soil hydrology and wood quality was investigated in order to explain the variety within this city.

3. Method

On the basis of the postal codes, each record in the database was given *x* and *y* RD-coordinates. If two or three piles appeared on one address, the *x*−*y* coordinates were adjusted a few meters in order to avoid more than one pile on the exact same location. From the database, information was extracted on service life (years in soil), timber species and depth of bacterial decay. The velocity was differentiated for severe and weak decay (according to a standard classification [4]) only, because the compression strength in severely degraded timber is significantly reduced whereas in weakly degraded timber there is no or only limited strength reduction. As the invasion of wood degrading bacteria is from the outside inwards, severely degraded timber is found at the outer rings of the stem and weakly degraded timber is found always deeper in the stem. As the compression strength is clearly decreased in severe degraded wood a distinction is made between *invasion or degraded zone* and *severe decay*. This information was plotted over the map of Amsterdam using Top10Smart 2006 (copyright: Alterra-WUR).

Furthermore, a map of Amsterdam was made with groundwater data, based on piezometric levels (m) from observation wells of the upper groundwater (phreatic water) and the deeper groundwater (first sandy soil layer). Subtracting of the two levels results in the difference in hydraulic head (m), that indicates the pattern in differences in hydraulic heads and the direction (upward or downward) of the seepage.

To study the appearance of bacterial decay over the pile length, information was available of 59 wooden foundation piles on the degree of decay as well as on the number of tree rings for both the pile head and the pile tip. The sampling was done in the period 2001–2011 in Alblasserdam, Amsterdam, Den Haag, Dordrecht, Haarlem, Leiden, Stockholm, and Zaandam. The piles vary in length (1–16 m), age (63–113 years), and diameter (14–25 cm).

4. Results and discussion

4.1. Database with approx. 2000 Amsterdam records

The majority of the Amsterdam records represented samples of pine and spruce. Therefore only these two species are taken into account. In Fig. 1, the map of Amsterdam containing the distribution of both species is shown.

In Fig. 1 the service life for each pile is given. The oldest piles are found in the city centre but it has to be realised that some of these piles are much older than 140 years (e.g. the Royal Palace on the Dam square and the Maritime museum both approx. 350 years old). Around the city, centre clusters of same-age piles can be seen, illustrating the expansion of Amsterdam in time. However within restricted areas the service life of the piles varies a lot, e.g. Vondelpark and Sarphatipark area (within a cluster of several streets the service life differs as much as 60 years).

The velocity of bacterial decay in the pile head of approx. 1000 spruce and 1000 pine wooden piles with a service life of 80–200 years was calculated. For both timber species frequency diagrams were made for the velocity of invasion and severe degradation (Fig. 2). In pine piles an invasion velocity of around 0.5 mm/year was most frequent, whereas in spruce most frequent invasion velocity ranged between 0.1–0.5 mm/year. Furthermore, the maximum velocity in pine was much higher than in spruce. For the velocity of severe decay, a similar but more pronounced pattern was observed. In pine piles a velocity of 0.25 mm/year was most frequent whereas in spruce it ranged between 0–0.5 mm/year (almost 0 mm/year was most frequent). Again, the highest velocities are found in pine. Besides an estimation of the velocities with the highest frequency, the mean velocity was also calculated. The overall mean severe bacterial degradation velocity in pine is 0.25 mm/year and for spruce it is 0.13 mm/year.

All graphs give relative high frequency of velocities of 0 mm/year but these values should be regarded as sampling failure. As most samples are taken with an increment borer (Ø 10 mm), it can be imagined that the most (rotten) outside part is easily lost during extracting of the core from the borer. Therefore the lowest velocity speed should be regarded being in the range of 0.01 mm/year.

From Fig. 2, it became clear that spruce has a different resistance against bacterial decay than pine. Therefore separate maps of each timber species were made. A differentiation between invasion velocity and the velocity of severe decay is necessary in order to deal with the influence of heartwood and sapwood. Pine sapwood is sensitive for bacterial decay whereas pine heartwood has a high resistance. The highest velocities of decay are found in pine sapwood whereas in pine heartwood the velocity is zero or almost zero [4].

Also, for spruce, it is believed that there is a difference between sapwood and heartwood in resistance against bacterial decay. Preliminary research on one of the foundation piles underneath the Royal Palace in Amsterdam gave evidence that in spruce heartwood, the velocity of bacterial decay is strongly decreased. An outside shell of approx. 1–2 cm shows collapse because of severe bacterial decay but the inside of the disk is sound. The boundary of the degraded wood gives the impression that it follows, at least partly, the sapwood–heartwood boundary. It is partly concentric and shows branch scars [7]. Unfortunately, the heartwood–sapwood boundary in spruce foundation piles after several decades in function cannot be distinguished easily, and therefore the decay-velocity found in spruce is a mixture of the velocity in sapwood and in heartwood. Sapwood statistics of spruce might offer an opportunity for a better differentiation.

It is clear that the depth of the bacterial invasion in pine piles does not extend over the sapwood–heartwood boundary and

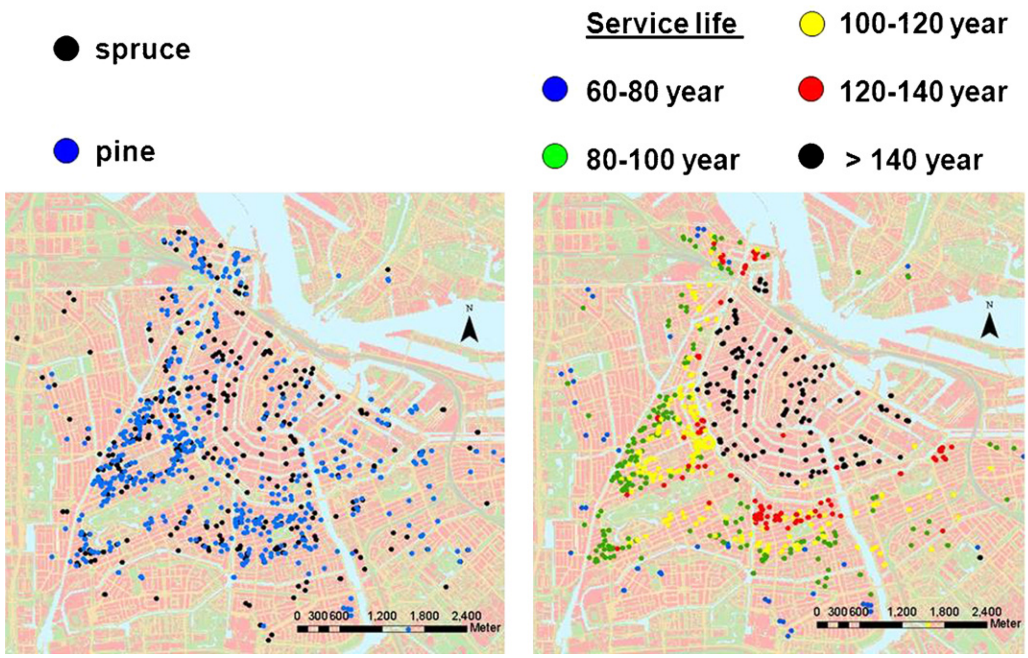

Fig. 1. Maps of Amsterdam with foundation piles: left locations and right service life.

occasionally it does not even reach this boundary. Because the exact date when the bacterial invasion reached the sapwood-heartwood boundary is unknown, the calculated rate of invasion velocity is underestimated. In many pine piles, the depth of severe bacterial decay is less than the depth of the invasion of wood degrading bacteria and can therefore be regarded as active. In spruce, the influence of the sapwood–heartwood boundary in piles of approx. 100 years in service is less clear.

In order to get an idea of the activity of the bacterial decay for each timber species, two maps were made: one with the invasion velocity and one with the velocity of severe bacterial decay.

The different sensitivity of spruce and pine against bacterial decay is confirmed by Fig. 3. The invasion velocity in pine shows much more black and red dots whereas for spruce much more blue and green dots are seen. For the velocity of severe bacterial decay, the blue dots are dominant in the spruce map (Fig. 3) whereas in the

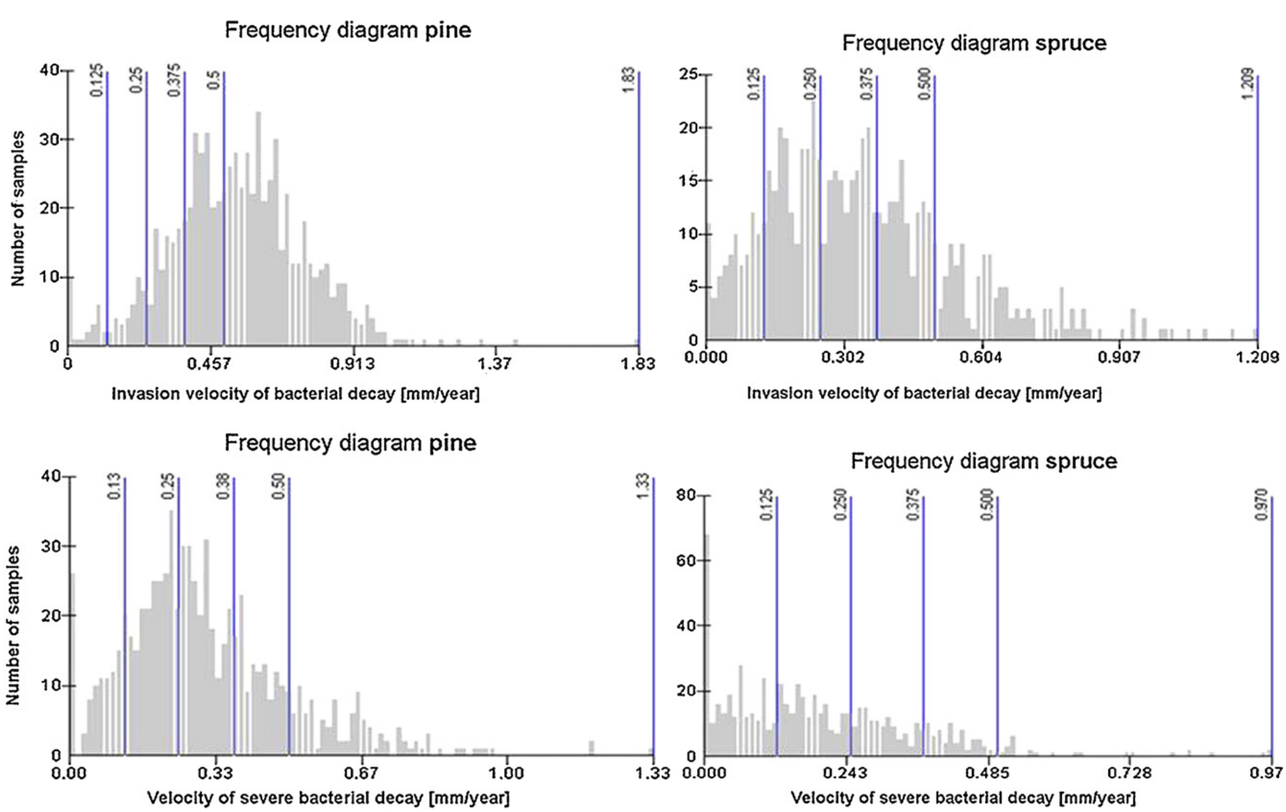

Fig. 2. Frequency diagrams of bacterial decay velocity (invasion and severe) in pine and spruce.

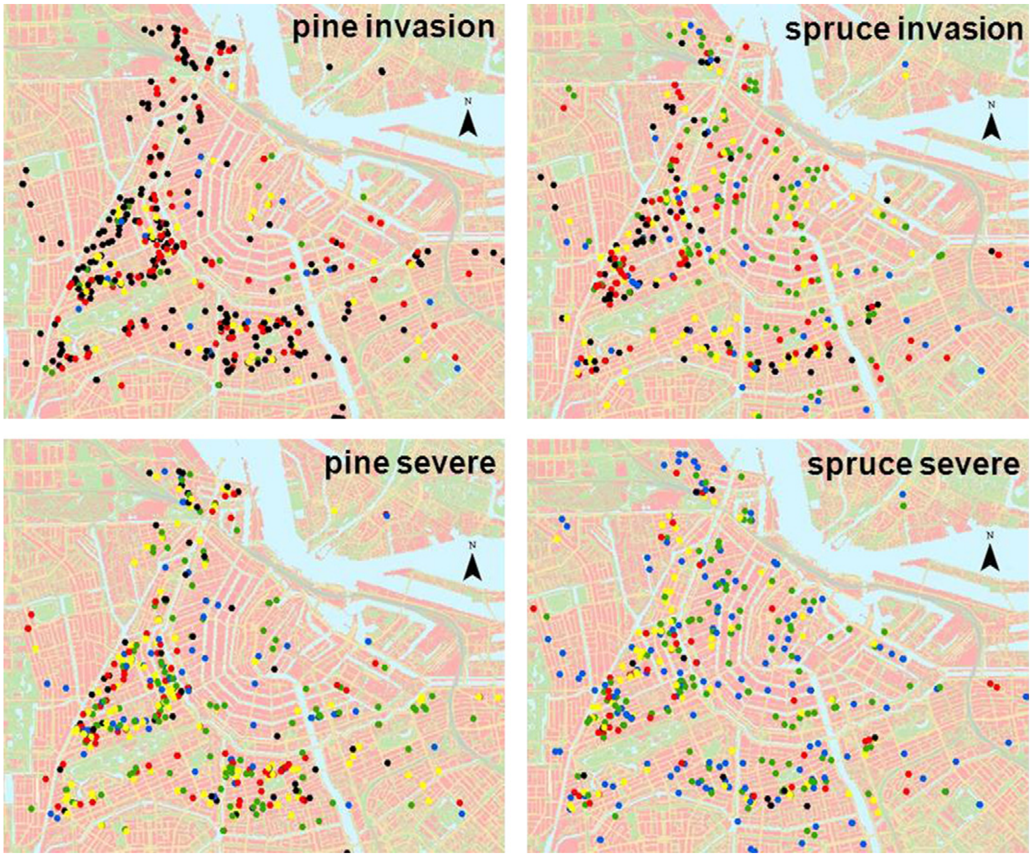

Fig. 3. Maps of Amsterdam with locations and velocities of bacterial decay (invasion and severe) of pine and spruce foundation piles (mm/year). 0.00 - 0.12 0.13 – 0.25 0.26 – 0.37 0.38 – 0.5 0.51 - > 1

map for pine more variety in dots colour is seen in Fig. 3, meaning that a wider range of velocities exists.

The maps with bacterial invasion show in general higher velocities than the maps of severe decay, which means that at least for severe decay, a boundary towards highly resistible wood against bacterial degradation, is not reached yet and the decay can be regarded as active in most piles. Therefore the velocities of severe decay are most discriminative. Looking at the maps of severe decay (Fig. 3), it is remarkable that there are no areas where pile clusters appear with a homogeneous high or low velocity. The finding of high and low velocities on the same area (Fig. 4) indicates that there are other parameters influencing the activity of bacterial wood degradation than microscale soil conditions only.

Although the impression is given that the velocities in the old town are lower than outside the old town, there are locations (outside the old town) where the velocity of bacterial decay is

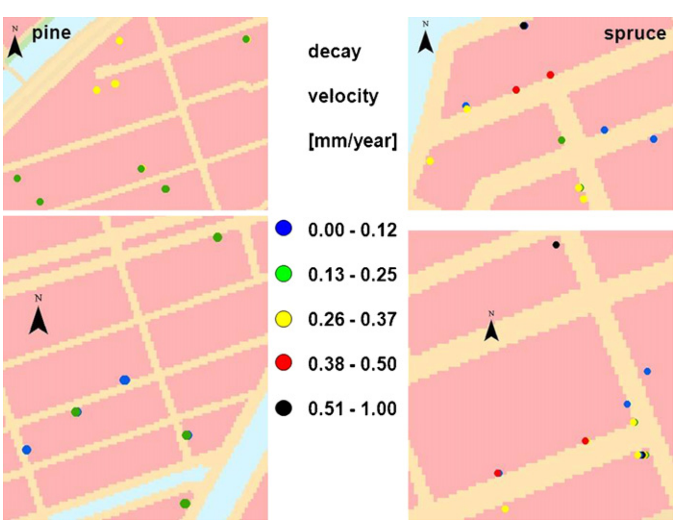

Fig. 4. Detail maps of areas in Amsterdam, left pine, right spruce, the upper maps show areas where the velocity of severe bacterial decay is more or less homogeneous and the lower maps show areas where the velocity strongly varies.

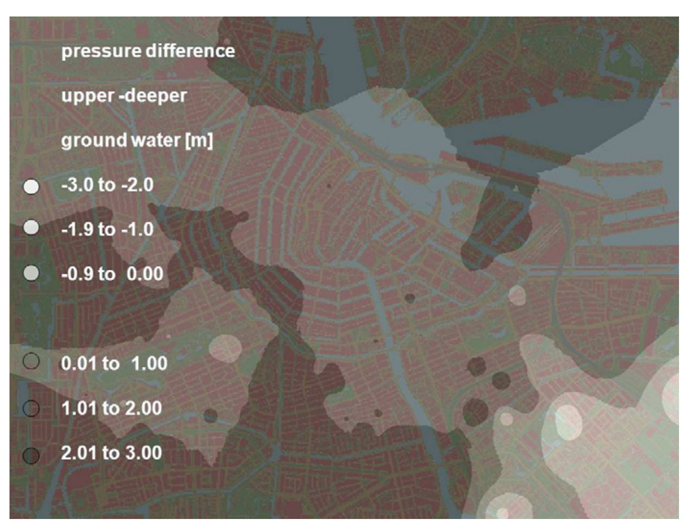

Fig. 5. Map of Amsterdam with difference in pressure between the upper and deeper ground water (m).

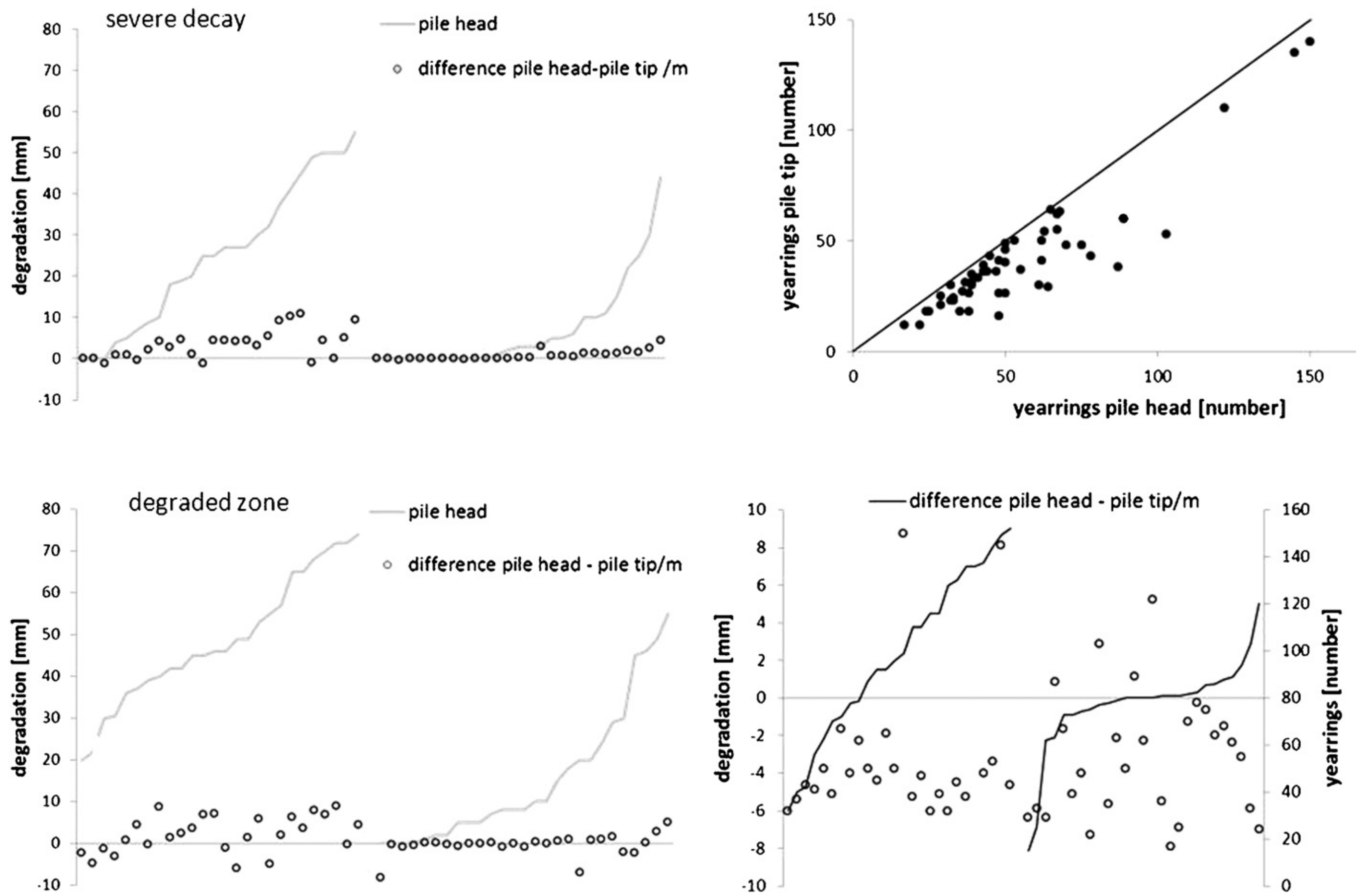

Fig. 6. Variation in year rings and bacterial decay over the foundation pile length. Graphs with degradation are sorted on timber species (pine, spruce) and degradation. Left: graphs showing the relation between the degree of decay at the pile head (above severe, below degraded zone) and the gradient over the pile length. Right: graphs showing year-ring parameters (above: differences in number between pile head and pile tip, below: relation between tree age and the gradient of the degraded zone over the pile length).

homogeneous low but there are also locations where there is a great variety. Fig. 4 illustrates this on a more detailed scale.

In Fig. 5, a map of Amsterdam is shown with the pattern of the pressure of the deeper ground water. No relation could be found between this pressure and the variety in degradation speed. Again, this indicates that other factors are important in explaining the differences in degrees of degradation. Only in one area (Watergraafsmeer) with negative pressure of the deeper ground water, several piles were found in which the velocity of bacterial decay was zero or almost zero. It is suggested that this negative ground water pressure could be the cause of these low velocities. Negative ground water pressure causes upward seepage, which has higher salt concentration than downward seepage, and thus conserving the foundation piles.

4.2. Preliminary study on bacterial decay over the pile length

An earlier study [8], based on a limited number of piles, concludes that bacterial decay is present over the full length of a foundation pile extracted after its service life. The dataset of this study was enlarged from 18 to 59 piles and now includes four fir, 26 pine, three poplar, and 26 spruce piles. Conclusions can be made for spruce and pine only because of the limited number of piles for the other species. Fig. 6 (left) shows the thickness of the degraded peal (severe as well as the whole degraded zone) at the pile head and the difference with the pile tip. It can be seen that the thickness of the severely degraded peal decreases towards the pile tip and that the gradient over the pile length in spruce and pine is always less than 20 mm/m. The data show that in half of the pine samples, and in all spruce samples, the tip is not severely degraded. The gradient in thickness of the whole degraded zone deviates from that of the thickness of the severely degraded peal, for e.g. in 15% of the piles, the degraded zone is thicker at the tip, and the gradient seems less related to the thickness of the degraded peal at the pile head. Fig. 6 (above, right) shows that the piles studied include variation in tree rings parameters that might be used to explain the differences in the decay gradient over the pile length (e.g. tree age is 20 to 150 years, differences in number of tree rings between pile tip and pile head is exceptionally larger than expected because of annual shoot growth of 20–100 cm). Tree age, average tree ring width and differences between the number of tree rings at the tip and the head of piles were compared with the gradient of decay over the pile length. Fig. 6 (below, right) shows that decay gradient of the pile length and the tree age were not correlated. Also with the other tree rings parameters, no correlation was found.

5. Concluding remarks

Although large differences in soil constitution (between cities) are of influence on the process of wood decay [4,9], this study shows that wood quality is of key importance also to explain the wide variety in bacterial degradation speed as found in pile heads from similar locations. In contrast, soil parameters seem to be of influence on the gradient of the decay over the pile length.

It is known that timber species and sapwood amount in pine are of influence on speed of bacterial decay in foundation pile heads.

But these parameters cannot explain all decay variation found in this study that appear independent from soil conditions. Therefore other wood parameters have to be taken in consideration.

First, the difference in resistance against bacterial decay between spruce heartwood and sapwood could be one of the underestimated parameters, as is suggested from the 350-year-old pile from the Royal Palace.

Secondly, the historical record mentions differences in harvesting and origin of the foundation piles. Winter as well as summer harvesting was common, Northern, Eastern, Middle Europe and the Netherlands were the main production areas and the time between harvesting and inserting in the soil differs from several days to several years [8] and affects pit closure, drying of the timber and fungal colonisation. All variables mentioned could have their influence on water movement in the wood, the key factor in stimulating bacterial wood decay. Additional proof pointing towards water movement as key factor is found in foundation constructions where wood is used in combination with concrete. After 1950, the use of wooden piles with a concrete upper part became more and more dominant in order to avoid the risk of a too low ground water table around the wooden pile head. Several empiric observations show a remarkable thin layer of weak shell (i.e. bacterial degradation) around the pile and it is suggested that this is caused by the closure of the wood structure by concrete, which seals the wood and prevents water movement. Because all samples studied here originated from full wooden foundations, this aspect is of no importance for this study.

Thirdly, tree growth dynamics affects the wood quality and this could be related to the susceptibility of the timber towards bacterial decay. The amount of sapwood, as a result of tree growth, is for pine a key factor and for spruce, a supposed factor in resistance against bacterial decay. Also, other tree growth parameters (e.g. tree rings appearances) could influence the process of bacterial wood decay on the pile as a whole but not to influence the decay gradient over the pile length.

Further exploration and understanding of the interaction between soil and wood parameters and bacterial wood decay would enable improvement of the methods to estimate the lifetime of a foundation and to improve the judgement of stem selection. This is particularly of interest because wooden foundations could additionally provide an important carbon sink and the costs of a wooden foundation are much lower than those of a concrete foundation.

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