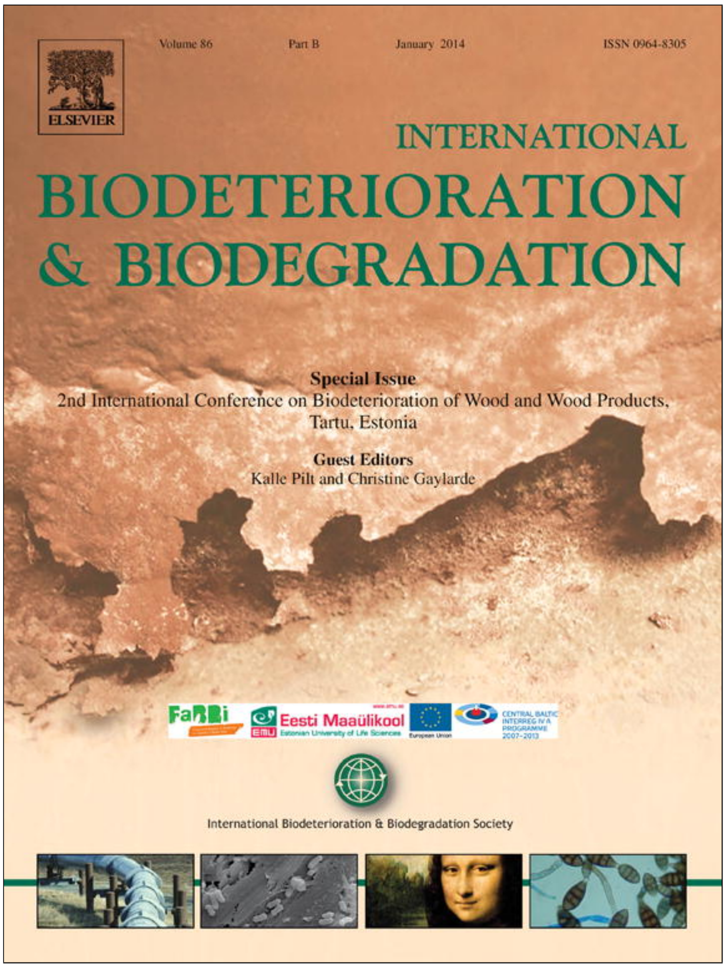
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Speed of bacterial decay in waterlogged wood in soil and open water

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A R T I C L E I N F O

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A B S T R A C T

Whereas most studies on bacterial wood decay are focused on the micro level by assessing degradation patterns in wood, this study is done on macro level studying the temporal dynamics of the process of bacterial wood decay across the diameter of a wooden object. During the last 15 years information on wood quality and bacterial decay intensity from more than 5000 heads of wooden foundation piles under buildings and quay walls was collected in a database. This allowed a comparison of the performance of spruce ad pine piles under two different anoxic regimes, i.e. in organic peaty or clay soil and open water environment. Bacteria wood decay seems to be less active in an open water environment and this tendency is most clear in spruce. Bacterial infection and water dynamics in the wood are regarded as most important factors causing differences in the activity of wood degrading bacteria.

1. Introduction

Bacteria are able to degrade wood in almost all environmental circumstances. Under water in nearly anoxic conditions erosion bacteria are active (Blanchette et al., 1990, 1991) and in this environment they are a serious threat for wooden foundation piles. Especially in long- and well-populated estuarial areas (e.g. The Netherlands, Bangladesh) where wooden pile foundations are crucial for carrying houses, buildings and water building constructions (e.g. quay walls, locks). For a long time this type of decay has been neglected because of the assumption that wood will not degrade under water. But already in 1931 Wijnpersse (1931) mentioned that pine foundation piles are sensitive for decay under the ground water table and in 1949 Varossieau (1949) described the unknown pattern of decay in pine piles. Other anatomical morphological studies followed, and the unknown pattern of decay was finally linked to the activity of erosion bacteria (Liese, 1955, 1970; Schmidt and Dietrichs, 1976; Nilsson and Holt, 1983; Daniel and Nilsson, 1986; Kim and Singh, 2000). Also studies were published that described the conditions under which wood degrading bacteria were active and relations were seen with the availability of nutrients and oxygen and the water movement in the wood (Boutelje and Bravery, 1968; Boutelje and Göransson, 1975; Klaassen et al., 2008; Huisman et al., 2008a,b; Kretschmar et al., 2008a,b). Studies on isolations and identification of the erosion bacteria were done by Björdal and Nilsson (2008a), Björdal and Nilsson (2008b), Nilsson et al. (2008). Despite all these studies the identity of the wood degrading bacteria and the process of decay is until now not fully understood.

Erosion bacteria are regarded as the most common type of bacterial wood decay in anoxic soils. They are rod shaped and attached to the cell wall with their slime sheet in which they release their enzymes to dissolve the woody cell wall. As the lignin component stays more or less unattached, severely degraded wood consists of a skeleton of the highly lignified S_1 and S_3 cell wall layers, only.

Wood degrading bacteria do not have a real movement apparatus but it is believed that limited movement occurs by the circulation of their slime layer and therefore they are called gliding bacteria that motile. Their invasion in the wood relies on water movement to and through the wood, mainly. Also to secure an active bacterial wood degrading process, water movement is required while these bacteria live in consortia of about 10 species. Each link in this chain of erosion bacteria depends on its successor and predecessor with regard to useful and toxic cell wall derivatives and for an active decay process, the intermixing of derivatives and bacteria is necessary.

In order to protect the wooden elements in the anoxic soils, more information is needed on the interaction between erosion wood decay, the soil environment and the timber quality. As the process of bacterial decay is extremely slow, experiments that run over decades are needed but because of this time component difficult to establish. However, there is a unique situation in the Netherlands that can act as a *Field Trial*. In the period between the

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15th to 20th century millions of wooden piles were inserted in the Dutch soil to give all kinds of constructions a stable basis. In the last few decades, on a regular basis, piles were inspected in order to judge the stability of the foundation construction. These inspections were done because of a variety of reasons. The analysis of wood samples is part of a foundation inspection and yearly the wood of hundreds of piles is studied. Earlier studies on bacterial wood decay in this Dutch *Field Trial* were done by Klaassen (2008), and Klaassen and Overeem (2012). Klaassen and Creemers (2012) gave an overview of the wooden pilings under Dutch buildings and their actual problems. Two main aspects are related to decay. The first one is too low ground water table, causing fungal decay in the pile head. The second one is water movement in the pile causing bacterial decay. It is believed that the water dynamics in the wooden pile is related to those situations where the pile contacting soil layers have different water potentials, or to variations in ground water table including significance time periods with air contact around the pile heads. According to Hoogvliet et al. (2012) climate change could have a negative effect on the general water table in the Netherlands and they calculated that in the next few decades the ground water table in Dutch cities could decrease up to 10 cm. This process increases the threat of decay in wooden pile heads, not only by the increase fungal activity but also by an increase of bacterial activity while the water dynamics in the wood is stimulated.

In order to improve the knowledge on the dynamics of bacterial wood decay, this third study in row regarding the Dutch *Field Trial*, (Klaassen, 2008; Klaassen and Overeem, 2012) is done. This time the effect of a soil and a water environment is regarding. For the soil environment piles under buildings are chosen and for the water environment piles under quay walls (including bridge headings) are chosen. Quay walls are the boundary between canals and streets, and in the downtown area of many Dutch cities most of these quay walls are standing on wooden piles. The quay wall length varies within the cities e.g. 28 km in downtown Rotterdam (CURNET, 2013) and 70 km in downtown Amsterdam (Damen et al., 2011). The number of piles and the distance between the piles depends on the estimated load of the quay wall construction and the expected load of products stored on the quay wall. The piles at the front side of the quay stand with their upper part in open water or sediment and water. During foundation inspections on quay walls or bridge headings wood samples are always taken from the piles directly adjacent to the canal. In this situation less water movement in the wood is to be accepted because the water pathway with the lowest resistance lies outside the piles in the open water. In soil environments there is almost no water movement around the piles because of the water tight soil layers enclosing the piles. In this situation the water pathway with the lowest resistance is through the wood. As bacterial activity is stimulated by water movement in the wood, it is to be expected that piles in water will have a greater resistance against bacterial decay.

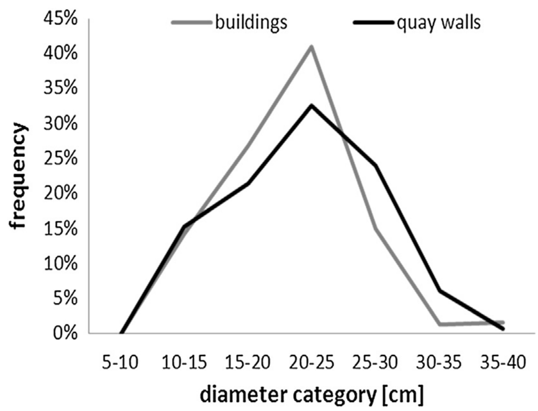

Fig. 2. Frequency diagram of the pile head diameter.

2. Method

From 1997 onwards, cores from wooden foundation pile heads were analysed with regard to timber species, sapwood amount (for pine and oak) and gradients of decay (type and degree), density and moisture content over the core (Klaassen, 2008). The cores were taken during foundation inspections carried out by 65 different companies. Immediately after sampling the cores with water are stored in a water tight tube and stored at a temperature of 4 °C before analysis. The core data were collected in a database together with information on the address and age of the building.

As the database is established on the basis of research which had a different aim than to learn more about the process of bacterial decay, the data are not randomly chosen over the country, over the serving time, over the timber species and over the type and size of the wooden constructions. It is realised that this causes restrictions to the statistical analyses and therefore the data are analysed in a descriptive way only.

3. Results

In Figs. 1 and 2 general aspects of the foundation construction under buildings and quay walls are compared. The number of piles

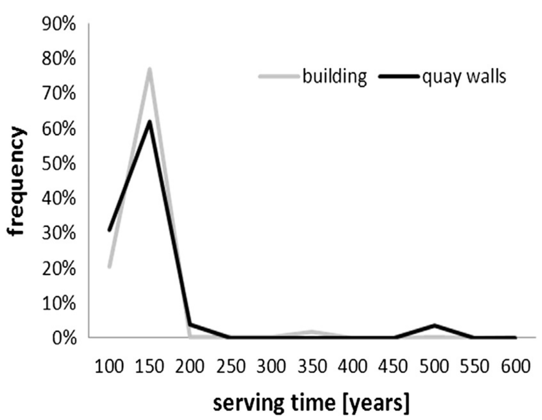

Fig. 1. Frequency diagram of the service time (0–100, 100–150, 150–200, 200–250, 250–300, 300–350, 350–400, 400–450, 450–500, 500–550, 550–600 years).

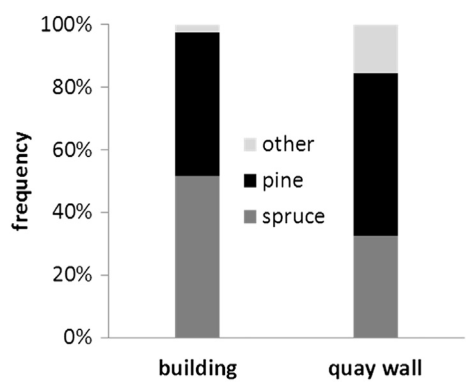

Fig. 3. Frequency diagram of the occurrence of timber species of piles under buildings or quay walls.

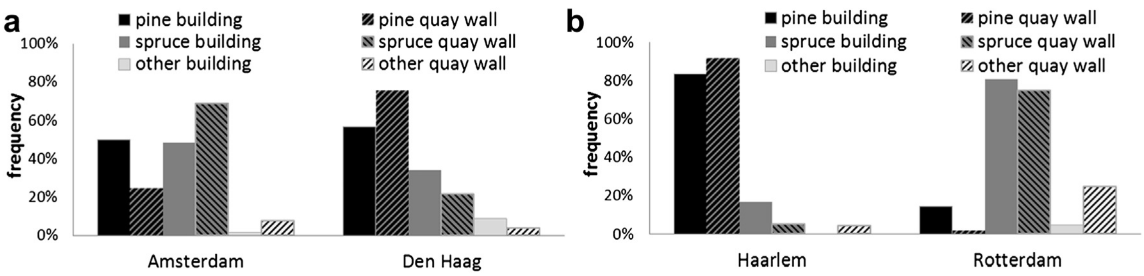

Fig. 4. Frequency diagram of the occurrence of timber species of piles under buildings or quay walls in and soil in Amsterdam, Den Haag, Haarlem and Rotterdam.

under building studied was 3000 and under quay walls 800. Fig. 1 shows that the building age of the quay walls does not differ from the age of buildings. Most objects are between 100 and 150 years old. For both buildings and quay walls, there is a considerable number of objects that is younger than 100 years (20–30%) and a limited number of objects that are several hundred years old. Fig. 2 shows the diameter of the piles. Most common diameter of the piles in both environments lies between 200 mm and 250 mm.

In Figs. 3 and 4 frequency diagrams of the species ratio are given. Fig. 3 shows the general situation for The Netherlands. Under buildings half of the piles are spruce and the other half is pine, whereas under quay walls half of the piles are pine but approximately 30% is spruce and approximately 20% consists of other species including fir, Douglas, oak and alder. Fig. 4 shows the species ratio of four Dutch cities. In Rotterdam and Haarlem the species-ratio of the piles under buildings and quay walls is comparable: most piles are spruce in Rotterdam and most piles are pine in Haarlem. On the other hand the species-ratio of piles under building and quay walls is different in Den Haag and Amsterdam. In Den Haag, in general, pine is more common than spruce, but the difference between both species is more prominent under quay walls than under building. In Amsterdam the use of pine and spruce under buildings is equal whereas under quay wall substantial more spruce is used.

In Fig. 5 a frequency diagram is given of the tree age of the spruce and pine piles used in the foundation. Other species are neglected in these figures because with spruce and pine more than 95% of all samples are covered. Most piles used in the Netherlands had a tree age between 20 and 80 years. The amount of young spruce trees used for pilings under quay wall is remarkably lower compared to the amount of spruce trees used under buildings or the pine trees used in general.

In this paper the depth of bacterial invasion is used to describe the whole degraded wood area (classified by Klaassen, 2008 as weak, moderate, severe and total disintegration). The depth of severe bacterial decay is used for that area in which the wood lost more than 70% of its strength (classified by Klaassen, 2008 as severe and total disintegration). As bacterial decay starts at the bark side of the piles and continues towards the pith, Figs. 6 and 7 show the depth of the invasion and severe bacterial decay in relation to service age. Also in Figs. 8 and 9 the relation between service time and decay is given but in these figures decay is expressed as velocity. Although Fig. 1 shows a similar frequency distribution in service age for piles under quay walls and building, Figs. 6–9 show that under buildings a few very young and a few very old piles were found. It is remarkable that especially in the young piles under buildings high velocities are found (Figs. 8 and 9). Figs. 10 and 11 show a frequency distribution of different decay-depth-classes. In both figures the bacterial activity in piles under quay walls is lower than in piles under buildings. From Fig. 10 it is seen that in approximately 70% of all quay wall piles the severe degradation is limited to the outer most 20 mm, whereas in piles under building, this percentage is not more than 40%. Fig. 11 shows that the trend of low bacterial activity in quay wall piles occurs in both spruce and pine but is most prominent in spruce.

The difference in depth between bacteria invasion and severe bacterial decay is given in Fig. 12 for spruce and in Fig. 13 for pine. Table 1 gives the percentages of samples in which the depth of bacterial invasion is equal to the depth of bacterial decay. Samples with an equal depth of bacterial invasion and severe bacterial decay occur more often in pine and in piles under buildings.

4. Discussion

In this study the activity of bacterial decay in wooden piles is compared between foundations under quay walls and buildings. The data set used, is a compilation of wood analysis done for hundreds of projects in which the primary goal was to predict the life time of the foundation construction of the single objects. The selection was therefore not randomly taken but related to the future of the objects in respect to damage control, change of owner and increase of the object. Although the data collection was not done in respect to the goal of this study and the data set for

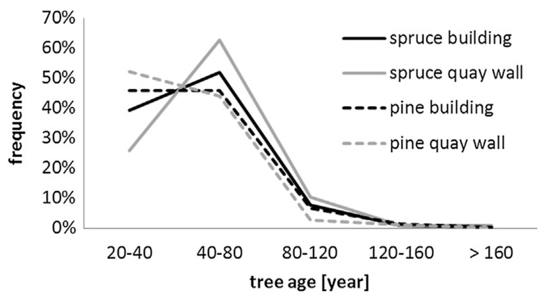

Fig. 5. Frequency diagram of the tree age of the pile head.

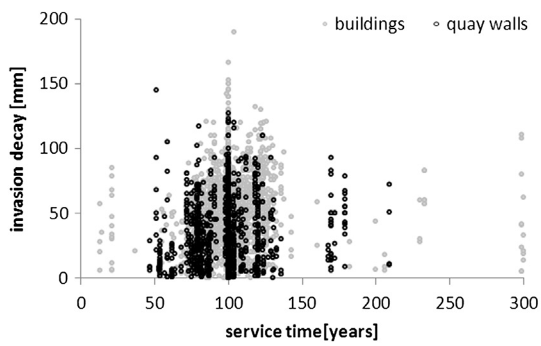

Fig. 6. Depth of bacterial invasion in piles under buildings and quay walls in relation to service age.

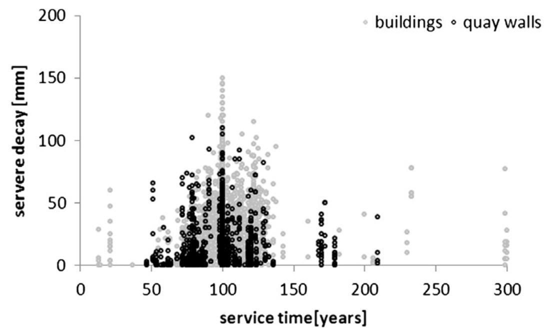

Fig. 7. Depth of severe bacterial decay in piles under buildings and quay walls in relation to service age.

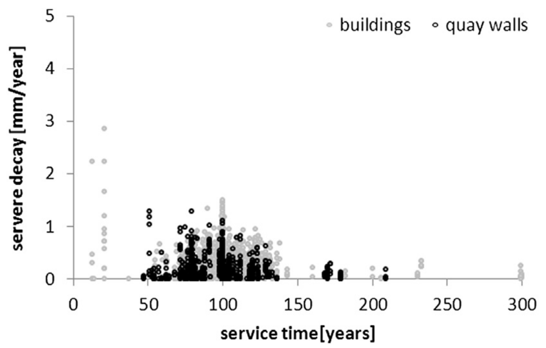

Fig. 9. Velocity of severe bacterial decay in piles under buildings and quay walls in relation to service age.

buildings is approximately three times bigger than that for quay walls, the frequency diagrams of service age, and pile diameter (Figs. 1 and 2) show a similar distribution. This means that the basis of both datasets, e.g. pile dimensions and the exposure time, is equal. Nevertheless variation was found between both foundation types in wood characteristics. Under buildings app. half of the piles are spruce and the other half is pine, whereas under quay walls less spruces piles and additional species like fir, oak and Douglas, occur (Fig. 3). The length of the piles needed on a specific location determined, at least partly, the timber species used and is related to the straight-stem-length of adult trees. From spruce trees, piles of up to 20 m in length can be produced, whereas the maximum length for pine piles is app. 12 m. In the Dutch forests of 1900, fast grown young pine trees were common and spruce trees were rare (Buis, 1985). The thickness of the weak soil layer in the Dutch area that were populated around 1900, varied from 0 to 18 m and in order to establish a stable foundation construction the piles should be so long that they reach until the first stable sand layer. Cities like Rotterdam needed long piles (16–18 m) and only import spruce piles could be used. Whereas in cities like Amsterdam, where piles of app. 10 m in length were needed, import spruce and pine piles could be used. In cities that needed shorter piles, also fast growing Dutch pine was an option. So in some areas piles could be originated from different production locations and the choices were made on an economic a quality basis depending on the demands and the budget available. A lower percentage of expensive (import) spruce piles under quay walls (like in Haarlem) could have an economic basis. The high number of piles needed and the relative high contribution of the foundation to total building costs of the quay wall, offer chances to achieve substantial reduction of building budget by using less expensive piles. For an ordinary Dutch family house about 16 piles and for a unit quay wall of 50 m about 200 are needed. The unit length of the quay wall is chosen arbitrary as minimum whereas most quay wall unit in the Netherlands are longer. Depending on the expected load on the quay wall in use, the foundation construction consists of regular spaced rows of two or more piles perpendicular to the front side of wall. Rows of four piles every 1 m is a common situation. Fig. 5 show that in general under quay walls more young trees were found. It is suggested that the choice for young pine trees originated mainly from the Netherlands was related to an economic advantage. It is unclear, if the import of young spruce tree were of any economic advantage, too. Fig. 4 shows that not in all cities the same choices were made for timber species in quay walls or buildings foundations. In cities like Rotterdam, there was almost no choice, while long old spruce piles were required. In other cities, the choices for timber species for quay wall piles could be based on economic reasons, like in Den Haag where more young pine is found, or on quality reason like in Amsterdam were more spruce is found. It cannot be neglected that the choice of specific piles for foundations could also be related to the differences in transportation towards locations where quay wall of building were constructed. The transportation of the large number of piles for quay walls occurred probably directly after harvesting through the water within rafts. Piles for buildings were transported at least for a part over land and as sizes of the deliveries were small it is plausible that they originated from storage places. This means that the chance for drying is much higher in piles for buildings and has therefore a direct effect on the sensibility for bacterial wood decay. If the moisture content in softwood species decreases below the fibre saturation point, piths will close resulting in decrease of the permeability of the wood. As bacterial wood decay depends on water movement through the wood, drying has a negative effect on its activity.

Because of the differences in the choice of the wood and the way of transportations between the piles for quay walls of building, the analysis was done for pine and spruce only and separately.

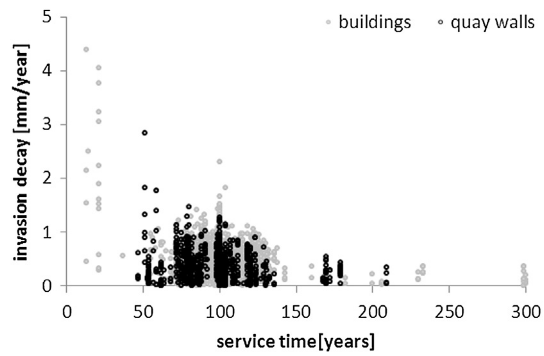

Fig. 8. Velocity of bacterial invasion in piles under buildings and quay walls in relation to service age.

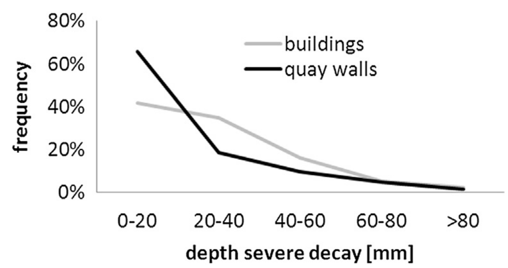

Fig. 10. Frequency diagram of the depth of severe decay in piles under buildings or quay walls.

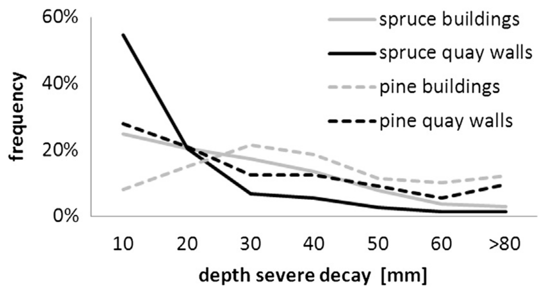

Fig. 11. Frequency diagram of the depth of severe decay in spruce and pine piles under buildings or quay walls.

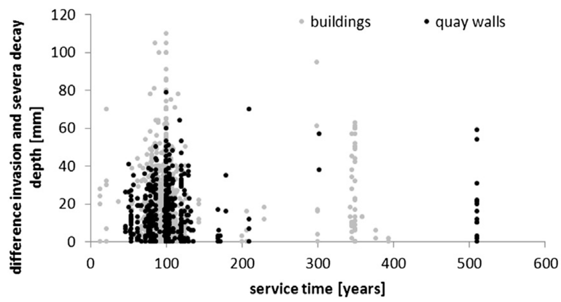

Fig. 13. Activity of decay in spruce piles under building and quay walls in relation to service age.

Furthermore the results are discussed also in the context of variation in tree age and drying ability.

It is known that pine heartwood has a low susceptibility for bacterial decay (Klaassen, 2008) and a quantification of this effect on the data used here is given in Figs. 14 and 15. For both invasion and severe bacterial decay, heartwood is a sharp boundary while in none of the samples bacterial activity was found outside the sapwood. This means that as soon as the bacteria reach the heartwood they are blocked and this is the case for app. 65% of the pine samples regarding invasion and app. 14% for severe decay. The difference between the depth of invasion and severe bacterial decay ($D_{i\text{-}s}$) can be used as an indicator for the degree of bacterial activity. If $D_{i\text{-}s} = 0$ then both invasion and severe bacterial decay are blocked and there is no activity any more. If $D_{i\text{-}s} > 0$ severe decay will continue until it reaches the same depth as the bacterial invasion. Table 1 shows that the percentage of active bacterial decay in pine is in general 35% and that under quay walls more pine piles have active bacterial decay. If $D_{i\text{-}s} = 0$ the depth of the decay is in most samples equal to the width of the sapwood. If $D_{i\text{-}s} > 0$, the invasion depth can be used to estimate the sapwood width but there is a change for underestimation while in 35% of the pine samples the bacterial invasion did not reached the heartwood yet. In the case of $D_{i\text{-}s} = 0$ the estimation of the sapwood width is more accurate but still in 6% of the pine samples the decay depth was less than the sapwood width. So beside sapwood there should be other parameters that cause a blockage for bacterial activity. It is suggested that water tight soil layers, closed wood structure through pith closure, growth of blue stain fungus and increased mineral content could have a negative effect of the permeability of the wood and therefore could prohibit bacterial activity.

Also in spruce, a blockage effect of heartwood on the bacterial activity is suggested. Klaassen and Overeem (2012) already showed examples of spruce piles with a service life of app. 350 years in which the depth of bacterial activity was equal to the sapwood width. They were able to detect the sapwood – heartwood boundary because their sample material consists of full disks. In disk samples the full concentric year rings give information on position of the sapwood – heartwood boundary by their pattern and their relation to decay. However, this study is based on core samples only, from which it is impossibility to detect the spruce sapwood-heartwood boundary and therefore spruce sapwood data are not included in the analyses. In order to find indirect evidence for a heartwood effect in spruce, the bacterial decay data of spruce are compared with those of pine. Figs. 16 and 17 show the relation in depth between invasion and severe bacterial decay for both species. The samples where $D_{i\text{-}s} = 0$ are visible in the graph as a diagonal row of points. It is remarkable that the diagonal row in the spruce graph is longer than in pine graph. This shows that the variation in sapwood width is higher in spruce than in pine. The percentage of samples on the diagonal row is for pine 65% and for spruce 21% (Table 1), showing that the percentage of samples with active bacterial decay is much higher in spruce and a relationship with lower bacterial decay velocities is suggested. The higher concentration of points in the proximity of the junction of the X- and Y-ax in the spruce graph, as well as lower mean values for bacterial-decay-velocities (Table 2) explain that within the same time span, in more pine samples, both invasion and severe bacterial decay have reached the heartwood boundary. The difference in velocity between both species is explained by the wood structure in relation to permeability. In pine the radial water pathway through the large cross field pits enables a fast invasion of the bacteria towards the pith of the stem. In spruce the water pathway is obstructed by the less permeable piciode cross field piths.

As in both species $D_{i\text{-}s}$ is always ≤0 it is suggested that in spruce heartwood is a boundary for bacterial decay, also. $D_{i\text{-}s}$ can be used in spruce as an indicator of bacterial activity and to estimate the sapwood width. However this estimation is much more uncertain than in pine because in less than a quarter of the spruce samples $D_{i\text{-}s} = 0$. Furthermore it was not possible to quantify the influences of other blocking systems because the sapwood width was not available. In pine sapwood 6% of the samples with $D_{i\text{-}s} = 0$, the sapwood width was wider than the depth of the bacterial decay. It is unknown if this percentage different in spruce.

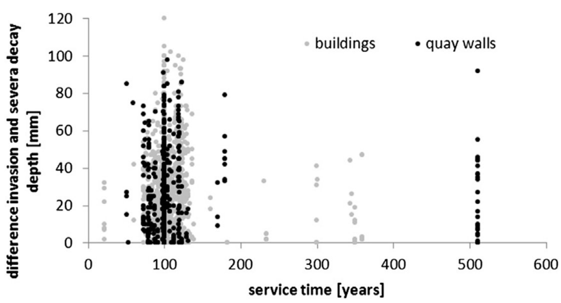

Fig. 12. Activity of decay in pine piles under building and quay walls in relation to service age.

Table 1
Percentage of the samples in which the depth of invasion is equal to the depth of severe bacterial decay, in all piles and specified for piles under buildings or piles under quay walls.

	Samples where depth of bacteria invasion is equal to depth of severe bacterial decay		
	Total	Quay walls	Buildings
Pine	65%	55%	68%
Spruce	21%	12%	22%

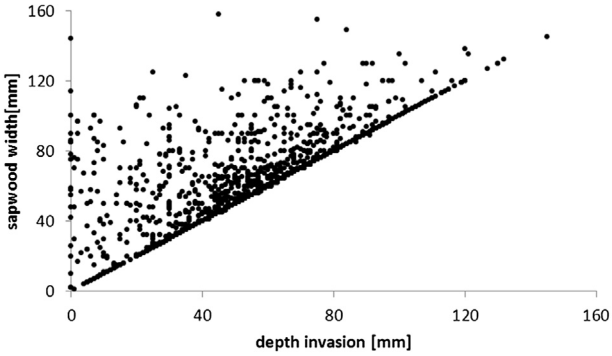

Fig. 14. Relation between pine sapwood width and depth of bacterial invasion ($N = 1859$).

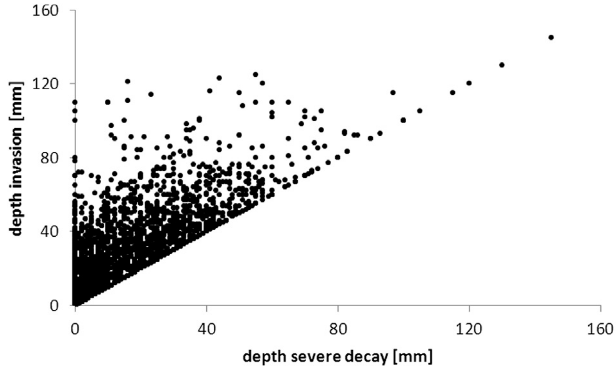

Fig. 16. Relation between thickness of depth of bacterial severe decay and invasion in spruce ($N = 1880$).

The influence of location on the bacterial activity in spruce is similar as in pine but more pronounced. Compared to quay walls, the bacterial decay velocity is higher in piles under buildings and is less piles the decay is still active ($D_{i\text{-}s} > 0$). These higher velocities are explained by an easier bacterial infection by piles surrounded by soil (Björdal and Nilsson, 2008a) and by a higher water dynamics in piles in soil. As foundation piles often crossing water tight soil layers, the water will take the pathway with the lowest resistance and that is the wooden pile. Whereas for quay wall piles the water pathway with the lowest resistance is outside the piles in the surrounding water. Beside heartwood, other blockage systems are recognized and have their effect on the bacterial activity. There are three acceptable possibilities for the additional blocking systems. The first one is pith closure as a reaction of drying. As explained before piles for foundations of building had in general more chances to dry. The second possibility that could initiate the closure of the wood structure is through inclusion of minerals or formation of pyrite (Huisman et al., 2008a). In soil surrounded piles under buildings more particles are available than in the water surrounding the piles under quay walls. The third possibility that could initiate the closure of the wood structure is the activity of blue stain fungi. Under ideal conditions these fungi grow fast and their hyphen could increase several centimetres per hour in length (Schmidt, 2006). They grow in the cell lumen of the sapwood and a blockage of the water pathway is supposed. Ideal growing conditions can occur between harvesting and use of the piles or during their service life when the pile head will be above the water level.

Although all three blocking stems seem to have more effect on the piles under buildings additional research is needed to distinguish between the different blocking systems and to quantify their effect for piles in different environments. Also a timber species dependency is suggested because of significant differences in wood structure of both species, resulting in differences in permeability. Additional research should explore the mechanisms of blocking in relation to wood structure and permeability which could be the basis of a conservation method of piles in situ.

Beside an effect of location, environment and species on the velocity of bacterial wood decay, a time aspect is suggested. Only in young constructions a wide range including extreme high velocities were found (Figs. 8 and 9). Because of the limited number of samples, it stays unclear if velocities beyond 1 mm/year are common in wooden piling from young constructions. Specific sampling strategies should be initiated in order to explore the degree of activity of bacterial wood decay in the first 50 years after the piling are placed in service.

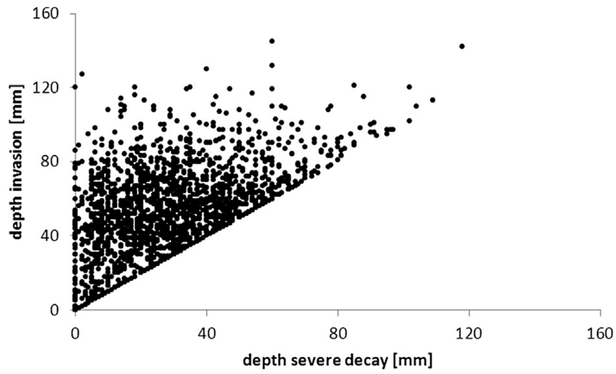

Fig. 17. Relation between thickness of depth of bacterial severe decay and invasion in pine ($N = 1859$).

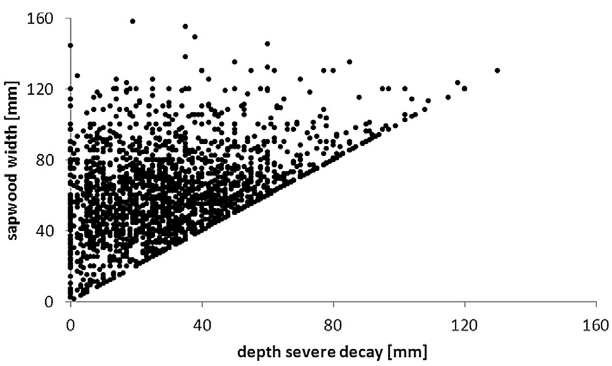

Fig. 15. Relation between pine sapwood width and depth of severe bacterial decay ($N = 1859$).

Table 2
Velocity of bacteria decay for all spruce ($N = 2494$) and pine piles ($N = 2376$) and specify for piles under buildings (N spruce = 2029; N pine = 1876) and quay walls (spruce $N = 465$; pine $N = 500$).

	Bacterial velocity [mm/year]					
	Total		Quay walls		Buildings	
	Invasion	Severe day	Invasion	Severe day	Invasion	Severe decay
Spruce	0.33	0.18	0.25	0.10	0.35	0.20
Pine	0.55	0.32	0.50	0.25	0.57	0.34

5. Conclusions

The susceptibility for bacterial wood decay in foundation piles in a water environment is less than in a soil environment. The bacterial infection rate of the piles as well as the water dynamics in the wood are regard as main causes.

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