A review and case studies of factors affecting the stability of wooden foundation piles in urban environments exposed to construction work

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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

Wooden foundation piles have been used since Roman times to solidify infirm soils prior to construction of heavy monuments like churches, buildings and bridges. These are known to have a long service life in waterlogged anaerobic environments where most biological wood decay processes, except for slow bacterial degradation, are repressed. However, large scale urban ground work may change the biogeochemical stability of the soil, increasing the microbial decay of the piles and resulting in settling damages to historic buildings. This paper evaluates and synthesizes present knowledge within this cross-disciplinary field in order to understand the complex processes during ground work that have detrimental consequences for foundation pile durability. We conclude that soil types, ground water levels and water flow, as well as the hydrogeological matrix are important parameters for understanding the stability of a site. These factors will affect the oxygen content available for development of more intense decay by erosion bacteria or additional attacks by aggressive wood rotting fungi. These interactions and thresholds should be studied further. Knowledge of local environments can determine the vulnerability of burial sites prior to disturbance, and enables taking preventative measures to counter effects thereof.

1. Introduction

1.1. Use of piling in history

Piling has been used as a building technique for over seven millennia, as known from the UNESCO world heritage site of the prehistoric pile dwellings in the Alpine region dating from as early as 5000 BC (Heumller, 2012). Piling was also used extensively by the Romans and was written about by Vitruvius in his famous treatise De architectura libri decem (“The ten books on architecture”, ca 30 BC), where he cites the importance of solid ground for laying foundations and describes how “If solid ground cannot be found […] it must be set with piles […] and the foundations laid on them in the most solid form of construction” (Vitruvius et al., 1914). The building technique is performed by hammering down several piles vertically into the soft soil at evenly spaced intervals, usually around 10–30 cm in diameter and often several meters long (Klaassen, 2008), to support the overlying foundations and transfer the load deeper into the soil. This can be done either using short piles (1–3 m long) set close together to compact the soil, or using longer, thicker piles (10–15 m long) that reach solid bedrock beneath overlying soft soil deposits (Przewłöcki et al., 2005). There are also structures built where the bedrock is inclined, for which part of the foundation rests on piles that reach a lower firm substrate and other parts are supported by closely set short piles. Timber logs of softwood species such as pine, spruce and larch were the standard material for foundation piles up until the middle of the twentieth century (Klaassen and Creemers, 2012), sometimes sharpened in one end to facilitate hammering into the soil.

Solidifying the ground beneath foundations in this manner meant that even areas with poor soil quality could be developed for housing. Land reclamation of marshland and wasteland colonization has been used as a method to expand territory since medieval times (Curtis and Campopiano, 2014), so piling came to be a common stabilizing technique throughout Europe and the world. Today, the materials used are different but the method is still relevant as expanding cities need to develop land reclaimed from the sea or utilize deep foundations to support high-rise buildings to save surface space (Jiao et al., 2006).

In waterlogged soils the wooden piles have a long service life and therefore many historical cities close to rivers, waterfronts and the sea are still standing on original wooden pileings. Several of these old towns with well-preserved historical buildings are today popular tourist attractions, such as Stockholm, Trondheim, and Amsterdam, and are an important part of our shared cultural heritage. This makes the study of wood decay in urban environments a cultural heritage issue as well as...
Fig. 1. A 100-year-old pile is excavated from outside the parliament building in Stockholm for analysis to determine decay.

1.2. Wood as a sustainable material

Wood is a strong natural composite consisting of small elongated hollow fibres mainly oriented along the stem axis. These are seasonally formed in the cambium, just beneath the bark, and are closely connected to each other by anatomical openings (pits) in the fibre cell wall which secure an even distribution of water, nutrients and extractives in the living tree (see Supplementary Material Fig. 1). Chemically, the cell wall consists of the polymers cellulose, hemicelluloses, and lignin, which are arranged in micro- and macro-fibrils (Bowyer et al., 2007). The outer part of the stem, named sapwood, transports water in the living tree whereas the inner part, named heartwood, is the mature non-conductive part of the stem which is rich in extractives. Extractives often contain natural pesticides and fungicides which generally makes heartwood more resistant to biological attack. However, like all organic material, wood may undergo a full decomposition by macro and microorganisms in nature (Eaton and Hale, 1993). Above ground and in access to oxygen and moisture, wood is rapidly degraded by aggressive fungi, whereas wood in waterlogged and anaerobic soils is highly protected (Blanchette et al., 1990).

From studies on wooden foundation piles, archaeological objects and historic constructions buried in deep anaerobic waterlogged soil, slow bacterial attack on the woody cell wall is the only type of degradation that occurs here and this process may take up to hundreds of years in a stable environment (Kim et al., 1996; Bjordal et al., 2000; Blanchette, 2000; Gregory et al., 2002; Macchioni et al., 2013). A large threat to stability of foundation piles will arise if the protective waterlogged environment changes and become more oxygenated.

1.3. Problems for urban infrastructural groundwork

Modern society places an increasing demand on urban infrastructure to house and transport growing populations, leading to expanding urbanization as well as development in and around existing constructions and buildings. It is estimated that more than half of the world’s population will be living in urban areas by the year 2030 (Palmer et al., 2004). Since surface space is limited, this puts a stress on the urban underground environments. This is especially true during the construction period, affecting the local subsurface soil environment at the construction site as the soil structure is disrupted and great amounts of soil are removed. A common effect of an active construction site is a local lowering of the groundwater table, e.g. when excavating a tunnel or laying deep foundations, by pumping away the groundwater that seeps out through the exposed subsoil at the sides of the dig site or into the tunnel. Although temporary dig sites mostly have a temporary effect on local groundwater levels, tunnels often have persisting groundwater leakage and therefore contribute to a long-term lowering of groundwater levels. It is common to screen off the area of an excavation site with vertical sheet metal walls inserted into the soil as a curtain, to avoid water flooding the dug hole and with the aim to keep the area outside the dig site untouched and unaffected, but the technique has its limits (Wang et al., 2016). Some studies have described situations where buildings in such areas may suffer from settling although it might take several years before it becomes evident (López Gayarre et al., 2010).

Keeping the environment stable is key for the function of a piled foundation, since the stability of piled foundations depend not only on the wooden piles but rather on the interactive system of wooden foundation piles, surrounding soil matrix and groundwater. To function as intended, all three components must be present. Infrastructure works can alter the environment locally and thus affect the function of the foundation. If the groundwater level is lowered it will lead to desiccation of the soil and give rise to a range of problems for the integrity and strength of the wooden foundation piles. When air and oxygen are introduced into the soil and reach the wooden foundation piles, a more aggressive biodegradation by fungi and bacteria will develop (Eaton and Hale, 1993). This will mainly cause damage to the pile heads, i.e. the part closest to the surface and in contact with the foundation above, leaving the majority of the pile length intact as the deeper buried material remains waterlogged and outside the range of the decay organisms. As the degradation weakens the material, the foundation piles will become unable to support their designed loads and the foundation piles will splinter and fail. Damages are most common where there is an uneven settling rate across the foundation and differential settling occurs. This can be due to different settling rates between soil and the piled foundation, or due to failure of single piles in a foundation. The part of the foundation that overlies failed piles will become unsupported, consequently leading to local settling damages and cracks in the building (see Fig. 2). In severe cases the entire building can collapse as settling damages can be devastating for the structure and the preservation of cultural heritage buildings.

Since the foundations are hidden from view, decay can proceed for a long time before visible damages are evident in the overlying structure, such as cracks in the façade or a tilt caused by uneven settling rates (Klaassen, 2008; Klaassen and Creemers, 2012). The long timescales involved make it difficult to determine what initiated the decay, and who is financially responsible for the damages: the owner of the building, or contractors that have performed recent groundwork in the area (González-Nicieza et al., 2008).
With this cross-disciplinary paper we aim to provide a comprehensive overview of main factors that affect the long-term stability of submerged wooden foundation piles in urban environments exposed to large-scale construction work. First, we describe urban soils and define the main factors that could affect the decay rate of wood immersed in these environments. Secondly, we provide an introduction to the microbial organisms responsible for wood decay in wet soils, and outline and summarize the biogeochemical factors known to influence the rate of bacterial degradation. Some experiences from previous case studies are given. Finally, we synthesize current knowledge from the different fields, and provide new perspectives as well as highlight areas where further studies are necessary in order to understand and, in the future, better control the environment at sites affected by construction work. Since the focus lies on protection of existing wooden piles, preservative different piling techniques or coating methods as well as different piling techniques or coating methods for reducing soil friction stress are not part of the study.

This work aims to be a bridge between disciplines and invite new perspectives. As such, we have chosen to treat all subject areas with the same level of detail and will not present e.g. stoichiometric relationships or specific biogeochemical processes in the soil. Our focus is not on the processes themselves but rather how these affect the degradation of wood. Presently, very little is known on the relationship between burial environment, site-specific soil processes and the rate of wood decay. With this work, we hope to inspire novel research ideas and to fill out this knowledge gap.

2. Urban site soil characteristics

2.1. Physical and chemical nature of urban soils

“Urban soils” is an umbrella term for all soils that have been “profoundly affected by urbanization”, or soils that have been altered from their natural state by human activity (Lehmann and Stahr, 2007). Here we use the term in the meaning anthropogenic inner-urban soils, disturbed soils that exist within the boundaries of a city. Urban soils are variable in their composition depending on the city age and location but share common characteristics of having been changed from their natural state by human activity, such as mixing soils from different depths and areas, filling natural troughs with foreign soil to level out or raise the ground, and/or contaminating the soil with foreign compounds. Not uncommonly, urban soils have lithological discontinuities from these activities, with older soils overlaying younger soils and abrupt changes between one layer and the next, creating interfaces between soils of different origin (Craul, 1985). Older cities can also have deposits of historic organic material underlying layers of soil and new buildings, known as cultural layers.

The uppermost layers of urban soils are often compacted, or compressed, due to amongst other things destroyed soil structure and heavy surface traffic. Compacted soils contain fewer pore spaces, which restricts both water infiltration and gaseous diffusion (Craul, 1985). The soil is often less hospitable to soil organism activity such as seedling emergence and plant root growth when compacted (Awadhwal and Thierstein, 1985), which further hinders both the aeration and water drainage of the subsoil underlying the compacted surface crusting.

It is common for urban soils to be slightly alkaline and the increase in pH is considered to be due to the weathering of construction materials and the application of de-icing products on roads and pavements (Lehmann and Stahr, 2007). Urban soils in general have elevated levels of organic carbon, nutrients and contaminants from combustion residues and atmospheric deposition of aerosols (Craul, 1985). Though there are plenty of nutrients accessible, the soil nutrient cycling is interrupted by the lack of soil organisms and restricted water movement. The soil has variations in both moisture content and nutrient concentration, with areas of both excess and limited supply.

Soil temperatures are comparatively higher in urban environments than in surrounding rural environments, as the compacted surface crust acts as an insulator and limits the heat exchange with the atmosphere (Fokaides et al., 2016). Buildings have been seen to have a warming effect on the soil, as soils underlying buildings were found to be warmer than the annual mean air temperature. However, the annual variability in soil temperature, oxygen content and water content all decrease with depth, with the top two to three metres being the most variable (Hollesen and Matthiesen, 2015).

2.2. The urban water cycle

Many urban surfaces such as roads and roofs are covered with impervious materials such as concrete, asphalt and sheet metal. Due to compaction, uncovered urban soil surfaces are also generally less permeable than natural or agricultural surfaces. When the precipitation rate exceeds the infiltration rate of the ground in a given area the rain will exit the system as surface runoff, i.e. water that flows aboveground (Fetter, 2001). Urban environments commonly use drainage systems to transport the excess surface water to natural waterways, further reducing local infiltration and groundwater recharge. Precipitation on roofs has largely been seen to contribute to surface water drainage systems, but there are systems which enables the roof runoff to feed into the ground for local soil moisture and groundwater recharge (Redfern et al., 2016). Runoff water from urban areas contain a higher concentration of pollutants, suspended particles and organic nutrients than forested or agricultural watersheds, attributable to the inability of urban soils to infiltrate water to filter out and absorb solutes (Yang and Zhang, 2011).

2.3. Ground water levels

Water that is stored in the saturated layers of soil is known as groundwater, as opposed to surface water such as lakes or streams. The level in the soil where the water pressure equals the atmospheric pressure is called the water table, comparable to the surface level of a lake. Due to capillary forces the soil can be fully saturated even above this point, and there can still be soil moisture in the unsaturated zone above this level which can drain down through the soil due to gravity and contribute to groundwater recharge (Fetter, 2001).

Groundwater level depends on input and withdrawal from the
system and naturally varies over time, due to e.g. seasonal variations in infiltration rates. In a steady state system where the runoff equals the input, the water table will stay constant. If the input is reduced then the runoff will slowly drain the system, even if no added withdrawal is made. These natural variations occur within a normal range determined by input and outflow, which is different in different environments. Altitude, local precipitation rates and soil type influence the natural groundwater level: an organic-rich valley in an area with high precipitation rates will have a higher water table than a sandy plateau with less precipitation (Fetter, 2001). However, human influence can incur a decrease in groundwater level, either directly by e.g. draining wetlands for peat production (Van Seters and Price, 2001) or withdrawing groundwater for use as a fresh water resource (Palmer et al., 2004), or indirectly by reducing the refill rate from natural infiltration of rainwater and altering subsurface water flow paths (Fetter, 2001).

Due to the layered structure of urban soils, it is possible for several groundwater reserves (aquifers) to exist in the different layers. Therefore, urban subsurface groundwater can affect the groundwater levels in several layers, depending on the location (Fig. 3).

2.4. Water transport in soils

Water always flows from high pressure to low, e.g. with gravity or laterally from input source to outflow. The hydraulic conductivity of a soil, or the soil's ability to transport water, depends on the particle size of the soil, the mean pore size distribution and the homogeneity of the soils. Generally speaking, a soil consisting of larger particles will contain more pore spaces for water to pass through and will therefore transport water faster than a soil with smaller soil particles. Likewise, the speed at which a soil dewaterers depends on the hydraulic conductivity, where a soil with high conductivity will drain faster and become aerated more quickly than a less conductive soil (Fetter, 2001).

In urban soils, the transport of water including solutes and nutrients from one area to another may be hindered by the altered soil structure. Previous ground work where filling materials of different character have been used creates heterogeneity in the ground, which makes it difficult to predict water flow. Furthermore, underground constructions such as building foundations, parking garages and sewers can obstruct flow paths, connect groundwater reserves or leak water into the system. Leakage from sewers have been shown to be an important source of groundwater, albeit contaminated (Schirmer et al., 2013), and leaking water mains have been seen to contribute to groundwater recharge in as large extent as irrigation (Lerner, 1990). This water is often considered to contain more oxygen than naturally occurring stagnant groundwater, but the effect of dissolved oxygen content in infiltrating water is debated (Matthiesen and Hollesen, 2012).

3. Wood decay in soils

3.1. Aerated topsoil

Wood above ground and in ground contact is decomposed relatively quickly by the action of wood rotting fungi (white rot, brown rot, soft rot) and tunnelling bacteria (Blanchette et al., 1990). These decay forms are well known in the topsoil, and their activity and decay rates are often described and assessed in studies where preservative impregnated wood stakes and non-impregnated controls are tested in field experiments (Eaton and Hale, 1993). One field experiment showed that control samples in ground contact were infected to a varying degree during the first year, and after four years all stakes were classified as "failures" according to standardized evaluation (Brischke et al., 2014). Similar results were found in other field tests where stakes were half inserted in soils (Mohobby and Miltiz, 2010), indicating that wood degradation in aerated topsoil develops very fast. When durability of sound and non-preservative treated pine stakes was tested in different natural soils, it was concluded that sites often have different site-specific dominating decay profiles where some are more aggressive than others (Edlund, 1998; Rapp et al., 2007).

3.2. Waterlogged anaerobic soils

As foundation piles are inserted deep into the ground where the environment is anaerobic and waterlogged, the degradation process differs from the topsoil environment. In waterlogged environments only so-called erosion bacteria (EB) are found able to degrade wood (Kim and Singh, 2000; Björadal, 2012). Analyses of foundation piles from different geographical locations have all reported on varying degree of EB deterioration in the wood surface layers (Boutelje and Bravery, 1968; Boutelje and Göransson, 1975; Grinda, 1997; Klaassen, 2008; Rehbein et al., 2013). The decay rate is generally extremely slow and therefore foundation piles can be in service for centuries. Archaeological wood material witness to still ongoing EB decay, e.g. in Viking piles submerged for 1000 years in marine sediments (Björadal, 2000). In a similar way, foundation piles are most likely continuously degraded by EB during their exposure in ground.

EB are 1–8 μm long rod-shaped bacteria with a diameter of about 1 μm (Holt and Jones, 1983; Singh et al., 1996; Nilsson and Daniel, 1997). Their way of degrading the wood cell walls and the decay pattern left behind are well studied, but their genetic identities are still unknown (Schmidt and Liese, 1994; Landy et al., 2008). Decay starts from the wood surface and proceeds slowly inwards via anatomical openings like rays, pits and/or vessels. Here they grow, divide and spread into neighbouring fibres. A typical decay feature of EB is the preferential decay of the cellulose-rich cell wall, whereas the lignin-rich
middle lamella surrounding the fibres remain intact (Fig. 4). During decay, residual material is left behind in the hollow centre of the cell (the lumen), and a honeycomb-like skeleton of the middle lamellae preserves the physical integrity of the wood as long it remains waterlogged. In this state, the wood is very weak, soft and spongy, but gives a false impression of being a well-preserved wood material as the outward appearance and original colour are intact (Björdal, 2000).

The bacterial decay alters the chemical composition of the wood, changing the mechanical properties of the wood in proportion. When the strength-providing cellulose is degraded, the density of the wood decreases and the water content increases, affecting both hardness and strength of the wood (Capretti et al., 2008).

4. Factors that affect the durability and lifespan of foundation piles

4.1. Drainage and aeration of soil

Draining soils and lowering the groundwater table can induce settling, a lowering of the ground surface due to compaction of the soil, as soil pore spaces that were previously filled with water are compressed. The air that fills the pore spaces when the water drains away is more compressible than water and is therefore less able to sustain the pressure of overlying construction (Budhu and Adiyaman, 2010). This compaction is often an irreversible process since the soil rearranges during drying and decreases in porosity, leaving fewer pore spaces for the water to fill. Organic-rich soils and soils with larger particle size are more prone to volume loss due to drying (Peng and Horn, 2007).

As the water table recedes, the soil becomes aerated and oxygen penetrates deeper into the ground. This can cause organic material in culture layers of the soil to decompose, further aggravating the land settling (Matthiesen, 2007).

Oxygen is regarded as one of the key factors for controlling wood decay rate in ground. In a fully water saturated environment, the dissolved oxygen concentrations in the pore water is near anaerobic, and since fungi demand more oxygen to maintain activity only EB are able to degrade wood. The decreased activity by EB observed along the depth gradient are suggested to be attributed the decrease of oxygen concentrations in the pore water system (Björdal et al., 2000; Hollesen and Matthiesen, 2015), but when oxygen is totally excluded and the environment is regarded as anaerobic, decay still takes place (Kretschmar et al., 2008a).

4.2. Soil pore water and nutrients

Soil pore water can contain not only dissolved oxygen but also, depending on the ion composition, oxygenated ion species which can be used as alternative electron acceptors during organic matter degradation under anaerobic conditions. There are microorganisms that can make use of the oxygen bound in ions and changes in pH can lead to the dissolution of soluble minerals in the soil. Soils have a natural buffering effect which can help protect against pH fluctuations, and while both organic and clay components are known to increase the buffering capacity of a soil (Weaver et al., 2004), care should be taken to make sure artificially infiltrated water and filling material match the chemical and physical properties at the dig sites before disturbance to minimize damages caused by a variable environment (Caple, 2004).

It has been suggested that increased levels of nutrients associated to a waterlogged site in Stockholm could explain the severe bacterial degradation observed in the piles (Boutelje and Göransson, 1975). But in a larger European study, no positive correlation was found between nutrient loading and bacterial growth (Huisman et al., 2008a; Kretschmar et al., 2008b). Contrarily, laboratory microcosms indicated that lower nitrogen concentrations promoted decay (Kretschmar et al., 2008a).

4.3. Soil type and physical environment

Foundation piles are mainly inserted in soft soils that are prone to settling; waterfront clays or muds, marshland peat or historic cultural layers of older cities. Clays and muds are fine-grained soils, such as alluvial deposits from the previous ice age or soils comprised of previous sediment, consisting of fine particles of unconsolidated material with small pore spaces. These types of soil have a low hydraulic conductivity and are slow to transport water. Some clays can contain chemically bound water and can physically swell in contact with water depending on the ionic composition of the clay mineral (Hulsen and Smit, 2002). Organic-rich soils on the other hand drain faster, as the soil is heterogeneous in terms of grain size, pore size, and permeability since the soils often contain different types of mineral and organic materials, such as roots, fungal hyphae and particular organic matter (Jastrow, 1996).

Different soil types have different water retention capacity, or ability to store water. There are several forces acting on soil water that can act to draw water upwards and maintain moisture in the soil above the groundwater table, such as capillary rise due to surface tension, cohesion of water to water and adhesion of water to soil (Fetter, 2001). These forces can help to counter the effects of sinking groundwater levels and keep objects in the soil waterlogged. Studying the micro-morphology of a burial medium can give information on water content of soils overlying the water table, illuminate active soil processes and indicate their spatial scale (Huisman, 2007).

Desiccation not only promotes increased microbial activity, but also increases the friction stress that acts on the piles from the unsaturated burial medium (López Gayarre et al., 2010). This stress, also known as “skin friction” or “shaft resistance”, reduces the load bearing capacity of the pile as the movements of the shrinking soil exerts force on the pile (Fellenius, 1972). Studies on the dynamic load-bearing characteristics of concrete foundation piles show that the moisture content of the soil matrix surrounding the foundation piles affect the piles’ capacity to withstand stresses due to soil movement. In a saturated state, the soil becomes more elastic and can move with the foundation pile, whereas a less saturated soil is stiffer. When exposed to stress, such as vibrations from heavy traffic, a saturated soil will shift and reshape around the pile and support the foundation pile evenly (Aubakirov, 1975).

Increased temperatures are known to promote bacterial activity in soils (Díaz-Raviña et al., 1994), and seasonal variations have been observed in the upper layers of wetland soil, with greater abundance and
respiration during the warmer spring and summer months. As soil temperature decreases with depth and becomes more stable and constant, the amount of bacteria and their activities also decreases regardless of the nutrient availability (Douterele et al., 2009).

5. Selected case studies on piles and archaeological wood

5.1. Case studies on foundation piles

During the 20th century a large number of foundation piles have been examined in connection with observed settlements and instability of buildings around the world, but only a few reports reached the scientific community. In 1968, Boutelje and Bravery described that testing of foundation piles in Stockholm had been ongoing for 20 years as infrastructural urban construction work had changed the ground water levels and raised a concern for the condition of the piles (Boutelje and Bravery, 1968). In their paper, results on morphology and strength of two pine and two spruce piles were given and decay of bacteria-like origin, not fungal, was observed in the surface layers. Since then, descriptions of EB decay patterns in piles have been reported. Sometimes these reports include information on correlated strength losses (Lundström, 1981; Pääjänen and Viitanen, 1988; Grinda, 1997), chemical analyses (Gelbrich et al., 2008; Macchioni et al., 2016), or both (Boutelje and Göransson, 1975).

The most complete study on foundation piles to date is probably the cross-disciplinary research project BACPOLES funded by the European Commission. The full title of the project is “Preserving cultural heritage by preventing bacterial decay of wood in foundation piles and archaeological sites”, and it took place in 2002–2005. In total 27 field sites in 6 countries were examined, of which 13 were sites with foundation piles of pine, spruce, fir, poplar, and oak. These were studied in their burial context and the degradation was assessed after burial for 100–2500 years. All piles showed degradation to a varying degree, almost exclusively by erosion bacteria (EB), but the heartwood often remained sound and un-degraded. The relative lignin content increased as the bacteria consumed the polysaccharides (Gelbrich et al., 2008). Despite in-depth statistical analyses, it was not possible to correlate decay rates to specific chemical or physical factors in the environment, although certain sites seemed more aggressive than others. A low redox potential of the soil did however indicate a more protective environment (Huisman et al., 2008b). Complementary laboratory experiments showed that increased nitrogen concentration in the surrounding soil matrix seemed to inhibit EB decay (Gelbrich et al., 2008; Kretschmar et al., 2008b). As the identification of EB was a major focus of the project, DNA analyses were given much effort. Results revealed a huge amount of bacterial diversity inside the wood, but it was not possible to identify EB within this mixed population. However, with help of specially developed isolation and cultivation methods and optical tweezer techniques, almost pure cultures indicated that EB could belong to the groups Cytophaga or Flavobacteria (Landy et al., 2008; Nilsson et al., 2008).

When full-length piles were examined, variations in degree of decay along the stem could be evaluated. From a large study in the Netherlands, a majority of 57 full length piles showed a clear decrease in decay with increasing depth in soil (Klaassen and Creemers, 2012). Similar results were found in 3 poles from Berlin (Grinda, 1997) and when piles from Venice were examined it was evident that longer piles showed a clear depth-gradient in decay whereas shorter piles of about 1 m were evenly degraded (Macchioni et al., 2016). An evenly distributed degradation was also found in two 7 m long piles from Stockholm. Here piles were inserted in soil on a small island, where oxygenated streaming water constantly passed by, which could explain the homogeneous decay along the full pile length (Berghund et al., 2006).

A more recent study conducted in Riga, Latvia, explored the degradation of foundation piles supporting the 13th century Riga Cathedral. It was concluded that erosion bacteria were the main degraders of the wooden foundation piles and future threats to the foundation stability were identified as where the wood was subject to a fluctuating groundwater level (Irbe et al., 2019).

Forensic analysis of collapsed foundation piles and the surrounding environments are rare. In two studies in Spain, pile failures with devastating consequences for the building above revealed a strong correlation to previous drainage and construction work in the neighbourhood. These changed environmental conditions increased the decay process until the piles could no longer bear their designed loads and collapsed. Experience from these events have made the authors suggest and indicate a number of conditions in which the strength of a foundation is at risk, such as lowered groundwater table, land subsidence and friction stress (González-Nicieza et al., 2008; López Gayarre et al., 2010).

The type of foundation is also important to consider, as a numerical study from Venice shows that the magnitude of settlement is higher in foundations with short piles than in foundations that reach a lower stable substrate. However, the short-piled foundations were less likely to suffer from differential settling. Both of these results could be due to the fact that completely degraded piles can still provide support as the friction between piles is still present (Bettiol et al., 2014). As the wood degrades, the stresses are transferred from the wooden piles to the surrounding soil matrix instead. The overlying structure is then dependent on the soil settling rate (Ceccato et al., 2014).

5.2. Case studies on archaeological wood

There is a wealth of knowledge to be found in archaeological research highly relevant to degradation of wooden foundation piles in urban environments. Sometimes large volumes of wood are found preserved in waterlogged environments as remaining historic evidence of houses, bridges, roads, and trackways, but delicate objects of much smaller dimensions are also found at sacrificial sites. A few of these important rural or urban archaeological sites have been carefully examined in order to understand the ongoing degradation processes, and to evaluate if the site has a future potential for long term storage of the find – an option called in-situ or reburial in site preservation.

The Rose Theatre in London, UK (remains of the old Shakespeare Theatre), was one of the first urban archaeological sites being scientifically investigated and reburied in situ. In the paper The Rose Theatre: Twenty Years of Continuous Monitoring, Lessons, and Legacy (Corfield, 2012) the background and decisions for site management and public display of The Rose Theatre are explained. Here, a review on in situ preservation is also given in a historic perspective with focus on northwestern Europe. It is emphasized that knowledge on the geophysical and chemical characteristics of the site itself is crucial in order to tailor-make a long-term protective environment with high water levels and anoxic water.

The urban archaeological deposits beneath the old town Bryggen, Bergen, Norway, is another example where site parameters were measured over a long period and analysed in order to establish a more protective environment around the organic remains. It was decided to preserve and secure the site by raising the groundwater level and reducing the oxygen concentration of the ambient water (Ryttner and Schonhowd, 2015). A new environmentally sustainable approach was developed where rainwater was used as infiltration water and de-oxygenated in soil beds before spreading into the cultural layers (de Beer et al., 2016).

In rural environments, drainage of wetland and peat bogs often threatens the stability and survival of organic archaeological remains. When the water level decreases, desiccation starts and allows air with oxygen to penetrate into previously anaerobic and protective soil layers where the archaeological remains are situated. Our understanding of these environments and degradation processes started with the investigation of individual sites.
One early example is the sacrificial peat bog Nydam in Denmark, containing a large number of delicate artefacts in wood and metal from the Iron Age. The wooden finds were situated relatively close to the soil surface and heavily degraded by mainly EB. A monitoring program was carried out to understand the geophysical and chemical parameters as well as variations and fluctuations in the area. Results from monitoring reveal a still anoxic waterlogged site with high water level and oxygen only in the upper centimetres of the bog (Gregory and Matthiesen, 2012). Today monitoring is still ongoing and modern sound wood samples are inserted as proxy indicators for periodic analyses (Gregory et al., 2008).

At two archaeological sites in the UK, large interventions have been carried out to preserve historic constructions in wetlands from desiccation. Observation of drainage in the area of the 2 km long Neolithic wooden trackway Sweet Track led to decisions on artificial water level raise to limit oxygen supply (Brunning et al., 2000).

At the Bronze Age site Flag Fen, results from environmental monitoring and examination of archaeological wood and inserted sound wood stakes indicated a microbial aggressive site with sinking water levels (Powell et al., 2001). Thus, an artificial lake with increased water levels was constructed in 1987 to flood the area. The condition of the site today is not known (Malim et al., 2015) although hydrogeological modelling indicates that many timbers are still situated in non-protected soil layers (Wagstaff et al., 2016).

5.3. Summary case studies

The lesson learned from case studies in terrestrial waterlogged environments, both on foundation piles and on archaeological material, is that the rate of degradation in wood depends on many factors, which interact in a complex manner that is not yet fully understood.

Many case studies point out single physical and chemical parameters that affect decay rates of organic material in general, such as soil type, depth of burial, nutrients, oxygen availability, ground water levels and water flow. Redox potential and pH give important information and values on the aggressiveness of complex interactions (Caple, 1994; Caple et al., 1996; Smit, 2004; Huisman et al., 2008a). In addition, factors related to the wood material itself such as wood species, durability, amount sapwood and heartwood, age of the wood, number and width of annual rings and late wood/early wood contribute to the complexity (Klaassen and Creemers, 2012), just as the age of the construction and the size/thickness are important variables. For full understanding and managing of a site containing organic material, additional information of the natural fluctuations due to weather should be included too (Matthiesen and Hollesen, 2012). As urban environments are often not uniform, site-specific groundwater conditions also need to be taken into consideration, such as at the archaeological site Bryggen, Bergen (Matthiesen, 2008).

6. Conclusions and future perspectives

When planning urban infrastructural projects, it is important to consider how coming intervention and ground work could affect the soil environment and potentially shorten the service life of pre-existing wooden foundation piles in the surroundings.

It is evident that a stable and high groundwater level is one of the most important environmental factors for long term durability of foundation piles. Uncontrolled local lowering of groundwater levels at urban construction sites starts a desiccation process in the soil surrounding the pile heads. Here, increased oxygen concentrations stimulate microbial wood degradation by fungi and bacteria, which will reduce the strength and consequently the service life of the piles. Little is known on the time scale of these processes; it is in terms of weeks, months, years or decades? When historic pile heads are analysed, observed decay status often reveals activity by EB in the surface layers of the pile, progressing inwards. Whether these are related to unavoidable slow decay in nature or accelerated decay caused by anthropogenic impacts is rather difficult to determine. However, presence of soft rot, white rot or brown rot decay in pile heads implies much faster degradation processes strictly related to a more oxygenated environment, which most likely correlates to more recent or contemporary changes at the site.

Urban soils are often characterized by elevated concentrations of organic nutrients. Among those are compounds which are known to stimulate many biological processes in soil and water. However, despite that some archaeological and rural sites have been characterized in regards to soil type and nutrients available, very little is investigated on their correlation to wood decay and especially to the speed of bacterial degradation. Perhaps surprisingly, preliminary results indicate that nitrogen does not increase decay by EB (Kretschmar et al., 2008a).

The hydrogeological water flow at a site is crucial for a better understanding of the oxygen and nutrient transport around the piles, both in the upper soil layers as well as in the deeper parts. Here we learned that water transport in urban sites is different from rural sites, due to the fact that impermeable ground surfaces in urban cities exclude an even distribution of rainwater. Horizontal water flow in conductive soil layers is therefore most important for maintaining a high groundwater level beneath streets and buildings. One factor that might hinder a free horizontal water flow is the building itself. As several hundreds of piles may support the foundation of a large building, set as close as 0.6 m apart (Pallav and Mats, 2013), deep exposed foundations piles may alter the hydrological behaviour of soft soils by damming the groundwater flow and reducing the hydraulic conductivity (Ding et al., 2008). The piles are often concentrated around the outer edges of a foundation and load-bearing walls, hindering water flow underneath the structure as the sides are blocked by the piles. The current dewatering methods for excavations in soft deposits fail to take this into consideration (Ma et al., 2014), and assuming a uniform drawdown around the excavation site would underestimate the effects near the foundation piles.

Another factor that causes uneven distribution of oxygen is the heterogeneous soil matrix, where complex interactions between the soil environment and bacterial decay take place. The significance of studying wood decay within its site context is highlighted in case studies of both archaeological and urban origin (Holden et al., 2006). The conditions of the site and the ability of the soil matrix to rebuff changes to the environment are crucial to the survival of the wood. Empirical analysis of well-preserved wood specimens can give us an idea of what constitutes a good preservation environment, and comparing these with data from forensic analyses of pile foundation failures could help identify environmental conditions that make buried wood more or less susceptible to decay. By identifying the main drivers of decay and developing a method to determine the hostility of different environments, predictive models can be developed that allow for protective measures to limit disturbances before exposed foundation piles are weakened to the point of failure.

During the management of archaeological sites, active intervention is sometimes used to maintain waterlogged conditions. At the Neolithic wooden trackway “Sweet Track” in Somerset, England, the effects of a locally lowered groundwater table were offset by continuously pumping water to maintain moisture (Brunning et al., 2000). Similarly, artificial infiltration of tap water is sometimes used to counter desiccation at urban sites. However, artificially infiltrated water often contains more oxygen than the original groundwater and might therefore increase bacterial decay even if it counters other adverse effects. Further studies are necessary to determine how serious this threat is. There can also be traces of chemicals in the water, either dissolved in the water at an earlier point (Bucheli et al., 1998) or accumulated at the infiltration site (Gschwend et al., 1990). Changes to the chemical nature of the soil pore water induced by artificial infiltration water may also alter the redox potential of the soil surrounding the wood and may stimulate degradation (Caple, 2004).

Redox potential is often used as an indicator to determine how
preserving an environment is. A nearly neutral pH and reducing environment co-occurs with anoxic conditions, thereby limiting the activity of decay organisms. Investigations and analyses from archaeological sites suggest that a redox potential below −100 mV or −200 mV indicates good preservation conditions for organic material (Caple et al., 1996; Jordan, 2001; Matthiesen et al., 2004), but the critical threshold values for wood degradation are so far unknown.

In order to accurately predict decay, the relevant timescales for wood decay must be considered and the so-called tipping points identified, i.e. the environmental limits beyond which an interference will cause damages. Furthermore, there is a need for increasing use of sacrificial samples and development of proxy indicators for decay, e.g. using typical degradation patterns to approximate the state of decay (Klaassen, 2008), as using entire foundations as test samples is unsustainable. Both field studies with samples of naturally decayed wood taken in situ as well as laboratory experiments with sound wood can give crucial insight into decay processes and environmental factors that either inhibit or promote bacterial decay (Gregory et al., 2008). Combining field observations with monitored lab experiments could give an added value, as the field studies provide a baseline and microcosm studies can simulate future conditions, such as altered groundwater levels or increased temperatures due to climate change or local disturbance from infrastructure projects (Kretschmar et al., 2008a).

This overview has compiled factors that have an impact on the degradation of pile foundations in urban environments. Biological, chemical, and hydrogeological factors interact in a complex urban system. When studying decay in urban environments, there are therefore several interlocking aspects that need to be taken into consideration. Results from case studies in both field and laboratory settings have highlighted the importance of studying samples within their site context, and for a further understanding of the processes affecting wood decay we need more detailed data providing us with threshold values, especially those related to oxygen concentrations in diverse water/soil settings.

Today there is a lack of detailed environmental parameters with threshold data correlated to wood degradation. Future research and studies must be designed with the relevant question in mind, so that guidelines describing protective and passivating environment during urban construction work can be given.

Declaration of competing interest

None.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ibiod.2020.104913.

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