

Microbial degradation of wooden foundation piles in urban context – causes and concerns

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Doctoral thesis



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2022

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Printed by Stema Specialtryck AB, Borås, Sweden 2022

Cover photo: Field sampling of clay, Johanna Elam

ISBN: 978-91-8009-849-6 (PRINT)

ISBN: 978-91-8009-850-2 (PDF)

Electronic version available at <http://hdl.handle.net/2077/71232>



*An author is a fool who,
not content with boring those he lives with,
insists on boring future generations.*

– Charles de Montesquieu

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Abstract

Modern infrastructural projects can endanger historical piled foundations supporting cultural heritage buildings, as groundwork can affect the subsurface environment by lowering the local groundwater level and increasing oxygenation in the soil. Wooden foundation piles are thereby placed at risk, as the durability of buried wood material is dependent on a stable, waterlogged, and anoxic environment. In this thesis, microbial wood degradation is explored, both in historical wooden piles and in proxy samples deployed in field and laboratory experiments. Observed degradation rates by erosion bacteria and soft rot fungi are related to burial conditions, with the aim to identify environmental parameters that promote wood degradation rates. A subsidiary aim was to identify threshold values for the onset of degradation in terms of relatively easily measured parameters such as groundwater level, oxygen content and redox potential. To explore the complex interactions, an interdisciplinary approach was taken, and considerable effort was placed on experimental design with a focus on ease of measurement. Nine field sites in the Gothenburg inner city area were used, where samples of historic wooden piles were extracted for analysis (Paper II) and proxy samples deployed in dipwells next to the pilings for long-term exposure (Paper III). Effects of groundwater level lowering was studied in a laboratory setting, performed in clay from central Gothenburg (Paper IV).

Results from an extensive literature review (Paper I) indicate that soil desiccation endangers buried wood material, but that further studies are necessary to better understand environmentally driven decay processes. Investigations at field sites in urban Gothenburg revealed no clear correlation between obtained environmental data and observed degradation of nine historic piles (Paper II), highlighting the importance of using proxy samples and environmental monitoring to explore current conditions and degradation rates. In a field experiment, proxy samples confirmed that degradation decreased with depth below groundwater level (Paper III). However, even with regular monitoring throughout the deployment time, the decay rate variation between the sites could not be related to groundwater level, oxygen content or redox potential, indicating that other local differences were of major importance (Paper III). In a laboratory setting, local differences could be eliminated, and the effects of lowered groundwater level could be studied as a single factor (Paper IV). Lowered water levels led to increased degradation rates but, surprisingly, fluctuating water levels had a protective effect (Paper IV). Lowered desiccation from soil surfaces also decreased decay rates.

In conclusion, maintaining a high and stable groundwater level appears to be the best protective measure, along with covering soils to reduce evaporation. No threshold values for redox potential or oxygen content were found at which soft rot or erosion bacteria sets in, and more detailed studies using more advanced instrumentation are necessary to identify these.

Implications for stakeholders during ongoing infrastructure work are summarized and ways in which to reduce the risk of increased wood degradation rates during construction are suggested. Further studies are proposed to develop a guide for best practice when performing groundwork in areas with wooden foundations that are sensitive to degradation.

Populärvetenskaplig sammanfattning

Projektet avser svara på vad som händer med pålade trägrunder som bär upp historiska byggnader av kulturhistoriskt värde när moderna infrastrukturprojekt förändrar miljöförutsättningarna under marken, såsom grundvattennivå och porvattenkemi. Vi utgår från en tes om att historiska byggnader som vilar på pålade trägrunder oavsiktligt kan komma till skada av att markmiljön påverkas av pågående byggprojekt.

Som med många andra vetenskapliga projekt är detta en fråga som för läsaren kan kännas som att man redan vet svaret på förhand, baserat på gängse uppfattning och logik. Det låter naturligt att om man ändrar miljön så kan det påverka trägrunden negativt – men hur fort och hur allvarligt? Hur nära måste byggarbete pågå för att det märkbart skall påskynda naturligt förekommande nedbrytningsprocesser? Det är frågor som dessa vi försökt svara på i det här projektet, för att hitta mätbara gränsvärden vid vilka skador riskerar att uppstå och därmed kunna föreslå skyddsåtgärder för historiska byggnader innan nya byggnationer utförs.

Vad är då pålade trägrunder? För att kunna bygga på instabil mark som lera eller torv behövs någon form av grundläggning för att staga upp lös jord och fördela byggnadens vikt djupare under mark för en stabil grund. Fram till mitten på 1900-talet var det vanligt att använda sig av trä till grundläggning, genom att påla långa stockar av trä ofta flera meter ned i lera och sedan lägga husgrunden på dessa pålar, som en sorts underjordiska stylvor. Trä är ett hållbart och lättbearbetat material som har använts till föremål, skepp och byggnader genom människans historia, men som alla organiska material är det nedbrytbart i naturen. Både rötsvampar och specialiserade bakterier kan bryta ned trä under rätt förutsättningar. Dessa mikroorganismer behöver tillgång till såväl fukt som syre för att kunna bryta ned trä, där olika typer av nedbrytare föredrar olika mycket av varje. Enkelt sammanfattat kan man säga att trä har god hållbarhet om det hålls antingen helt torrt eller helt vattendränkt, men allt där emellan utgör en risk då det gynnar nedbrytning. I en helt vattendränkt miljö kan endast en viss typ av bakterier, så kallade erosionsbakterier, bryta ned trä då dessa kan vara aktiva även vid väldigt låga koncentrationer av syre till skillnad från andra nedbrytningsorganismer. Nedbrytning av erosionsbakterier är en väldigt långsam process som verkar över flera hundra till tusentals år, medan rötsvampar kan bryta ned motsvarande mängd trä inom loppet av månader eller något år.

Vi har främst studerat erosionsbakterier då miljöerna som pålarna befinner sig i ofta är vattendränkta och syrefattiga, men vid vissa platser har vi även påträffat betydligt mer aggressiva mjukröte-svampar (eng: *soft rot*, även känt som *mögelröta*). Vi har undersökt hur olika miljöer kan vara mer eller mindre skyddande mot mikrobiella angrepp, samt hur uttorkning av trä och den omgivande leran påverkar nedbrytningshastighet. För att få svar på detta har vi först utfört en omfattande litteraturstudie, där vi samlat kunskap från många olika områden, till exempel mikrobiologi, för att undersöka vilka levnadsmiljöer som bäst gynnar de nedbrytande organismerna; hydrogeologi, för att

undersöka hur vattenrörelser i mark påverkas av byggnation under mark; ingenjörsvetenskap, hur grundläggning påverkar tryckförhållanden i jorden under byggnader; och arkeologiska fältstudier, som också tittar på tränedbrytning, men över längre tidsskalor och i andra miljöer. Resultatet av denna samlade bild bekräftade det vi misstänkte: att infrastrukturarbete kan påverka husgrunder negativt. Vi identifierade de främsta faktorerna som kan påverka nedbrytningshastighet till grundvattennivå (ju djupare trä befinner sig under grundvattennivån desto mindre nedbrytning), syrehalt i marken (ju mer syre desto snabbare nedbrytning) och redoxpotential (ju lägre redoxpotential desto mindre nedbrytning). Redoxpotential är förkortat från reduktions-oxidationspotential och innebär enkelt uttryckt ett materials förmåga att ge ifrån sig eller ta upp elektroner, där en lägre redoxpotential bidrar till en mer skyddande miljö för organiskt material. Ett exempel på en vanlig redox-reaktion i hemmet är hur äpplen blir bruna när de skalats för att fruktköttet oxideras och börtjar brytas ned rent kemiskt – men i en miljö med lägre redoxpotential sker inte denna oxidation, vilket är varför äpplet inte blir brunt om man följer husmorsknepet att lägga det skalade äpplet i en skål med vatten och lite askorbinsyra. Husgrunder är visserligen inte äpplen, men samma kemiska principer gäller.

Med dessa tre viktiga faktorer som utgångspunkt utförde vi flera experiment, både i labbmiljö och vid befintliga husgrunder med träpålar runt om i Göteborgs innerstad. Vi inledde med att undersöka markmiljö och historiska husgrunder vid nio platser i centrala Göteborg för att kontrollera att den tes vi utgår från har belägg i verkligheten. Vi fann tydlig variation i hur nedbrutna de olika husgrunderna var med ett samband till pålens tjocklek: pålar med en tjockare diameter var friskare än de med tunn diameter. Fysiska skador i träpålarna, t.ex. sprickor, hade lett till att nedbrytningen trängt längre in i pålarna. Vi kunde även konstatera skillnader i nedbrytning runt pålens omkrets, vilket kan bero på vattnets flödesriktning i marken. Vattenflödet kan föra med sig lösta ämnen som syre och näringsämnen eller sprida bakterier och svampsporer. Däremot hittades inga samband mellan nedbrytningsgrad och uppmätta värden på vare sig grundvattennivå, syrehalt eller redoxpotential, vilket kan bero på att miljön sett annorlunda ut under de 88-273 år som pålarna stått i marken och att nedbrytningen som vi ser har skett tidigare under andra förhållanden.

För att bedöma hur nedbrytningen ser ut på platserna idag, under nu rådande miljö, följde vi upp med ett fältförsök där alla proverna hade samma utgångspunkt. Vi satte ut helt friska, icke-nedbrutna prover av trä i samma miljöer och lät dem utsättas för den lokala miljön i tre tidsomgångar (6, 12 och 18 månader) så att vi kunde följa nedbrytningen över tid. Under samma tidsperiod mätte vi grundvattennivå, syrehalt och redoxpotential vid varje plats, så att vi fick en bild av vilka förhållanden som råder och hur mycket de varierar. Försöket visade att erosionsbakterier var aktiva vid samtliga platser, men nedbrytningsgraden varierade, vilket indikerar att det finns lokala skillnader i hur mycket miljön gynnar bakteriell aktivitet. Vi konstaterade att

grundvattennivå var den viktigaste förklarande faktorn för nedbrytning, då nedbrytningsgrad avtog proportionellt med hur djupt under grundvattennivå proven befann sig. Vi kunde bekräfta att det inom samma plats pågick mindre nedbrytning vid lägre syrehalt, samt mindre nedbrytning vid lägre redoxpotential, men vid jämförelser mellan platserna visade varken syrehalt eller redoxpotential något samband med nedbrytning. Vi kunde därmed inte hitta några belägg för ett gränsvärde för nedbrytning: samma värden uppmättes vid en provplats med mycket nedbrytning som vid en provplats med väldigt lite nedbrytning. Vi kan därför inte rekommendera provtagning av syrehalt eller redoxpotential som enda verktyg för att bedöma hur pass troligt det är att nedbrytning sker utan den mest pålitliga metoden är att undersöka träprover. Att det förekom stora skillnader mellan provplatserna indikerar att det finns andra faktorer i miljön som påverkar nedbrytningsgraden mer, såsom vattenrörelser i marken eller hur den lokala sammansättningen av mikroorganismer ser ut.

Nästa steg var att simulera hur förändringar av miljön kan påverka hur fort trä bryts ned; specifikt hur olika grundvattennivåer i en lerjord påverkar trä som är begravn i leran. I detta syfte utformade vi ett experiment där behållare med lera från centrala Göteborg utsattes för olika simulerade grundvattenförhållanden, genom att styra vattentillgången i behållarna. Vi hade även med en behållare fylld med sand för att kontrollera för lerans vattenhållande förmåga: den mindre porstorleken i lera gör att vatten kan hållas kvar längre i lera än i sand och kan sugas upp av kapillära krafter så att fukt stiger ovanför grundvattennivån. Efter att vi utsatt träprover för fem olika behandlingar i ett års tid kunde vi jämföra hur nedbrutna proverna blivit i de olika behandlingarna. Vi såg en tydlig skillnad i nedbrytning mellan jordmaterial, där prover från den behållare vi fyllt med sand hade betydligt mindre nedbrytning än övriga lerfyllda behållare. Eftersom sanden inte kunde hålla fukt ovanför den simulerade grundvattennivån kunde träet ovanför denna torka ut helt, varpå ingen nedbrytning kunde ske. Prover utsatta för en varierande vattennivå var lika nedbrutna som prover utsatta för en konstant vattennivå som var lika hög som den högsta nivån. Detta visar att regelbunden uppblötning av marken kan ha en skyddande inverkan på begravn trä.

Det sammantagna intrycket av resultaten i projektet är att det bästa skyddet för en trägrundläggning är att bibehålla en hög grundvattennivå med så lite horisontellt vattenflöde som möjligt. I de fall där en lokal vattenavsänkning måste göras på grund av pågående arbete eller för att hålla en källare torr rekommenderar vi därför att skärma av området snarare än att installera pumpar, då pumpning bidrar till vattenrörelser i jorden. Vidare finner vi inga bevis för lätt mätbara gränsvärden för vare sig syrehalt eller redoxpotential, vilket innebär att man inte bör förlita sig på provtagning av dessa som ett sätt att bedöma hur utsatt en trägrundläggning är för nedbrytning.

List of scientific papers and author contribution

Paper I

Johanna Elam & Charlotte Björdal. 2020. **A review and case studies of factors affecting the stability of wooden foundation piles in urban environments exposed to construction work.** *Published in International Biodeterioration & Biodegradation, available online from 4 February 2020.*

Paper II

Charlotte Björdal & Johanna Elam. 2021. **Bacterial degradation of nine wooden foundation piles from Gothenburg historic city centre and correlation to wood quality, environment, and time in service.** *Published in International Biodeterioration & Biodegradation, available online from 3 July 2021.*

Paper III

Johanna Elam & Charlotte Björdal. 2022. **Long-term study on wood degradation in urban soil-water systems - implications for service life of historic foundation piles.** *Published in International Biodeterioration & Biodegradation, available online from 17 December 2021.*

Paper IV

Johanna Elam & Charlotte Björdal. 2022/To be determined. **The influence of lowered groundwater level on degradation rates in buried wood.** *Manuscript. Planned for submission to International Biodeterioration & Biodegradation.*

Respondent part: The respondent contributed to formulation of review aim and research questions and to the design of field and lab studies. Of the practical work, the respondent performed field measurements, monitoring data analyses, wood sample analyses and was responsible for regular monitoring and maintenance of the lab setup. The respondent was main author of the manuscripts for Papers I, III and IV. For Paper II, as second author the respondent collated data and wrote the section on environmental monitoring parameters, produced graphs and assisted in wood sample analyses.

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1. Introduction

1.1. Historic buildings and cultural heritage

In the past as well as today, proximity to water has been essential for cities as it provides opportunities for trade as well as a source of drinking water and food supply. Therefore, it is not uncommon for historical cities to be located near riverbanks or on former floodplains where the ground is soft and unable to support heavier construction. As these cities expand, land reclamation has often proved necessary to house the increasing populations (Curtis and Campopiano, 2014). By setting the infirm soil with wooden piles, so called deep foundations can be laid that are designed to transfer the load deeper into the soil and set the ground firmer for construction (Vitruvius et al., 1914). The historic use of wooden foundations dates back at least seven millennia (Heumller, 2012) and has been linked to development of different social structures, as the land reclamation of unfit soils led to increasing availability of land for housing at a lower cost (Curtis and Campopiano, 2014). In 1700s Venice, pile driving using a handheld pile driver was recorded in art as part of daily life, and the traditional method was still in use as late as the 1970s (fig. 1). The preservation of these structures can thus be considered to be conservation of both material and immaterial cultural heritage (Klaassen and Creemers, 2012).

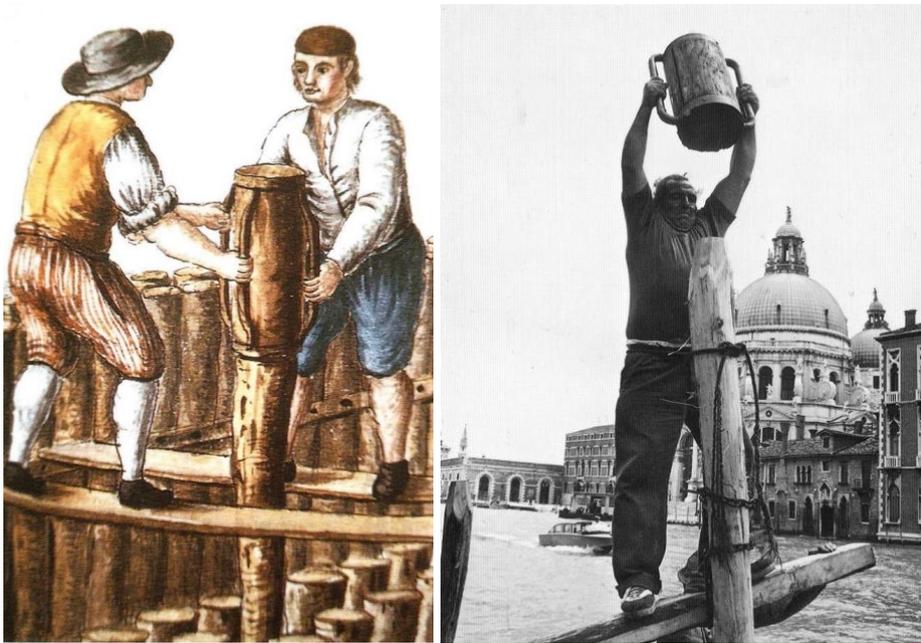


Figure 1: Pile drivers in Venice, using a handheld pile driver. Left: watercolour painting by Giovanni Grevenbroch (Venice, 1731-1807). The painting is in the public domain. Right: pile driver in the 1970s, using the same traditional method. Photo reprinted with permission from the Collezione museale Arzanà, Venice, Italy.

The wood used for foundation piles are usually logs of around 10-30 cm in diameter and often several metres long, sometimes reaching down to solid bedrock beneath the soft deposits (Przewłócki et al., 2005). Generally, the shorter the piles are, the more and closer together they need to be set in the soil. By setting the piles closely, the friction between the piles and the soil becomes more important for the stability rather than the individual piles (Bettiol et al., 2014). The interaction between the soil and wood means that the mechanical properties of both the soil and wood, fresh or fully degraded, are important to understand in order to determine the stability of piled foundations.

1.2. Wood material and wood degrading organisms

Wood, the tissue of trees, is a strong organic polymer which consists mainly of cellulose, lignin and hemicelluloses. Anatomically, wood is made up of different types of cells that serve different functions in the living tree (Wiedenhoeft and Miller, 2005). Composition and distribution vary between wood species, so that species identification is possible by observing the anatomy (Wheeler, 2011). Spruce and pine which are commonly used as piling material are so called softwoods that have a simple structure compared to hardwood and is mostly made up of tracheids (around 95%) and rays. Tracheids, also called fibres, transport water and nutrients vertically upwards in the tree trunk, whereas rays store and transport horizontally from the bark to the core (fig. 2).

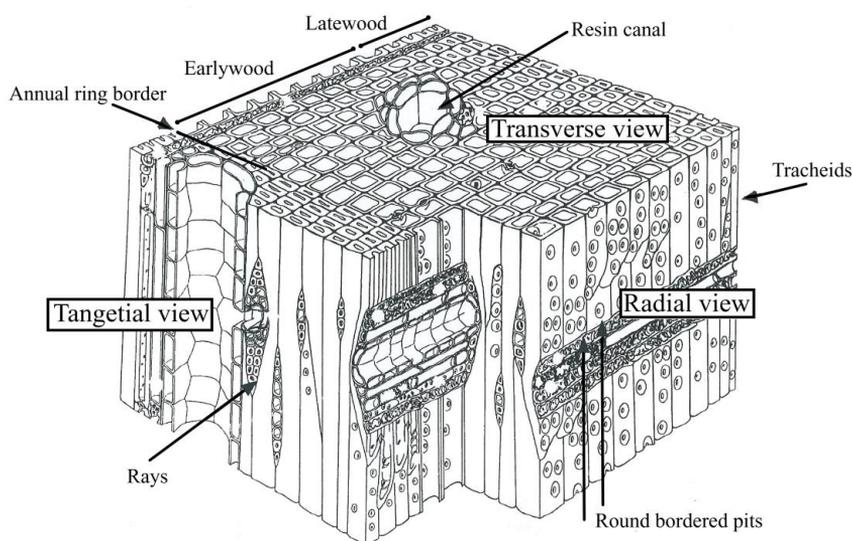


Figure 2 Anatomy of softwood material. The three directions in which cuts can be oriented are labelled: transverse view, cut laterally in a plane across the tree trunk; radial view, cut vertically in a plane from bark to core; and tangential view, cut vertically in a plane along the annual ring direction. Earlywood and latewood are shown as well as the annual ring border. Resin canals, rays, tracheids and bordered pits are marked with arrows. (Modified from (Siau, 1984))

Each fibre is made up of a layered cell wall surrounding an empty hollow at the cell centre known as the lumen (fig. 3). It is within the lumen that water and nutrients are transported. The cells have anatomical openings known as pits in the cell walls, allowing exchange between neighbouring cells. The cell wall consists of a primary and secondary cell wall, where the secondary wall is separated in three layers. The cell wall consists mainly of cellulose and hemicelluloses, where the polymers are arranged in bunches called microfibrils which are oriented in different angles in the different layers of the cell wall to provide both flexibility and stability/strength. Between the cells, there is a lattice framework of middle lamellae which serves as a gluing layer holding the cells together. The middle lamellae consist mainly of lignin (Butterfield, 2003).

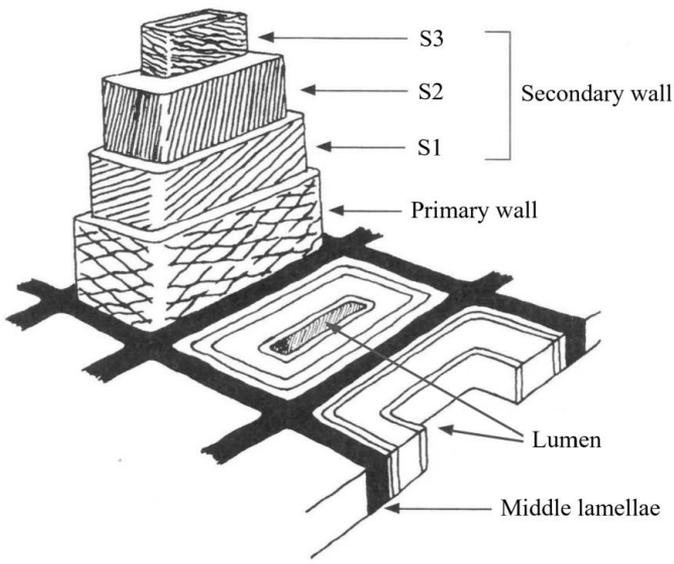


Figure 3. Cell wall structure. (Modified from (Eaton and Hale, 1993))

While wood can survive for thousands of years provided the soil is waterlogged and free of oxygen (Heumler, 2012), it is still a biodegradable material which can be consumed by naturally occurring insects, fungi and bacteria. The different organisms have different preferences for their living environment and activities in terms of moisture content, oxygen availability or temperature (Eaton and Hale, 1993).

In aerated topsoil and ground contact wood is degraded relatively fast by wood rotting fungi, which can be divided in three main types named according to the appearance of the wood after severe degradation: brown rot, white rot and soft rot (Goodell and Jellison, 2008). The type can be identified in light microscopy due to the differences in degradation pattern, for example soft rot hyphae creates visible round holes in the transverse cut, and in the radial cut they leave a typical spiral pattern of arrow-ended

cavities where the hyphae follow the microfibril angle in the S2 layer of the cell wall (fig. 4).

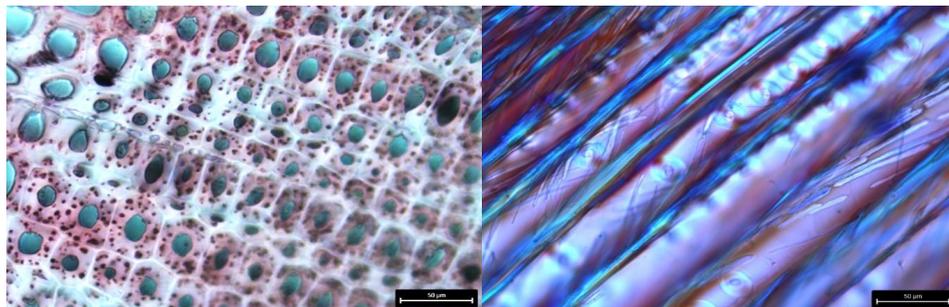


Figure 4: Soft rot cavities in transverse cut (left) and radial cut (right). The round holes in the cell wall and the spiral pattern following the microfibril angle are very distinctive.

Each type can actively degrade wood within its own ideal range of temperature, moisture and oxygen. Most species require the presence of gaseous oxygen for respiration, as well as a minimum of ~30% moisture content, i.e., sufficient moisture in the wood material for fibre saturation. Out of the three types of wood rotting fungi, soft rots are able to be active at the highest moisture content as they are able to degrade at near full saturation of wood cell lumen (Goodell and Jellison, 2008). At full saturation, the low access to gaseous oxygen limits the activity, although some species can transport oxygen through their mycelium and survive for short periods in fully saturated wood. However, fungal spores can often survive for long periods of time outside the range of their living preferences and become reactivated once conditions again favour their growth.

The main degrader of wood in waterlogged environments are rod shaped so-called erosion bacteria, which are the only known organism able to degrade wood under waterlogged and near-anaerobic conditions (Björdal, 2012; Kim and Singh, 2000). The decay process can take several centuries, as the decay is continuous but extremely slow (Björdal, 2012). Decay by erosion bacteria starts from the exposed wood surface, proceeding inwards via the anatomical openings present in wood. The preferential decay of erosion bacteria breaks down the cellulose-rich cell wall but leaves the lignin-rich middle lamellae, leaving behind a honeycomb-like pattern that is easily identifiable under light microscopy (fig. 5).

Since this framework of middle lamellae remain, the wood can outwardly appear quite unaffected (fig. 6), but the mechanical properties are altered by the decay as the strength and hardness both depend on the cellulose content (Capretti et al., 2008).

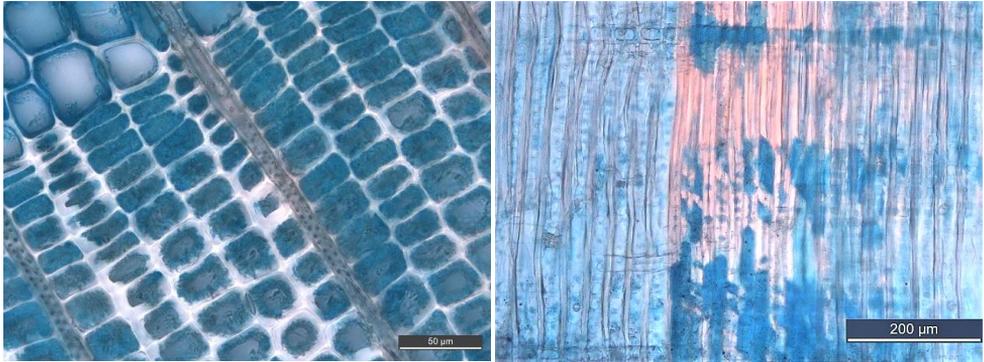


Figure 5: Degradation by erosion bacteria in the transverse cut (left) and radial cut (right) of a historic pile sample, examined for paper II. The decay progresses from the lumen outwards, seen here as blue areas in contrast to the undegraded white areas. The degradation can be seen as a sharp rhombic pattern in the radial cut.



Figure 6: Wood foundation pile that has been degraded by erosion bacteria, appearing normal but soft enough that a pin can easily be pushed into the wood by hand. The wood material is spongy and even pressing with a finger can make an indentation.

Wooden foundation piles are normally buried long-term in a moisture-rich and near-anoxic environment where the conditions favour erosion bacteria, so the degradation processes can be expected to be slow. However, if the environment becomes more oxygenated, wood rotting fungi can become active and a faster, more aggressive degradation can occur (Björdal et al., 1999; Blanchette, 2000). The service life of the wooden foundations is therefore dependent on the stability of the soil environment.

1.3. Urban soils, infrastructure work and groundwater abstraction

Urban soil environments can be defined as soils that have been profoundly affected by urbanization (Lehmann and Stahr, 2007). The soils are often stratified and contain elevated levels of nutrients, organic carbon and contaminants (Craul, 1985). Temperatures are also often higher in urban areas than in rural counterparts (Fokaides et al., 2016). Increased temperatures are known to increase bacterial activity in soils (Díaz-Raviña et al., 1994), whereas the increased nutrient loading in urban soils shows no positive correlation to growth of erosion bacteria, which instead show a negative response to increased nitrogen in both field and lab studies (Huisman et al., 2008a; Kretschmar et al., 2008a; Kretschmar et al., 2008b). Urban soils normally have less water infiltration and gaseous exchange, due to soil compaction and surface crusting by e.g. tarmac for roads. Groundwater levels in urban soils are therefore at risk of sinking deeper as the refill rate is reduced by the lack of natural infiltration by rainwater, at the same time as withdrawal is increased by extraction as a source of drinking water. Furthermore, water which has been artificially infiltrated to refill groundwater reserves often contains initially more oxygen than naturally occurring groundwater, but whether the increase in oxygen is large enough to affect the soil microbial community is currently under debate (Matthiesen and Hollesen, 2012a).

Increased population density in urban areas leads to increased demands on available land, where the need for more efficient and aesthetic land use can be fulfilled by utilizing the subsurface for e.g. car parks and transportation to free up surface space (Chow et al., 2002). Construction of tunnels or trenches can however affect local groundwater levels (Budhu and Adiyaman, 2013; Sundell et al., 2017; Wang et al., 2016; Yoo, 2016), causing drainage and aeration of the surrounding soil matrix and exposing nearby piled foundations to increased risk of both physical stress and biological attack. Settling of the soil matrix surrounding the piles, induced by lowered groundwater levels, increases the stress on the foundation piles as the weight borne by the receding soil is placed on the foundation piles instead (Budhu and Adiyaman, 2010; Peng and Horn, 2007). At the same time, aeration of the soil increases the friction stress acting upon the piles from the soil, reducing its load-bearing capacity (Fellenius, 1972; López Gayarre et al., 2010). Furthermore, lowered groundwater levels and aeration of the soil promotes increased bacterial activity in foundation piles and organic archaeological deposits (Björdal et al., 2000; Hollesen and Matthiesen, 2015), and shrinking movements in the wood due to

desiccation can open up cracks, enabling the bacteria to spread further into the wood. Changes to the environment can thus have a negative impact on the durability and lifespan of foundation piles, and existing structures that depend on soil stability need to be protected from new stresses in the subsurface environment.

Risk assessment before construction can help minimize unforeseen costs arising from damages by e.g. setting limits on groundwater drawdown to reduce the risk of ground settling due to groundwater removal at construction sites (Sundell, 2018). The method of groundwater removal used should be chosen to mitigate environmental impacts (Preene, 2008). Physical stresses in the soil can be included in risk assessment, as studies evaluating effects of groundwater removal or leakage incurred by infrastructural projects have been performed from a geotechnical standpoint (Powers, 1985). However, since these studies primarily deal with the effects on the soil matrix material and do not take the potential for increased rates of wood degradation into account, any proposed safety measures may yet fall short of protecting cultural heritage resting on wooden foundations. Examining the leading causes of wood decay in urban environments could help in the development of possible protective measures to limit wood degradation. By relating the risks of increased wood degradation to the common practices by construction companies, suggestions can be made for e.g. safe levels of groundwater lowering to keep degradation at a minimum.

1.4. Valuable environmental indicators of increased risk for degradation

Since foundations are hidden below ground, often the presence of microbial attack will not be discovered until it has progressed so far that cracks appear in the building or structures collapse. Therefore, many examinations are forensic rather than preventive and can only conclude what might have been the cause for harm. By studying currently ongoing degradation rates and environmental processes before the degradation has progressed to such a degree that the foundation pile can no longer bear its designed load and collapses, this thesis can provide valuable insight for developing methods to prevent degradation before it occurs.

The wood material, the clay-rich soil burial environment as well as the natural processes such as wood decay, groundwater fluctuations, oxygenation etc., are all important factors that play a part in understanding the degradation of wooden piles in urban environments. Certain processes affecting foundation stability are known, such as the decreased mechanical strength of microbial degraded wood (Ceccato et al., 2014; Eaton and Hale, 1993) or the rate of ground settling in clay deposits due to lowered groundwater levels (Guo et al., 2015; Yong et al., 1995), but the mechanisms of the complex interactions within the system are not yet fully explored. By taking a broad, interdisciplinary look, the effects of environmental disturbance on wood degradation rates can be clarified and vulnerabilities and threshold values can be investigated.

Previous studies have tried to find a correlation between wood degradation and environmental parameters (Huisman et al., 2008a; Klaassen, 2005; Kretschmar et al., 2008a; Kretschmar et al., 2008b; Zborowska et al., 2020; Zborowska et al., 2007), but so far, no clear correlation has been found. Building on these results and experiences, the experiments in this thesis focus on lowered groundwater level, high oxygen content and high redox potential. The three parameters are strongly interconnected, commonly measured in field, and each is connected to wood degradation as wood degrading organisms need moisture and oxygen to actively degrade wood (Goodell and Jellison, 2008). Groundwater level determines soil and wood moisture content, and as previously stated wood degrading organisms are only able to actively degrade wood within specific moisture optima. Too much moisture can inhibit fungal growth, and while soft rot fungi can be active also at full saturation like in aquatic environments (Eaton and Hale, 1993), erosion bacteria are the only degrader known to be active in fully saturated and anoxic conditions. Groundwater level also directly relates to soil oxygen content, as each pore space in the soil which is filled with water reduces the contact with air (fig. 7). In waterlogged conditions, i.e., soils which are fully saturated by water, gaseous oxygen is depleted rapidly.

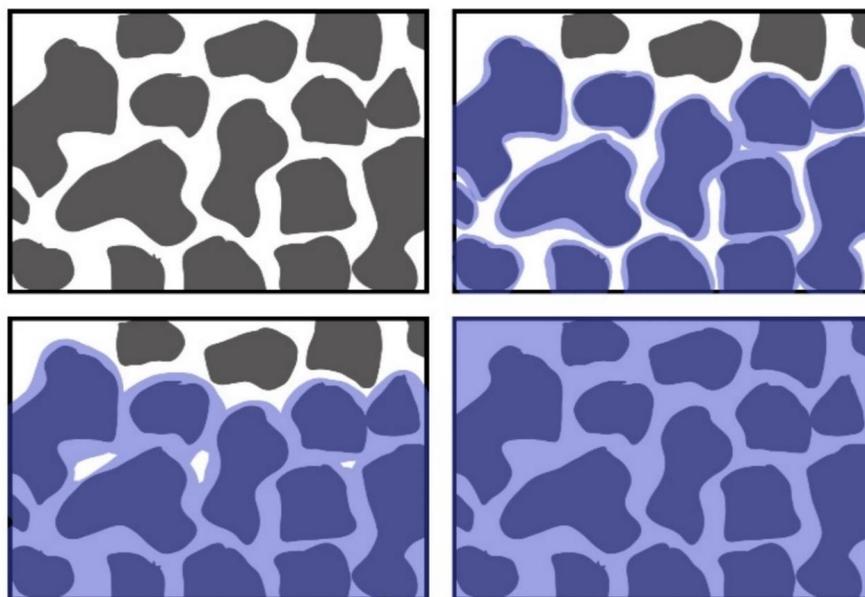


Figure 7: How increased moisture content in soil reduces oxygen availability by excluding air. Soil particles in grey, moisture in blue, air in white. Top left: no moisture. Each soil particle is in contact with air in the soil pore spaces. Top right: Presence of soil moisture. Due to surface tension, moisture adheres to the soil particles while air is still present in pore spaces. Bottom left: near saturation. Air is present above water level and in few remaining pockets. Bottom right: fully saturated. The water has filled all pore spaces, excluding air from the soil.

Metabolism in all organisms is mediated by oxidation-reduction (redox) reactions where electrons are moved from one compound (electron donor) to another (electron acceptor) in energy-yielding reactions. A compound's redox potential, commonly measured in mV, is thus its overall tendency to lose or gain electrons, i.e., become oxidized or reduced.

Oxygen is the most favourable electron acceptor for the oxidation of organic matter, and environments with high oxygen availability have high, positive redox potentials, whereas zones where oxygen has been depleted have lower, negative redox potentials. Here, alternative electron acceptors are utilized by microorganisms to oxidize organic carbon (Scholz, 2015). As such, determining redox potential values for a waterlogged environment allows an estimate of the presence of oxygen in the soils available for wood degradation. It is not currently known at which redox potential values either soft rot or erosion bacteria become active, and the biochemical processes and identity of erosion are not yet described (Landy et al., 2008; Nilsson and Björdal, 2008; Nilsson et al., 2008).

2. Aims of thesis

The aim of this thesis is to increase current knowledge on the effects that construction work can have on degradation rates of piled wooden foundations in urban environments, during different time frames and in different soil conditions. By increasing the current understanding of these degradation processes, the hope is to provide suggestions that aid the development of more efficient methods and techniques for protection of existing structures during urban groundwork.

The thesis includes four papers, each with the goal to explore different aspects of the overarching thesis aim: a cross-disciplinary literature review, a field study on historic foundations and environmental conditions at the field sites, a long-term field study on proxy samples exposed to current conditions, and finally a laboratory study on wood buried in clay exposed to different water regimes. Different aspects of wood degradation in urban settings are explored and the findings correlated to likely effects of nearby groundwork, such as the introduction of fungal activity by increased oxygenation from dewatering. Wood degradation is analysed and correlated to environmental parameters known to affect preservation conditions, such as groundwater levels, oxygen content and redox potential. In Paper IV, sinking groundwater levels and the consequences on wood decay rates are explored, which to our knowledge has not been done before.

Wood analyses are performed by light microscopy throughout the studies as this is the most reliable tool to determine type of degrader and degree of degradation. Physical and chemical properties of the wood material are not characterized. The thesis focuses on

wooden foundation piles, but the results are also applicable to archaeological wooden remains or other wooden artefacts in similar soil environments.

3. Methodological considerations

In this section, considerations prior to design of each experiment are described. For details on how each experiment was performed it is referred to each respective paper.

3.1. Selection of literature for review paper (Paper I)

As the research questions are of an interdisciplinary nature, with complex interactions between wood, degrading organisms, environmental conditions in the soil and forces that drive external disturbances, it was beneficial to consult literature from each specialized field rather than only consult studies that pertain directly to wood degradation. There is a wealth of knowledge to be found on each individual part of the puzzle, in terms of microbiology, soil pore water chemistry, hydrogeology, urban engineering, etc. The challenge was to collate the data and tie in all the different aspects of the problem to give a comprehensive overview of how each factor relates to wood degradation and can affect foundation pile service life. By taking a broad interdisciplinary approach and placing the scientific evidence in the perspective of historic wooden foundations, overlap between fields as well as knowledge gaps could be identified.

A major benefit with this approach of broadening the search outside one's own narrow field was the different perspectives given to key aspects of any given process. Information on specific processes may get lost across boundaries between traditional scientific fields due to a tendency to prefer different terms for the same process. For example, the same process of a receding groundwater level in soil can be referred to as dewatering, soil desiccation, drainage, groundwater drawdown, or groundwater abstraction, with each research field preferring the use of a specific terminology as it best relates to the purpose of why the process is studied.

3.2. Description of field test sites

The field study area Gothenburg, Sweden, is built on top of infirm ground made up of stratified glacial sediment deposits in a former river delta, and like many other European cities its historic city centre rests on wooden foundations. The city also faces increasing tourism and population size, which place increasing demands on the urban infrastructure and thus the subsurface environment. Several cultural heritage landmarks are situated where the infrastructure demands are highest, as the historic centre overlaps with the modern urban centre. One example of ongoing urban infrastructural work which may affect the central Gothenburg area is the West Link tunnel (Swedish: Västlänken). The

ongoing construction work for the West Link tunnel proceeded concomitantly with the experimental work of the thesis, where the groundwork could provide access to field sites with historic foundations supporting cultural heritage buildings. For building stakeholders, participating in this project gave the added benefit of regular monitoring performed during the time of disturbance.

Via the Swedish Transport Administration, access was granted to nine sites with historic foundations in central Gothenburg, as well as to a site of clay sampling for laboratory experiments (fig. 8).

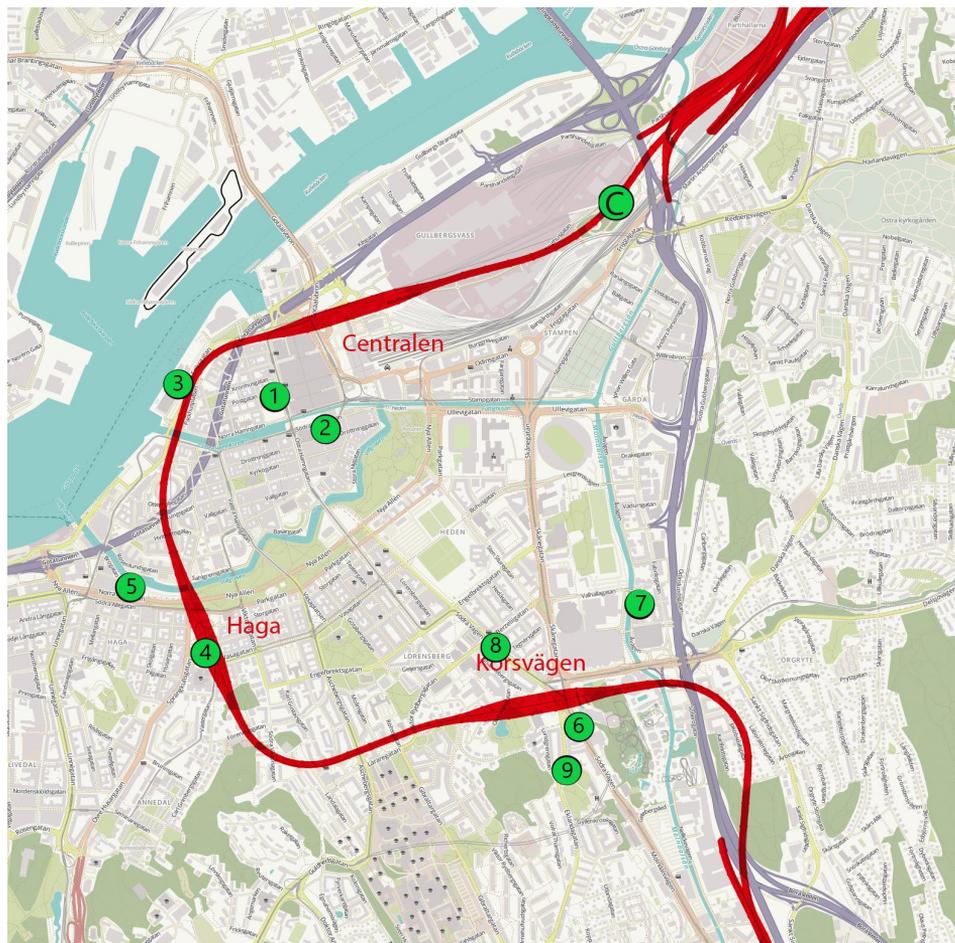


Figure 8. Map of central Gothenburg where field sites with historic foundations are shown (1-9), as well as ongoing construction for the West Link tunnel project (marked in red) and site for clay sampling for laboratory study (C).

Due to the value of the historic structures and the invasive nature of the sampling, gaining access to more sites unfortunately proved to be too difficult given the time

constraints. Several stakeholders were reluctant to allow the invasive procedure of sampling the historic foundations, as this entailed digging a trench for extraction, with soil disturbance, aeration and dewatering as a result. The trenches were of course filled in immediately after sampling, but some stakeholders withdrew their initial interest as they felt that this could place the foundations at risk.

The sites are all within close distance to the ongoing West Link tunnel construction and could be considered at risk for altered groundwater conditions due to ongoing digging (see fig. 8). The selected sites are spatially distributed to represent different groundwater conditions in the city, placed near the riverbank, in natural troughs from dried-out tributaries and on steep hills.

Most of the site work took place in basements and crawlspaces beneath buildings, as the wooden foundations are situated several metres below ground (fig. 9). Many sites had no flooring in the basements, so the soil was open to atmospheric exchange.

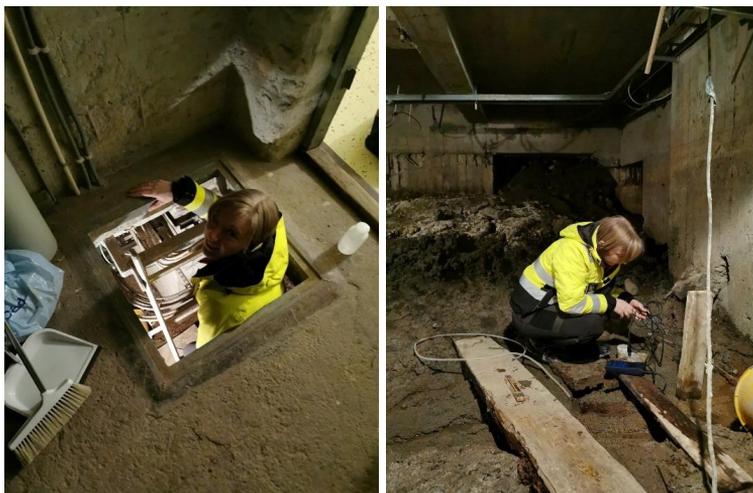


Figure 9. Example of access hatch (left) and crawlspace (right) at one field site. Planks were laid on the exposed ground to avoid sinking into the clay during sampling.

Each site was thoroughly investigated in terms of physicochemical parameters of the soil environment by Golder Associates, employed as a subcontractor to the Swedish Transport Agency (see Paper II). From 2015 - 2017, partly before start of this project, wood pile samples were taken from the historic foundations by removing a ca 30cm high block/disc of wood from one pile top at each location. Both type and degree of decay were then determined by analysis of 1cm subsamples across the pile diameter. At each site two slitted groundwater-wells were installed in the soil reaching down to the pile heads in order to provide field test sites for this project. Due to an unforeseen issue at one site which resulted in flooding and remodelling of the basement, the site was later on dropped from further study, leaving eight used for long-term monitoring and

deployment of samples. This is a constraint as it would of course have been advantageous to have more sites for better statistical accuracy. For future studies, it would be interesting to have a bigger sample size as well as to have sites of different soil types, since all sites included in this study have similar soil composition.

The site for clay sampling was accessed in April 2020. A horizontal clay shelf was prepared at the edge of the dig site pit and the experimental tubes pressed vertically into the soil to preserve the natural layering and structure in the clay soil (fig. 10).



Figure 10. Left: Preparing the clay shelf. Middle: Pressing the experimental tubes into the clay. Right: Clay and tubes removed en bloc.

3.3. Measurement techniques

For better comparison between field and laboratory experiments, the goal was to find instrumentation that works for all measurement needs. The only points of access at the field sites were water-filled monitoring dipwells of a set diameter, inserted in the soil adjacent to the existing foundations and reaching down to the top of the piles (fig. 11). This placed strict limitations on size and flexibility, both in terms of wood samples and instrumentation for *in situ* chemical sampling.

Each field site was thoroughly examined in terms of soil and pore water parameters by accredited laboratories prior to start of the long-term field study. Based on these data (for details see Paper II) and which parameters were proved most useful in environmental monitoring at archaeological sites (Caple, 1994, 2004; Caple et al., 1996; de Beer et al., 2012; Gregory, 2002; Gregory et al., 2008; Gregory and Matthiesen, 2012; Hollesen and Matthiesen, 2015; Huisman et al., 2008a; Huisman et al., 2008b; Klaassen, 2005; Matthiesen, 2007; Matthiesen, 2008; Matthiesen et al., 2008; Matthiesen et al., 2004; Matthiesen and Hollesen, 2012a; Matthiesen et al., 2016) according to the literature review (Paper I), the focus lay on groundwater level, redox potential and oxygen content for the long-term monitoring of the field sites and laboratory setups. The same hand-held instrument was used for monitoring redox potential in both field and lab settings (Mettler Toledo Seven2Go pH meter S2) equipped with redox probes using platinum ring indicators (Mettler Toledo InLab ORP Redox combined electrode and PaleoTerra custom Pt. redox probes respectively).



Figure 11: Size and accessibility of two monitoring dipwells through the concrete floor in the basement of field site Södra Vägen 65 (white plastic tubes, top right corner of photograph). The top dipwell is covered with a lid as it contains the exposed wood samples, the lower dipwell is temporarily opened for active monitoring of oxygen. Hand and calibrating instrument are shown for scale.

Proxy samples of fresh undegraded pine sapwood were used in both field and lab experiments, in order to ensure that the resulting degradation would be comparable across samples: the observed degradation could be measured from the same initial condition (wholly undegraded) and similar degradation rates might be expected (same species and similar composition). The material was of Swedish origin and from the same supplier. It was important to have as similar test material as possible, and it was therefore carefully selected by visual inspection (naked eye) to be comparable in terms of amount earlywood to latewood and annual ring width. All wood decay analyses were performed under light microscopy, using the same methods and magnifications to ensure that the results were comparable across and within the different experiments. Both degree of degradation and type of degrader were highlighted by use of chemical staining techniques or polarized light.

3.4. Experimental design

Within the relatively short timeframe afforded in a PhD project compared to the time it takes for microbes to develop decay in wood, lab and field work had to be conducted simultaneously. Both lab and field experiments placed a high demand on experimental design, and the development work was an integral part of the project. A significant amount of time was spent on developing sturdy and efficient sample sets that were easy to produce, deploy, maintain, and analyse. The goal was to develop designs that were

easily reproducible, to provide a blueprint for others who are interested in performing studies in similar environments.

Co-evaluating environmental parameters with wood decay analyses is an emerging science, so there is not yet any standard method or given set of measurements to employ. During this project new methods were developed and designed.

3.4.1. Field experiment (Paper III)

The field experiment (Paper III) utilized the two slitted dipwells installed at each site. Of these, one was used for groundwater level monitoring and water sampling; the other to house the experimental wood material during long-term exposure to the site environment. By using two dipwells in this way, soil pore water could be monitored throughout the deployment without disturbing the samples. The design allowed simultaneous monitoring of the site conditions during the deployment of the wood proxy samples, yielding insights into how the current soil environment related to the rate of decay. The samples were deployed at two specific depths in each sample dipwell: at the level of the pile heads and at the mean groundwater level, as exploring the difference in degradation between the two levels could indicate how the degradation rate at pile head level could be affected by a lowered groundwater level. The setup is similar to other investigations of wood decay in urban environments (Huisman et al., 2008b; Klaassen, 2005; Klaassen, 2008a, 2014; Klaassen and van Overeem, 2012), with the exception that proxy samples of fresh, non-degraded wood were used instead of parts taken from historic pile structures. These previous studies show how much decay has occurred in the piles up until the point of extraction, much like the setup in Paper II, whereas the aim of this experiment was to explore the currently occurring degradation at the sites and how the rate of decay was related to any given change in environment during the period of observation. This novel approach reports on the present rate of decay at the sites, since the state of the wood samples prior to burial is no degradation, and the exact exposure time is known and can be correlated to depth and variability of the groundwater level and soil/water chemistry.

3.4.2. Laboratory experiment (Paper IV)

For the laboratory experiments (Paper IV), sample units of urban clay and wood encased in PVC tubes were placed in containers with externally controlled water level, where the clay was only in contact with water through holes in the bottom of the tubes. This simulated groundwater pressure and limited lateral fluxes of water and oxygen along the length of the tube. As the clay inside the tubes was thus only in contact with air at the top surface, and with water at the bottom of the tube, any changes observed in the clay could only be due to vertical fluxes.

The different water regimes were chosen to represent what is regarded as “safe” levels of groundwater lowering by construction companies and common practice, to explore whether this is also the most crucial zone for pile decay. Other experiments exploring wood degradation in relation to groundwater level have not varied the water level externally but rather compared material buried at different depths or placed in different layers in stratified soils (Zborowska et al., 2020). By placing the sample material at the same depth from ground surface in all treatments and instead controlling the water level, effects due to depth of burial could be eliminated. Furthermore, the effect of fluctuating water levels could be studied, which is not possible if the samples are buried at fixed depths. The soils were uniform to reduce effect of soil composition, and the water supply was common for all experimental containers to reduce the influence of water source on soil redox potential.

In order to accelerate the degradation that would be expected in a natural system, the wooden rods were treated with a microbial community mixture from a degraded foundation pile recently collected in central Gothenburg. This method of inoculation is sometimes used in laboratory wood durability trials, where wood samples can be exposed to pure or mixed cultures of degrading organisms prior to incubation to ensure degradation during the experiment time (Edlund and Nilsson, 1998). While inoculation with pure strains is a traditional laboratory method, yielding good results with high reproducibility (Råberg et al., 2005), it is unusual to inoculate samples before burial in soil.

The tubes were open to atmospheric exchange in order to mimic a normal desiccation process, whereas one tube per treatment was covered to reduce evaporation. Though results from the field experiment (Paper III) showed that degradation had developed after 6-18 months exposure in soil pore water, accelerated degradation rates were preferable due to the short duration of the experiment.

Oxygen measurements proved to be somewhat unreliable in the field experiment (Paper III) and obtaining instrumentation that would work in the designed laboratory setting was problematic: installing large oxygen optodes without disturbing the natural layering of the clay, creating air pockets or harming the sensitive instrument seemed unnecessarily difficult. Thus, one special redox probe designed for long-term use in natural soils was installed in one separate tube per container to limit disruptions in the soil due to measurements, and in one tube duplicates were inserted to check accuracy (fig. 12).



Figure 12. Redox probes installed in experimental tubes for regular monitoring throughout the experiment, one per treatment (left) and with a duplicate in T2 (right).

In the field study (Paper III), there were large constraints on sample size due to both dipwell diameter and ceiling height. Samples needed to be of a small diameter and placed on flexible fibreglass rods, limiting the amount and length of wood deployed. As it would be interesting to look at more depths, and the laboratory study (Paper IV) did not have the same constraints based on flexibility as the field study, whole lengths of wood rods were installed in the laboratory study. Analysis was later on performed on subsamples extracted at three depths (-5cm, -30cm, -55cm), corresponding to the same three depths where redox potential was measured.

4. Main findings

4.1. Paper I – Review of current knowledge base

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

Literature study. Published, DOI: 10.1016/j.ibiod.2020.104913

Highlights:

- *Urban infrastructure work may endanger service life of wooden foundation piles*
 - *Groundwater changes affect the microbial susceptibility of waterlogged wooden piles*
 - *Oxygenating waterlogged soils increases bacterial decay and introduces fungal decay*
 - *Urban soil structures and processes affect wood degrading microbes in complex ways*
 - *Oxygen availability, thresholds, and in-soil processes need to be studied further*
-

This comprehensive literature review was performed to provide an overview of current knowledge within the subject and place the project in context of current level of knowledge in the field.

Infrastructure projects that involve underground construction may change either the soil composition, the soil pore water chemistry, the aeration of the soil or any combination

of the above. By collecting results from studies from several different fields of research, ranging from temperature effects on respiration rates of soil bacteria (Díaz-Raviña et al., 1994) to mechanics of land subsidence due to groundwater pumping (Budhu and Adiyaman, 2010), an overview of how infrastructure projects could affect wooden foundations in urban areas was synthesized. Selected case studies that provided practical demonstrations of wood decay observed in different settings were included. These highlighted the often complex and not fully understood interactions of chemical and physical factors in the soil environment and distribution of decay with depth in soil (Grinda, 1997; Klaassen and Creemers, 2012) as well as how changed environmental conditions can cause pile failures and even foundation collapse (González-Nicieza et al., 2008; López Gayarre et al., 2010).

While not directly applicable to urban piles, studies on degradation of archaeological wood provided insight on both environmental factors and behaviour of ongoing degradation processes, as archaeological sites are often studied *in situ* and under long periods. Keeping the groundwater level above the wood in order to ensure a waterlogged and anaerobic environment is currently known as the most effective method to preserve wood. Both artificial raise of the groundwater level as well as reducing the oxygen content of infiltrating water are methods discussed and implemented *in situ* (Bunning et al., 2000; Corfield, 2012; de Beer et al., 2016; Rytter and Schonhowd, 2015).

In conclusion, a pro-active approach to damage-control will save both time and money in terms of protecting cultural heritage, as the damages are difficult to detect in time. By examining proposed construction sites and taking the local environmental conditions into account, it should be possible to determine if an area is at risk prior to any environmental disruption. A knowledge gap is identified where further study is warranted; since many previous studies are forensic in nature, it is currently not known at which point in time conditions changed and irreparable damage occurred. Determining threshold values or tipping points at which environmental disturbance will cause damages to existing structures can aid in risk assessment prior to construction. Furthermore, there is a need to further understand the complex interactions between different factors that affect bacterial degradation of wood in urban soil environments.

Based on these results, the experiments in papers II-IV were designed to evaluate degradation rates and relate these to results from environmental monitoring of groundwater level, oxygen content and redox potential. Evaluating degradation rates prior to a disturbance can provide a valuable baseline to determine if the disturbance has caused a lasting negative impact.

4.2. Paper II – Investigation of field sites and historic foundations

Bacterial degradation of nine wooden foundation piles from Gothenburg historic city centre and correlation to wood quality, environment, and time in service.

Field study. Published, DOI: 10.1016/j.ibiod.2021.105288

Highlights:

- *Erosion bacteria decay reports on stable anaerobic waterlogged environments at all sites since the time of construction.*
 - *Decay variations around a pile might be related to direction of water flow in soil.*
 - *Small diameter piles are more susceptible to decay than large diameter piles.*
 - *Damages in pile head top allow bacterial infection of heartwood through cracks.*
 - *Neither depth of exposure, ground water level, wood species, annual rings, soil type, or differences in soil/water chemistry showed any significant correlation to development of decay.*
-

In order to determine the differences in wood decay between the nine sites and provide background information on the condition of the historic piles and their environment, results from a previous project carried out during 2015-2016 at the same sites were evaluated and further analysed.

Burial duration in the soil for the historic piles ranged from 88 to 274 years. The decay of the wood was analysed by light microscopy and scanning electron microscopy. All *in situ* measurements and sampling related to the soil and water was performed by accredited laboratories, and the analyses were performed according to standards in the field. The environmental parameters were evaluated and correlated with the observed decay of the individual wood samples in order to determine the vulnerability of each site.

Results show that the wood piles, of varying age and species (spruce and pine), were all attacked by erosion bacteria and only minor variation existed in both depth and degree of decay. The sites were all similar in chemical and physical attributes, with soil characteristics being more consistent across the sites and water chemistry showing more variability both between sites and between measurement occasions. The soils consist mainly of clay and have a mean water content of 52%. All sites show a consistently low oxygen content, with values below 1 mg/l, inhibiting decay by wood degrading fungi. The measurements of redox potential further show that these are anoxic reduced environments, with all measurements showing negative values.

In conclusion, the Gothenburg field sites generally only show degradation in the outermost few centimetres of the foundation pile, with some exceptions. The parameter that appears to have the closest correlation with degree of decay is time in ground,

closely followed by groundwater level in relation to pile head depth. This is to be expected, given that the longer the piles have been in the ground, the longer the exposure to decay organisms. However, since all the samples had been buried in the ground for a long time that also means that there was no way of differentiating decay that has occurred recently from historical decay when the conditions at the site could have been different from the current levels measured in this study. It is thus not possible to draw any conclusions on how much longer the sampled foundations will remain stable based on their current degradation unless the current rate of degradation is also known.

From the results of this study, it is evident that co-evaluating environmental monitoring with exposure of previously undegraded proxy samples is necessary to separate the effects of current conditions from historic damage that has occurred over time, and the following studies were aligned to incorporate this.

4.3. Paper III – Long-term field study on wood degradation in dipwells

Long-term study on wood degradation in urban soil-water systems - implications for service life of historic foundation piles.

Field study. Published, DOI: 10.1016/j.ibiod.2021.105356

Highlights:

- *Erosion bacteria degrade wood in soil pore water at different urban sites*
 - *Degradation rates vary, indicating local differences*
 - *Degradation decreases below groundwater level and decrease is proportional to distance below groundwater level*
 - *Measurements of redox potentials and oxygen concentrations show no correlation to wood decay*
 - *Analysis of proxy samples is the best tool for understanding ongoing wood decay processes in situ*
-

In this long-term field study, wood decay was analysed in relation to different environmental conditions at eight sites in the central Gothenburg area previously studied in Paper II. Sound wood samples were deployed in dipwells for 6, 12 and 18 months. Oxygen concentration and redox potential were monitored *in situ* at three occasions during the deployment.

Results show that at all sites, the proxy wood samples had been exposed to bacterial degradation. The degree of degradation varied between the different sites, but the variation could not be explained by observed variations in oxygen content or redox potential. Increased distance below groundwater led to less degradation, further

illustrating the importance of maintaining high groundwater levels. It is important to note, however, that exposure depth below groundwater level alone was not an accurate indicator of degradation. At each site, the degradation at pile head level was lower than at groundwater level, and the relative decrease in decay was proportional to the distance between the two levels. By calculating the relative degradation at pile head level in terms of percent of degradation at groundwater level (degree at pile head level / degree at groundwater level), the effect of distance below groundwater level could be gauged separate from the effect of more aggressive degradation at some sites. For example, even if samples from Eklandagatan at 74cm below groundwater level were more degraded (15 fibres) than samples from Härberget at 27cm (12.5 fibres), the relative degradation at Eklandagatan at 74cm (43% of degradation at groundwater level) was less than at Härberget at 27cm (63% of degradation at groundwater level), showing that the protective effect of a high groundwater level was proportional to the height of groundwater above the pile head level. This is one of the more intriguing results from this paper, as it implies that there are other site-specific factors that are more important for degradation rates than groundwater level, oxygen content or redox potential.

In conclusion, bacterial degradation was less severe with increased depth below groundwater level, and more aggressive degradation by soft rot fungi was only found above groundwater level. Thus, maintaining a high groundwater level is a good method to protect piled foundations. The large differences in degradation between sites could not be related to oxygen or redox measurements, and there are thus other factors in the local environment that influence decay. More studies are necessary to identify these.

It is evident that proxy wood samples are necessary to understand wood degradation at different sites, and there is not yet any easily measured environmental condition (groundwater level, oxygen content, redox potential) that can replace wood sampling to accurately predict the degradation ongoing at any given site.

4.4. Paper IV – Laboratory study on effect of lowering of groundwater level

Degradation of wood buried in soils exposed to lowered groundwater levels.

Laboratory experiment. Manuscript. Submission planned for International Biodegradation and Biodeterioration.

Highlights:

- *Degree of degradation decreases with depth of burial and higher water level*
 - *Fluctuating water levels (high – low) is just as protective as fully saturated soil*
 - *A relative correlation between redox potential and decay rates by soft rot is observed*
 - *No redox potential threshold values for onset of fungal decay could be concluded*
 - *Soft rot decay at +80mV was just as intense as at higher redox potential, suggesting that a threshold was reached*
-

To explore the effects of varying groundwater level on wood degradation, including when critical situations occur such as increased microbial decay (including wood rotting fungi), a long-term laboratory study on wood degradation in clay soil exposed to different groundwater level regimes was performed. Based on the results and experiences from Paper III, the laboratory study was designed to eliminate effects of local environment by using the same depth of exposure in all treatments and clay from a single source. The experiment also included a control scenario with sand instead of clay as the soil matrix. Wood proxy samples were exposed in the soils for 1 year, during which the groundwater levels were controlled externally. While it is generally accepted that there is a correlation between a lowered groundwater table and increased decay of wood, there is no data at present to indicate whether the degradation is controlled by the maximum, minimum or mean water level in a given soil. By measuring the moisture content in the soil after 1 year, important insights were also gained into how well the surrounding soil matrix can maintain moisture when the groundwater level drops. Redox potential measurements were used to monitor and describe the soil environment and soil moisture content was measured at start and end of experiment.

It came as no surprise that degradation decreased from near the surface to deeper in the soil, as this is in line with results from previous studies (Björndal et al., 2000; Macchioni et al., 2016; Zborowska et al., 2020). Degradation rates also depended on water level, where degradation was highest in soils with a low water level. In this experiment, redox potential was measured at the same depths as where the subsamples for analysis were taken from the exposed wood rods. Redox potential values could thus be compared to the degradation rates of wood observed at each depth. Analyses of data reveal four distinct intervals of redox potentials: stable highly oxidized conditions in sand at -5cm and -30cm (C2); stable oxidized conditions in clay at -5cm (T1, T2, T3, C1); slowly increasing redox potential in clay at -30cm (T1, T2, T3, C1); and stable highly reduced

conditions in both clay and sand at -55cm (T1, T2, T3, C1, C2). Degree of degradation was similarly grouped, with severe degradation occurring in the samples near the surface at -5cm, moderate degradation at -30cm as the soil slowly desiccated and conditions changed further down in the column, and little to no degradation in the unchanged soil in the bottom of each tube.

Analyses of both soil moisture content and wood degradation showed that covering the soils led to less desiccation and degradation, indicating that covering soils at dig sites could reduce negative effects of removing surface crusting. Somewhat surprisingly, the variable scenario with alternating high and low water level in cycles to mimic fluctuating conditions yielded the same degradation as the scenario maintaining a stable high water level, indicating that the regular water level rise was enough to maintain good preservation conditions. These results indicate that although horizontal water flow in soil might increase wood decay (Paper III), regularly raising the groundwater level may instead have a protective effect.

A specific value of redox potential at which the onset of degradation occurs could not be identified – more experiments are needed to explore the lower ranges of redox potential in soils and when degradation by different organisms occur. As there was little to no degradation at -55cm in any of the test scenarios, this suggests that disturbances shorter than 1 year may have a limited effect on wood material which is buried deeper in the soil. Further studies should consider a three-dimensional structure to explore whether this is also true in lateral directions in the soil, in order to determine horizontal margins for construction next to wooden foundations.

5. Discussion

The overarching aim of the thesis, to increase knowledge of effects that construction work can have on degradation rates of piled wooden foundations in urban environments, assumes (1) that urban infrastructure work influences subsurface soil environments, and (2) that this may endanger service life of wooden foundation piles. By performing a comprehensive literature review, the above assumptions could be validated and any potential gaps in the current knowledge base could be identified.

The influence of infrastructure work includes e.g. removing surface crusting, leading to higher atmospheric exchange and thus higher oxygenation in the soil; reducing groundwater levels, which reduces the soil moisture content and introduces gaseous oxygen; and artificial infiltration, which can increase oxygenation as stagnant soil pore water is replaced by oxygenated water. Changes to groundwater level or oxygenating waterlogged soils can accelerate degradation, as increasing local oxygen content can increase microbial decay rates (Matthiesen and Hollesen, 2012b) or activate fungal

decay (Schmidt, 2006). In previous studies performed on both wooden foundation piles and organic archaeological material, there is ample evidence of negative effects due to changed groundwater conditions or increased oxygen content (Brunner et al., 2000; Huisman and Mauro, 2012). Furthermore, since urban soils are altered by impermeable surface coverings that limit groundwater recharge (Palmer et al., 2004) and increased chemical load due to surface pollutants (Lehmann and Stahr, 2007), urban degradation processes may differ from those in rural environments.

While these results may not be surprising, the novel approach of including studies from vastly different fields provided added value. Thus, Paper I provided a theoretical basis for the design of the experimental work included in this thesis. Oxygen availability, thresholds, and in-soil processes in these environments need to be studied further to increase understanding of how a changing environment may affect wood degradation.

Based on the identified needs to explore local in-soil processes and current local decay rate for historic foundation piles, a field study was performed in which the degradation was related to various environmental parameters (Paper II). At all nine sites, erosion bacteria were found to be the principal degrader, with only minor attacks by soft rot and white rot at two sites. This reports on stable anaerobic waterlogged environments at all sites since the time of construction. Water flow is theorized to play an important part, as observed decay variations around a pile may be related to the direction of horizontal water flow in soil. Physical properties of the pile, such as pile diameter and mechanical damages to the pile head affect the depth of bacterial penetration. However, as this was an end point analysis after 88-274 years of burial, there was no significant correlation between accumulated degradation rates and the monitored environmental parameters of today. Neither depth of exposure, ground water level, wood species, annual rings, soil type, or differences in soil/water chemistry showed as single factors any significant correlation to development of decay. From these results, it is evident that ongoing degradation needs to be determined in order to separate historical effects from the current degradation rates affected by current conditions.

In the long-term field study (Paper III), samples were deployed at local mean groundwater level and pile head level, exploring current degradation rates *in situ*. The observed degradation at groundwater level could indicate how the degradation rate at pile head level might change if the groundwater level were to fall to pile head level. Again, the results indicate that erosion bacteria are present at the eight different urban sites, and wood degradation is actively ongoing in wood exposed in soil pore water at all sites. The degradation rates varied between sites but showed no correlation to discrete measurements of groundwater level, oxygen content or redox potential. This could be due to the frequency or reliability of field measurements, so that continuous monitoring or more sensitive instrumentation might give more indicative results. However, based on current results, analysis of proxy samples is still the best tool for understanding

ongoing wood decay processes *in situ*. The clear difference in degradation rates between the eight sites indicates that there are other local differences that affect degradation, such as groundwater flow in the soil. In other studies which observed large differences in degradation rate despite similar burial conditions, the differences in degradation were assumed to be due to differences in wood quality such as growth rate or origin (Klaassen and van Overeem, 2012). However, as the proxy samples exposed in this experiment were of the same origin and carefully selected to be of similar composition, with samples cut from longer lengths and randomised across the sites, the effect of wood quality could be ruled out.

Degradation decreased with depth and at each site the decrease was proportional to distance below groundwater level. The distance between these two points was not constant across the sites, enabling us to compare different depths below groundwater level across sites. It would be interesting to compare the same distance below groundwater at all sites.

The laboratory experiment (Paper IV) again confirmed the result that degradation rates decrease with deployment depth, and the results indicate that degradation of buried wood depends on water level in soil. The large effect of depth of deployment beneath soil surface on wood degradation rates, with degradation near the surface occurring regardless of groundwater level or soil covering, indicates that subsurface projects can affect wooden foundation piles even if groundwater levels remain high and stable. This is an interesting result, which should be explored further.

In contrast to the two field experiments (Papers II & III), the main degrader in the laboratory experiment (Paper IV) was found to be soft rot. That a different decay type was dominant was not surprising, as the experiment was designed to explore the effects of soil desiccation, whereas the samples in the long-term field experiment were deployed in dipwells filled with the local soil pore water. It is however interesting to note that both types of decay decreased with depth in soil and depth below groundwater level.

The similar degree of degradation observed in T3 and C1 despite different redox potential values observed in the soil indicates that a threshold value had been reached at +80mV, allowing severe decay to develop. While a threshold value for onset of degradation has not been identified, this result is nonetheless important as it provides a value at which severe degradation can develop. Previous work, performed with the objective of exploring preservation conditions *in situ*, has only given an indication of the ranges of redox potential in which each organism is active. Studies from Biskupin, where redox monitoring in the soil ranged from -250mV to -150mV, found colonization by several fungal and bacterial species but only slight degradation of wood (Zborowska et al., 2007). Gregory et al. (2008) summarized work performed at archaeological sites in Denmark and arrived at a classification of three environments: Oxidised, reduced and

highly reduced. Under fully oxygenated conditions in an unsaturated environment (Bryggen), severe degradation had occurred by soft rot fungi. In fluctuating conditions with low oxygen content (Nydam Mose), both soft rot and erosion bacteria were found to actively degrade wood. In fully saturated and anoxic conditions (Veksø Mose), very little degradation had occurred by only erosion bacteria. The ranges for soft rot fungi are thus believed by the authors to be from -200mV to +400mV, and for erosion bacteria from -400mV to 0 mV (Gregory et al., 2008). In Paper IV, severe soft rot decay was observed at +80mV. Since redox potential at -30cm depth slowly drifted over time from -400mV to +250mV, more frequent sampling of wood could potentially have revealed at which redox potential the onset of soft rot degradation took place.

Perhaps the most surprising result was that the variable water level yielded less degradation than the stable level with the same mean water level, as it seemed likely that a fluctuating level would increase oxygenation in the soil when the water level was lowered. Furthermore, previous studies have indicated that the physical flow of water is detrimental to the protection of wood, as this could allow bacteria to penetrate deeper in the wood (Klaassen, 2008b) or possibly expose the wood to oxygen and nutrients transported with the flowing water (Björddal and Elam, 2021; Elam and Björddal, 2022). The degradation rates in wood exposed to a variable water level were instead equal to rates observed in wood exposed to a stable level equal to the highest level in the variable case. This could be due to the low oxygen content in the stagnant water source, whereas lateral flow that transports water from a different area in the soil could be richer in oxygen and thus increase oxygenation (de Beer et al., 2016; Matthiesen, 2008). It is thus possible that lateral water flow in soils risks bringing oxygenated water and having a negative effect on wood degradation, whereas vertical flow due to rising groundwater levels can have a positive effect. Since the tubes were only in contact with the water source at the bottom of the tubes, changes in water level raised the stagnant water from lower in the soils vertically upwards, with no influx from the sides. In field settings, groundwater levels are more likely to be raised by artificial infiltration adding water from the surface. Furthermore, it is also possible that the cycle of variation was too short for effects to emerge, as the accidental surface rewetting in T1 showed how slow the system is to adjust deeper in the soil. The result is intriguing regardless, as this in combination with the effects of surface covering allows the recommendation to cover soils to reduce evaporation and to also keep the surface moist. Regularly raising groundwater levels and/or rewetting surfaces could help maintain low redox potential in the soil and reduce the degradation rates.

From the project as a whole, it is evident that not only the physical aspects of soil need to be considered when performing groundwater control. For durability of wood and stability of piled foundations, the conditions for microbial growth need to be taken into account.

To summarize, wood degradation decreased with distance below ground and distance below groundwater. There are environmental factors at sites with similar soil composition that affect wood degradation rates which cannot be explained by discrete measurements of oxygen content or redox potential. Discrete measurements can reveal if conditions are worse than at an earlier measurement occasion but cannot be directly correlated to a specific degradation rate. Ongoing degradation should instead be measured with the deployment of proxy samples. Water flow has been discussed in connection to increased degradation rates (Björdal and Elam, 2021; Elam and Björdal, 2022; Klaassen, 2008b) but maintaining waterlogged conditions with fully saturated soils has also been connected to better preservation conditions when oxygen concentrations are low. The focus of future studies should be on these seemingly contradictory results, in order to find threshold values for disturbance.

The three-dimensional aspects of degradation in buried material are very interesting and should be explored further, as dig sites for construction open vertical shafts next to the buried material, offering an insight into how lateral flux of water and oxygen can affect buried material. This can be compared to how archaeological material is excavated in the field, where often entire areas are uncovered, the topsoil removed, and the material examined before decisions are made on conservation or *in situ* preservation.

6. Implications for stakeholders and developers

As risk assessment during construction currently focuses on geotechnical effects of groundwater lowering and subsidence, there is a need to develop the risk assessment process to include the risk of increased degradation rates in wood. Accurate risk assessment can then be used to develop a guide for best practice, to ensure that cultural heritage buildings are not exposed to risk during urban groundwork. This could be expressed as e.g. maximum allowed groundwater level drawdown, preferred method of groundwater abstraction or threshold values for oxygen content/redox values in artificially infiltrated groundwater. By formulating protective measures that are easily measured and verifiable *in situ*, building stakeholders and construction entrepreneurs can ensure that a good protective environment is maintained in the field.

Maintaining a high groundwater level is instrumental in reducing risk to historic piled foundations. It is therefore recommended to use a less intrusive method of groundwater control, such as exclusion by a barrier rather than pumping, as a barrier keeps water away from dig sites without causing additional flow in the soil. At dig sites, covering the soil to reduce evaporation and regularly rewetting soil-air interfaces can help reduce the risk of more severe degradation.

Regular monitoring of groundwater and soil pore water chemistry can indicate if the conditions at a site have changed compared to prior measurement occasions. However, as the variation in wood decay rates between sites could not be explained by local groundwater level, oxygen content or redox potential, it is not recommended to simply measure these parameters to estimate wood degradation rates. When exposed to risk due to ongoing groundwork, it would be advisable for building stakeholders to analyse samples of the pile foundations during the construction planning phase prior to disturbance. The degree of degradation prior to the disturbance can then be known, and by also installing fresh, undegraded proxy samples, the degradation during the disturbance can be determined. Thus, both historic decay and current ongoing degradation can be stated.

7. Conclusions and future outlook

With the aim to explore effects of urban construction work on wood degradation, and use the results to argue for protective methods, this thesis contributes to the field by studying not only historical degradation of wooden foundation piles but also simulating what could happen in the future if conditions change in the soil burial environment. In Paper III, the site-specific degradation rates were determined at pile head level and at the current groundwater level, and by comparing the two the effect of lowering the groundwater level can be inferred. In Paper IV, proxy wood samples were deployed in soils exposed to different water regimes and the wood degradation at three discrete depths were compared, allowing the effects at different depths to be compared. These studies can be used by developers to gauge what safety measures to implement during construction.

Each of the four papers included in this thesis build successively upon the results from previous papers, as lessons learned from the first shape the design of the second, and so forth. Method development was a large part of this project, as methodology was improved by identifying the knowledge gaps and monitoring demands.

As it is generally agreed that maintaining a high groundwater level is the best way to protect wooden material immersed in soil, future studies should further explore the influence of groundwater fluctuations on this vulnerable organic material that includes both foundation piles as well as archaeological artefacts buried in ground. Of the wood sample material used in Paper IV, only 1cm subsamples from three specific depths were analysed from each sample rod. The remaining material not used was preserved in alcohol and stored refrigerated. Since the material is available, it would be interesting to perform a small follow-up study which determines at which depths degradation is encountered in each scenario.

The impermeable nature of urban soil covering reduces groundwater recharge by natural infiltration of rainwater, potentially leading to slower rise of groundwater levels after groundwater lowering during construction. It would be interesting to repeat the laboratory study in an urban field setting, installing a pump to reduce groundwater levels in soil at 6-week intervals, to study if natural groundwater recharge in an urban system is comparable to the laboratory scenario with variable water level, where water was added.

For future studies, the effects of oxygenated water on wood degradation in soils exposed to artificial infiltration should be explored. A mesocosm study was planned within this project but had to be excluded from the thesis due to time constraints.

The results obtained have been met with a very positive response, indicating that this is a field that can greatly benefit from improved collaboration over traditional scientific boundaries and with society. In a rapidly changing modern world dependent on infrastructure reforms, the problems faced by foundation piles supporting historic cultural heritage are complex. It stands to reason that they require a similarly complex scientific effort to solve them.

8. Acknowledgements

First and foremost, I would like to thank my main supervisor Charlotte Björdal, for being a supportive mentor and a good friend for the past five years. I feel very lucky to have had such a great relationship with my supervisor. I'm also thankful for all the advice and support from my co-supervisors Helle Ploug, Roland Bartel and Bengt Åhlén throughout this project. I also thank my examiners: Sten-Åke Wängberg, for helping me balance the different aspects of doctoral studies (courses, research, and teaching); and Katarina Abrahamsson, for stepping in during the last semester before defending.

I'm very grateful to all who have given access to field sites, both economic stakeholders and estate managers. As the legal access was negotiated by The Swedish Transport Administration, I have mostly been in contact with individuals on site, including building managers Göran Hansson (Higab), Oskar Olsson and Johan Herlogsson (Hufvudstaden), Per-Eric Lång, Ola Spång, Martin Hall and Lars-Gunnar Noaksson (TidX), as well as tenant owner's association representatives Bitte Nygren, Albert Mårtenson, Ann Kronander and Rolf Eriksson. Thank you all for your interest and personal commitment which allowed us to examine both historic piles as well as current conditions at various sites in Gothenburg. I'm especially grateful that you continued to meet with us personally and engage in the sampling despite the ongoing pandemic. I'd also like to thank construction manager Peter Holmberg and the team at Västlänken work site E03 for site access and help with sampling. It was a very strange request that you helped with, and I enjoyed your ingenuity in helping me figure out how to perform the sampling – with an excavator! It gave me the perfect cover image for this thesis.

Sander Smit, thank you for your enthusiastic and interested help during the development of the experimental design of redox probes for our lab study! We were lucky to receive such valuable input.

Thank you to Jörg Fromm, Elisabeth Magel, Katharina Erdt and Olaf Polak at Universität Hamburg for an unforgettable practical course at the height of the pandemic. It was an amazing experience.

A big thank you to all my colleagues and fellow PhD students at Marine Sciences, for celebrating every success and commiserating with every setback, no matter how big or small. It's been a pleasure to teach courses together, bounce ideas for experimental setups or just plain socialize. I thought I'd better not start naming individuals or I'd never stop – but I'll have to mention a just few: Kristie, Ella, Liz, Louise, Astrid, James, Romain, Erik, Lars, Seb, Kjell, Per, Irina, Eva-Marie, Adele, Phoebe, Michelle, Maria, Kajsa, Åke and Sven!

All my love to Rune, who never got to read this, and to Hedvig, who cannot read yet. My family and friends, Mattias and Torun – you already know.

8.1. Funding

The Swedish Transport Administration has provided funding for the project under the grant TRV 2016/74547 awarded to Charlotte Björdal.

The University of Gothenburg, Department of Marine Sciences, funded the PhD salary for 1 year.

A scholarship from Adlerbert Scholarships was granted in 2019 and used for travel expenses for the ICOM-WOAM conference in Portsmouth in 2019.

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