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Wooden foundation piles and its underestimated relevance for cultural heritage

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ABSTRACT

For centuries, wooden pile constructions support buildings in areas with unstable soils in Europe, and many other parts of the world. Depending on the local soil conditions and the building above, pile foundations differ in construction type, pile length, timber species and timber quality applied and the degree of conservation. It is estimated that millions of wooden foundation piles are still in service, carrying small buildings like family houses, or bigger buildings like churches and palaces or constructions in water-like quay walls or bridges. Many of these buildings are old and therefore wooden foundations are an important asset for cultural heritage. This is not always realised probably because foundations are hidden in the soil and therefore not visual as part of the building and because the wooden pile is replaced by concrete from the 1950s and onwards. There are many examples of wooden foundations that have been in service for several hundreds of years, but there are also examples of severe settling of buildings founded on wooden piles in historical town cities like Amsterdam or Venice. All foundation problem causes are known and are explained in this article. However, the process of bacterial wood decay, one of the causes, is not yet fully understood and the immense population of wooden foundation piles in the European soil offers a unique chance to learn more about it. As bacteria can degrade wood under water, it is also one of the main threats of waterlogged archaeological wood. A better understanding of bacterial wood decay does not only give chances to improve the conservation of wooden foundations, but it can also improve the in situ conservation of wet archaeological sites. Conservation of wooden foundation piles does not only save the building above its construction but saves also a unique archive related to building history and past timber trade connections. This article advocates the importance of foundation piles on the cultural heritage agenda as key issue for wood conservation in wet soils and saving a huge building historical achieve.

1. Research aim

Based on the historical record and the information from Dutch building inspections including inspection pits, this paper gives a survey of the behaviour of wooden foundation over time. Threats and consequences for the wood quality are described as well as situations in which wooden foundations maintain their load-bearing capacity for centuries.

2. Introduction

2.1. History of use of wooden foundation piles

Except for the Netherlands, no systematic country surveys of the use of wooden foundation piles are available, but their use is reported in many countries. The use of wooden foundations under buildings is well known from Scandinavian countries. Most of the large cities in Sweden (e.g. Gothenburg, Malmö, and Stockholm) have areas where mainly 19th and 20th century buildings and a large amount of family houses are supported by wooden foundations piles. The Stockholm parliaments building, originating from 1890s and standing on 15,000 piles was recently investigated and its calculated life expectation was at least a hundred years. It is also known from Helsinki that many 19th and early 20th century buildings have wooden pilings and the Norwegian UNESCO cultural heritage monumental city area of Bryggen in Bergen has very old horizontal wooden foundations. In Denmark many old cities are fully founded on wooden foundation piles.

In Eastern Europe, wooden foundations are known in Poland, Baltic countries (e.g. Estonia coastal lowlands cities Tartu, Pärnu, Haapsalu, Kuusalu), and Russia (e.g. St. Petersburg [large parts of historic town including the Hermitage], Archangelsk, several buildings in Moscow).

In middle Europe, wooden foundations are recorded from Germany (e.g. Hamburg (Speicherstadt), Berlin (Reichstag [1]), Bremen, Leipzig), and although not common in the UK and France, in the UK wooden piles are known under some houses or buildings in the

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Fig. 1. A commonly used foundation construction in the Netherlands of pile pairs, the so-called *Amsterdam foundation type*.
Photo: fugro.

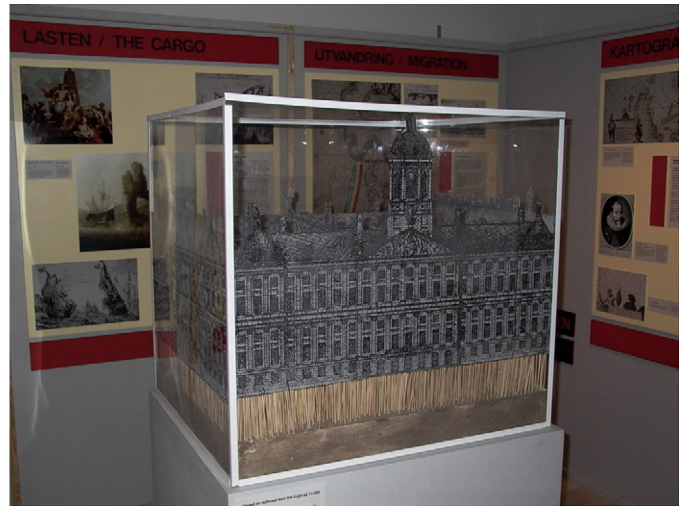

Fig. 2. Royal palace on Amsterdam Dam square.
Model: Museum of Flekkefjord, photo: Niels Bonde.

cities of Hull and Bristol, under the Docklands of London and under bridges and churches in various parts of the UK. In France, wooden pilings are mentioned under numerous bridges on the Loire, Seine and Garonne rivers as well as some major historical buildings (e.g. Paris: Grand Palais, Orsay station, parts of the Louvre; Bordeaux, Nancy).

In southern Europe, wooden foundations are not common. Venice is an exception with almost all historical buildings, originated already from the 12th century onward. Short oak, pine and alder piles (⌀ 120–200 mm, 2–4 m long) were common (e.g. ca. 300-year-old bridge "Ponte Balbi" [2]).

Even from the USA, examples are known of wooden foundations like under a Church in Boston (> 100 years old, on 4800 piles [3]).

As more information is available on the Dutch situation, a more detailed description of foundation piles in this country is given below.

In the Western parts of the Netherlands, the peat soil is too weak to carry heavy stone buildings. This is why already the Romans used short oak, ash or alder piles in their foundations. During the middle ages, Dutch houses were mainly made of wood requiring no or only a simple foundation. However, over time houses increased in size and when stone entered as building material, buildings had to be founded on wooden piles. Amsterdam is regarded as a city completely built on wooden piles. This holds certainly true for the old centre. From excavations, we know that already in the beginning of the 14th century in Amsterdam, horizontal (alder) stems were used in foundations. Somewhat later, ca. 1 m long alder piles were spaced closely together to improve the soil stability. Later, longer (c. 6 m) and thicker, mainly softwood piles were kept together by a wooden frame. Not before the end of the 16th century, long piles were punched through the weak peat into the stable sandy layer in Amsterdam [4]. As the depth of first stable soil layer varies locally, each of the Dutch cities built on weak soils needed piles of different length for their foundations. In Amsterdam, piles had to be 10 to 12 m long, Rotterdam needed longer piles of up to 18 m and in Haarlem and The Hague, shorter piles of 2 to 6 m match requirements for a stable construction (Fig. 1). With the changes in length of the foundation piles also, the timber species and the origin changed. Short piles were often pine whereas longer piles were imported as spruce or fir stems. These long spruce and fir stems became available due to a general increase in timber import from the 16th century onwards. In this period, especially the request for oak was high because of increasing building and shipbuilding activities facilitated by the invention of wind-powered saw mills [5]. Rafting of heavy, water-saturated oak stems only became possible by adding lighter softwood stems that kept the raft floating [6]. In addition wood for long piles was also imported from Scandinavia, Poland, Germany and Belgium. Many 17th century buildings standing on long wooden piles still exist, e.g. the Royal Palace on the Amsterdam Dam square (1640, 14,000 spruce piles 11 m long, Fig. 2), the Amsterdam Maritime museum (1656, spruce and pine piles originating from southern Sweden), and the tower of the Rotterdam St. Laurens church (1655, 500 pine piles 14 m). Until the use of motorised equipment, the transport of logs into the town and the installation of the foundation of wooden construction required many hands and was a tough job. Approximately 40 men were needed to drive the piles into the soil by pulling up a falling block of 200 to 400 kg in a strict rhythm singing (dirty) songs [7].

A huge amount of piles was used around the beginning of the 20th century when many Dutch cities expanded. It is estimated that approximately 25 million wooden piles are still in service in the Netherlands. Half of these piles are carrying buildings and the other half was placed under water constructions, like quay walls and bridge heads.

2.2. Archive of building history, past timber trade and climate reconstruction

Foundations are hidden in the soil and thus, are less acknowledged than above ground construction elements. Nonetheless, it is obvious that they are crucial for the stability and thus, lifespan of a building. Besides knowing that wooden foundations can fulfil their functions over hundreds of years, archaeological wood can be conserved sometimes for thousands of years in its wet and anoxic environment. The millions of wooden foundation piles used in the last millennia all over the world, offer a huge building history archive preserved in wet soils and are waiting to be explored. It can tell us about the progress in construction technology of building, as well as the development of the timber use (in species and quality). Specific marks at the pile tips applied by the craftsmen, traders or salesmen (Fig. 3) can provide information on the origin and on how the timber was transported. Tree-ring analyses on wooden piles enable us to exactly determine the cutting date and origin of trees that were used for foundations and hence make it possible to determine the approximate age of a foundation and to reconstruct timber trade across centuries, e.g. [8]. Wooden

Fig. 3. Signs on pile tips of > 100 years old extracted piles.

foundations piles can therefore give additional information for historians to complete their understanding of the way of building in the past, e.g. [9].

As climate influences are stored in the structure and chemistry of wood, the wooden foundation pile population offers also a huge archive for climate reconstruction. As the techniques to extract climate signals from timber are still in progress, future analyses based on dendrochronology, isotopes or other techniques will be able to extract more detailed climate information. Millions of foundations piles are available and offer a complete view of the wood development during the lifetime of a tree, whereas each pile has a stem part of several meters in length and includes the whole area between pith and bark. A better understanding of the conservation of the wooden foundation piles in situ could save this huge archive for future generations with more advanced analysis techniques to learn from our past in order to save our future.

3. Present use and threats

From the period after the Second World War, concrete replaced wood as material for foundation piles. Concrete is believed to be a material with a long-life span and can be produced in almost every dimension wanted. In 2009, the longest concrete foundation pile was inserted for a sound barrier wall at the Dutch motorway A15: it was 39 m long and had a weight of 20,000 kg. These dimensions are impossible to get in wood. At the moment, the wooden pile is only used in niche markets like greenhouses, sewerage systems, small building projects and restoration projects in historical city areas. Still about 200.000 piles are inserted every year in the Dutch soil and to secure the life span of a wooden foundation, the quality and species used (douglas fir, larch, spruce, fir) are regulated in a standard [10,11] and in areas where the pile head can reach the upper level of the ground water table, concrete upper parts are used [12].

Within the building design, CO_2 neutral production, the use of renewable materials, low-energy housing concept, Cradle to Cradle are actual topics and a lot of money is invested in innovation. In contrast, the use of wooden foundation piles is still decreasing although it fits perfectly in this actual philosophy, e.g. it is produced in sustainable forests and it offers a huge and durable CO_2 sink. The use of wooden foundations is not restricted to giving buildings stability but other possibilities are developed. The *Deltares Kyotoway* ensure the stability of the soil under a motorway by the use of wooden pilings or the *Van Biezen pinning method* improves the stability of embankments by the use of wooden piles. The reasons that wooden piling is ignored in innovated building are their bad and non- or old-fashioned image. One cannot be proud of a beautiful innovated foundation which is in the soil, so not visible and it is difficult to realize that old building techniques can compete with innovation of the 21st century. Most dominant in the image of wooden foundations are, however, the bad experiences. Already, in 1902, the tower on the San Marco square in Venice collapsed not because of rotten wooden piles but because of a bad construction. Therefore, it was rebuilt with another foundation construction using a greater number of wooden piles [2]. In the Netherlands, the Amsterdam *Beurs van Berlage* (1898, 4880 spruce and pine piles of 13 m [13]) showed within 8 years after building severe cracks and several repair measures were necessary to give the building sufficient stability. Finally, in 2001, 713 concrete piles of 15 m long were installed. In the 1990s of the last century in the city of Haarlem in the *Amsterdamse buurt*, several houses collapsed because of decayed foundations. This problem proved to be typical for large parts of the area and whole blocks of houses had to be rebuilt or given a new concrete foundation. The cost of a new foundation varies between €40,000 and €100,000 per house. In the first years of the 21st century, severe foundation problems appeared in the city of Dordrecht. Typical for this city is that houses with and without foundation piles are mixed. In time, the water saturated weak soil is compressed (approx. 2–10 mm yearly) and houses without a pile foundations often follow the settling without problems (e.g. no cracks, no distortion). A consequence of settling are lower groundwater tables, which cause wood decay at the pile heads under houses with a wooden pile foundation. In this city, the problems with too low ground water table were so huge that a society was founded that united owners of houses with a bad wooden foundation (*Stichting platform funderingen*, www.platformfundering.nl). In Rotterdam, several houses show severe settling although those houses are standing on a pile foundation, while in other areas of Rotterdam wooden pile foundations are severely degraded because of too low ground water tables.

As the causes of all these different problems with wooden foundations are understood, they can be prevented from happening in new projects by the use of the right timber species, the right wood quality, making the right construction calculations and using the specific soil and ground water parameters for the foundation design (pile number, the use of a concrete upper part). However, many existing constructions were built without the awareness of the threats that affect the quality of the wooden foundation. In order to guarantee the stability, it is important to judge the quality of the foundation and to make an inventory of the actual threats. These threats can be divided in three main groups:

- too low ground water table;
- too high load;
- wood decay under water.

If the pile heads are above the ground water level, the high oxygen supply through air will allow wood degrading fungi to be active. The velocity of the decay is determined by the duration of the time that pile heads are above the ground water and the length of the pile head which is above the ground water table, as well as the water-bearing capacity of the soil and the timber species used. It is estimated that the maximum degradation velocity of fungi that attack water saturated wood (softrot) is approximately 10 mm/year. Whereas fungi that attack wood with a moisture content of 25–100% (brown- and white rot fungi) are with a maximum of 100 mm/year much faster. Too low ground water tables can appear because of insufficient water management by the local government. The western part of the Netherlands exists in a patchwork of polders, each with its own pumping system and,

Fig. 4. Adaption of the street level to the houses with a high but homogeneous settlement because of negative skin friction, Rotterdam 2010.
Photo: Jan Stoker

Fig. 5. Three-hundred-and-fifty-year-old spruce pile (⌀ 16 cm) degraded in the sapwood only by bacteria.

specific street- and groundwater table level. For security reasons, it is accepted that the lowest ground water table is at least 50 cm above the pile head but in some areas, the height difference to the street level is less than 20 cm, which makes the water management extremely difficult. The Dutch law is not appropriate to protect house owners sufficiently against too low ground water tables and a large law suit on this topic is going on at the moment between the city of Dordrecht and the *Stichting platform funderingen*. Too low groundwater levels can also appear locally because of broken sewerage systems, which, being situated under the groundwater table, can act as drainage. Other causes of local low groundwater tables are evaporating trees in the spring and summer, building pits (with depths > 10 m) resulting in water extraction for several months or street work like renewing the sewage system. If temporary ground water extraction is planned, it is wise to inventory the quality of surrounding wooden foundations in order to prevent collapse because of fungal activity.

The bearing capacity of wooden foundations under most buildings is overestimated. Nevertheless, additional load because of enlargement of the building or additional load because of surrounding sand layers were not taken into consideration. Especially, the so-called negative skin friction is a phenomenon that only after WWII was included in construction calculations. The problems with the *Beurs van Berlage* were related to this phenomenon. After a part of the river Amstel was closed, it was filled with sand and on this sandy layer the *Beurs van Berlage* was built. As the underlying weak Amsterdam soil (peat and clay) was compressed by the sand, within 5 years the heavy sandy layer was kind of ‘hanging on’ to the foundation piles, increasing the load on the piles tremendously and causing problems. The *Beurs van Berlage* is just one example but as sand layers were often used to develop new building areas, the problem is widespread over the Western part of the Netherlands (Fig. 4).

Until the 1980s of last century, it was believed that no decay was possible when wood was stored under water. Colonisation by bacteria of ponded wood was not to be considered as real wood decay [14]. Those bacteria cause an increased permeability by attacking the pith membrane but were thought to ignore the woody cell wall. Professor Nilsson from Uppsala, Sweden was one of the first scientists that showed that there are also bacteria that degrade the woody cell wall. They degrade wood in consortia of several species and are always present where wood is in soil contact. Their decay velocity is low but they can be active without oxygen supply [15–17]. In all Dutch wooden foundation piles investigated, bacterial decay was found over the full length but the intensity varies. In some piles, only the outermost 1 mm is degraded over a period of approximately 100 years, whereas in other piles, an outermost layer of 50 mm and more of decayed wood over the whole pile length can be caused by bacteria in 50 years. Although the process of bacterial wood decay is not yet fully understood, in the last decades much new knowledge has been gathered [18–43]. As wood degrading bacteria are in themselves immobile they need water flow for entering and colonising the wood and intermixture of the consortium species. Permeability of the wood and groundwater flux are believed to be the key parameters to determine the velocity of bacterial decay. Permeable wood structures that allow water movement, like alder, poplar and the sapwood of pine and oak are typically susceptible for bacterial decay. The amount of sapwood is in oak and especially in pine crucial for its quality as foundation pile because, within several decades, the sapwood can be fully degraded whereas the heartwood stays sound for hundreds of years, as shown in the pine heartwood foundation elements investigated from the 350-year-old *Amsterdam Royal Palace*. From the thousands of foundation inspections carried out in the Netherlands, spruce piles showed to be less susceptible for bacterial decay compared to pine. It is believed that this is related to the low permeability of the spruce sapwood. Although, compared to pine, the difference in sap- and heartwood of spruce is much more difficult to determine in the wood itself and more difficult to predict on the basis of tree age and stem circumference [44], evidence is found that also in spruce a sharp demarcation between sound heartwood and severely bacterially degraded sapwood is common in foundation piles (Fig. 5). SHR has a database, which was built up in the last 15 years and contains information on more than 5000 foundation piles, their location, species, building age, and type and intensity of the decay. This database shows that there are large differences in velocity of bacterial decay between cities e.g. velocities are low in Rotterdam and high in Amsterdam. In order to determine the velocity of bacterial decay, one should regard the speed in which the wood structure is invaded by bacteria and the speed of severe cell wall degradation caused by wood degrading bacteria. Ref. [31] offers a qualification system based on light microscopic observations and the first signs of decay (weak) is a tool to describe the invasion of bacteria in the wood and at the stage of severe decay, the timber is regarded to have lost almost all its compression strength. The SHR database show that the invasion velocity of wood degrading bacteria ranges between 0 and 1.1 mm/year and that of severe

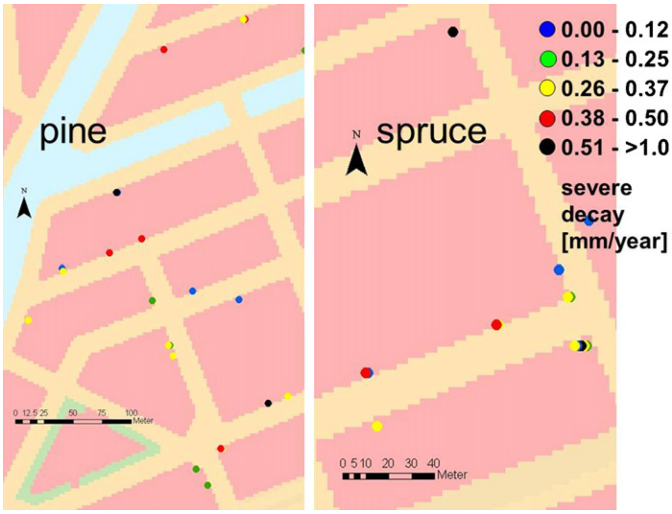

Fig. 6. Two locations in Amsterdam with piles of same timber species showing a wide variability in bacterial decay velocity.

bacterial wood decay between 0–0.8 mm/year [34]. Although these values are low, they can have an enormous impact on the stability of the buildings, for example. In the Dutch city of Haarlem, many houses are standing on pine piles with a length of approximately 6 m and with a diameter of approximately 14 cm. Most of the piles have a wide sapwood layer which is sensitive for bacterial decay and where high degradation rates can be expected. However, in 70 years, the whole sapwood layer is severely degraded and those houses are actually standing on broom sticks of less than 3 cm.

It has been shown [35] that bacterial decay degrades wooden foundations piles over their full length from the top towards the smaller tip that stands in the stable deeper sand layer. The dynamics of bacterial wood decay over the pile length is not studied in detail but more information is necessary as the tip of the foundation piles is, with its smaller diameter, the most vulnerable part of the pile. Because of decay, the sound diameter will decrease and the load on the sound wooden tissue will increase, resulting in failure of the pile. Furthermore, the interaction between wood and soil is changed because of degraded wood and this might affect the carrying capacity of the soil.

A case study of the Amsterdam situation, showed that local variety in hydrology or soil chemistry are not related to bacterial wood decay activity. It was found that piles of the same species under one building can differ enormously in degree of bacterial decay (Fig. 6), and it is supposed that besides sapwood percentage, also wood quality and the handling around harvesting could be crucial in sensitivity to bacterial decay [35].

Of the processes that threaten wooden foundation piles under buildings, only bacterial wood decay is not fully understood and additional research is needed to enable the safeguarding of our cultural heritage buildings on weak soils. Effective and practical conservation methods can be developed when additional information is available on the process of bacterial wood decay and when its relation with wood quality, harvesting techniques and pile length is understood. Although the process of decay is very slow, conservation techniques are necessary because our cultural heritage should be secured for a long time. The EU project BACPOLES [30] mentions the possibility to develop simple and practical conservation methods that could stop or slow down the process of bacterial wood degradation in the soil. Such a method could prolong the lifetime of family houses with several decades and prevent an early destruction. Or it could prevent old monumental buildings from severe settlement and safeguard them into the next century. The conservation methods developed can also be of great use in the archaeology where many sites will not be excavated and wooden fragments will be stored in situ. Conservation is needed to ensure that later generations with new technologies will still have access to these wooden remains for research purposes.

4. Future perspective

As wooden foundations are carrying a significant part of our built environment, as they vary in age from 75 years to more than 700 years, include a variety of historical information and offer a huge source for the study of wood degradation in the soil, they are worth to protect. Cooperation on European level is necessary to explore this area of research in its whole extent and, therefore, support of the European committee is needed. As wooden foundations are invisible and regarded to be more related to craftsmanship than to innovation, it is a great challenge to convince the EU of the relevance of this theme.

Once the exploitation of this field of research has started, benefits can be expected for conserving wood in the soil in the sense of cultural heritage, in general, as well as for innovative durable building techniques. New wooden foundations construction designs with a guaranteed long life time could improve the bad image of the wooden piles resulting in a revival of the use of this relatively cheap, CO_2 fixating and renewable material.

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