IMPROVING INSPECTION TOOLS FOR WOODEN FOUNDATIONS AND ITS SIGNIFICANCE FOR CARBON SEQUESTRATION

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ABSTRACT

Before the introduction of concrete, only wooden foundations piles were used in the Netherlands. Nowadays millions of wooden piles are still in use storing large amount of carbon. Yet, problems related to exposure of foundations to oxygen and bacterial decay under water call for monitoring of the actual condition. Detecting the condition of wooden pile foundations is crucial to come up with tailor-made repair and maintenance measures. Currently, inspection guidelines are available, to evaluate the actual load carrying capacity and predict the associated life expectation of a foundation. The common field method of assessing the residual strength of foundations uses an impact hammer. Here, this device is tested for reliability by comparing it with the results of wood anatomical analyses on the same piles. Results indicate that predictions of the remaining pile strength based on impact hammer measurements with current models are too uncertain especially for constructions in water. Suggestions are given to improve these predictions. Improving current inspection methods is relevant not only to increase the service life of existing wooden foundations but also to promote the use of wooden foundations in the future. Both developments can have a positive contribution to enhance and increase this sink for carbon sequestration.

Keywords: wooden foundations, decay detection

INTRODUCTION

The Netherlands has a long history in supporting buildings on wooden piles due to the presence of weak soils across the western part of the country and near riverbanks. During the last century, wooden foundations were gradually substituted by other materials such as concrete. Because of decay problems the use of wooden foundations is strongly reduced. Decay occurs either due to temporarily lowered groundwater tables or due to slow bacterial degradation along the entire pile length under anoxic conditions. Although the Netherlands is well known for having wooden foundations and decay problems, it is a worldwide phenomenon in areas with weak soils (e.g., Elam & Björdal, 2020; Stockholm: Björdal & Elam, 2021; Venice, Italy: Macchioni et al., 2016 and Ceccato et al., 2013 and 2014; Riga, Latvia: Irbe et al., 2019; Hamburg, Germany: Lukowsky et al., 2018; Europe wide and especially Poland: Przewlócki et al., 2005; Saint-Petersburg, Russia and Kazakhstan: Zhussupbekov, 2013). During recent dry years in the Netherlands (2018, 2019 and 2022) the situation worsened through long-term reduction of water levels. Nowadays the use of wooden piles in foundations is mainly limited to sewer systems, greenhouses, stables and small, inner city house expansions. The number of existing wooden foundation piles in the Netherlands is estimated to amount to around 25 million with a service life of between 40 to 350 years or even many more (Klaassen and Creemers, 2012 and 2019; Klaassen and Overeem, 2012) and an estimation is made on the amount of carbon stored in this pile population.

The actual shortage of houses together with the ambition to promote the use of renewable materials, such as wood, can lead to a new interest in wooden foundations. The past has shown that wooden foundations were designed and applied to carry various types of buildings, ranging from small houses to large monumental buildings. Conservation of existing buildings, and prolonging their lifetime, not only benefits the actual owners but also ensures the CO_2 remains captured in existing constructions. To come up with tailored conservation measures, it is crucial to assess the current condition of a wooden foundation. In 1998, a wooden pile inspection guideline was developed to judge the quality of existing foundations under Dutch buildings (Keijer et al., 1998). This guideline was continuously updated, and also received input from international experts (Klaassen et al., 2005). In 2001, 2003, 2011, 2012, 2014, 2016 and 2022, new editions of the guideline were published (Keijer et al., 2001; Keijer et al., 2003; F3O, 2011; F3O-CURnet, 2012; F3O, 2014; SBR CURnet F3O, 2014; F3O SBR CURnet, 2016 and KCAF RVO, 2022). A specific guideline for the assessment of wooden foundations under construction in water does not exist but a Dutch standard on the assessment of existing geotechnical constructions (NEN 8707) was published a few years ago including some remarks on wooden foundations.

For evaluation of the remaining strength of a pile it is important to quantify the thickness of the severely decayed outer layer of the pile. The wooden pile guideline describes one method to determine the mean thickness of the non-load-bearing outer layer with an impact hammer and provides calculation rules to estimate the actual pile load bearing capacity. The impact hammer is used on at least three but often four positions by measuring the penetration depth of a small pin, which is in a controlled way forced into the pile. Furthermore, the wooden pile guideline describes the estimations of the future load bearing capacities on the basis of increment core analysis on wood species, depth and decay characteristics, density, sapwood amount, moisture content, and remaining compression strength. The wooden foundation guideline version from 1998 refers to the possibility to use the impact hammer to assess the diameter of the remaining sound wood of a foundation pile. The impact hammer is an efficient tool as it is easy to use even under difficult conditions like in a narrow and wet excavation pit and even underwater.

A common type of impact hammer was the Pilodyn (made by Proceq Switzerland and introduced for Dutch foundations inspections in 1997), and in combination with wood it was applied to study the thickness of the soft outer layers degraded by bacteria, not only in pile foundations but also other types of wet timbers like in the archaeology (Hoffmeyer, 1978; Hoffmeyer, 1981; Micko et al., 1981; Cown, 1981; Muhs, 1981; Uhlenberg, 1981; Niemz, 1999; Klaassen and Vosslamber, 2002; Gregory et al., 2007). In 2009, when the production of the Pilodyn stopped, an alternative Dutch impact hammer (Specht) was developed by Profound (Profound, 2016) and implemented in the wooden pile guideline. For inspecting foundations, the impact hammer evolved and improved over time, e.g., by optimizing the size of the pin, enhancing the readability, and also by introducing better control of the force that is applied to shoot the pin into the wood. Moreover, in the most recent wooden pile guideline it is required that the impact hammer has to be calibrated each year.

Given the relevance of the detection method for determining appropriate conservation measures, it makes sense to conduct a comparative study to assess the precision of the method to detect the mean thickness of the soft layers of the piles. In the last 20 years many inspections of wooden foundations included impact-hammer based measurements but also information gained from increment cores.

In this study we compared the results from the impact hammer with those from analyses of increment cores. As specific environmental conditions matter for decay patterns we differentiated in our analyses between inspection done in inspection pits under buildings and inspections done underwater on foundations of quay walls and bridges. Results are discussed with respect to further improvement of inspection and conservation strategies of existing foundations.

MATERIAL & METHOD

For this project we used measurements provided by inspection companies in the Netherlands and based on the guidelines for foundation inspections. Our analyses are based on 1314 samples, of which 45% originate from foundations under buildings, and 55% from foundations under constructions in water (Fig. 1). Two species are most common, Norway spruce (54%) and Scots pine (38%). Other species are fir (5%), European oak (3%), black alder and Douglas fir (<1%) (Fig. 1).

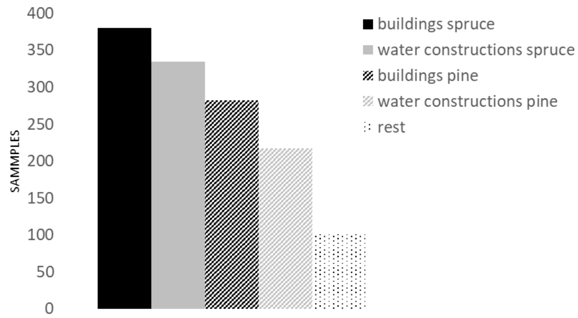


Fig. 1. Sample set divided by construction type and timber species (N=1314).

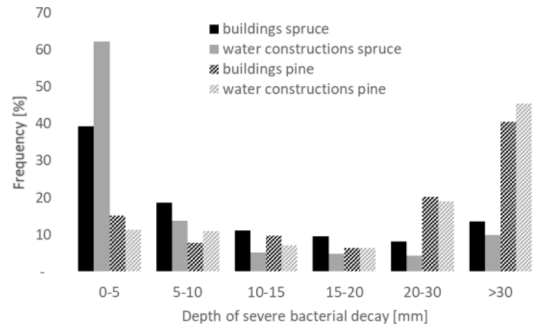


Fig. 2. Share of Norway spruce (filled beams) and Scots pine (hatched beams) samples (1207) with different depth of severe decay in buildings (black) and water constructions (grey).

The dataset includes results of increment core analyses and the results of impact hammer measurements.

Increment cores - With an increment borer (diameter 10 mm) one core is taken per pile at 15 cm distance from the pile head. Directly after sampling, the increment cores are stored in water-filled plastic tubes, which are sealed and sent to the laboratory for wood-anatomical analyses. At the laboratory the cores are further processed to determine the wood species, wood density, sapwood amount, moisture content, as well as depth and characteristics of decay, according to Klaassen (2008). This includes a classification of the intensity (sound, weak, moderate and severe) of the bacterial decay in different layers from outside inwards.

Impact hammer - According to the wooden pile guideline the thickness of the soft peel (wood without any strength) is determined by the average penetration depths of a pin (diameter 5 mm) shot (5m/s, 4J) in the pile with a calibrated impact hammer on three or four positions around the pile at 15 cm distance from the pile head.

First, a survey is provided of the depth of severe decay in all 1314 studied piles separated by species and type of construction (water construction, buildings) based on wood-anatomical inspection of all increment cores. To gain information on the precision of the assessment of the thickness of the outer layer with severe decay by taking only one increment core, an additional analysis was performed on 22 extracted piles. The variation in thickness of the layer with severe decay was detected on four locations around the pile by extracting and analysing multiple increment cores at the same height in the pile.

In a second step, a comparison is made on the detection of the outermost, severely decayed pile layer, based on results gained by the impact hammer (penetration depth) and the increment core (wood anatomical analyses). Pearson correlation analysis is carried out to assess the relationship between the results gained by both methods. The analyses is also performed separately for building and water constructions as well for Scots pine and Norway spruce in the two construction types.

In order to improve the estimation of the stored carbon in the extending piles in the Netherlands, pile statistics based on the core analyses of the last decades concerning timber species, diameter, decay and originating under buildings or water constructions was used too.

RESULTS

The general survey of the depth of severe decay in piles made of Norway spruce and Scots pine and originating from buildings and water constructions based on wood-anatomical core analysis shows clear differences, both related to origin but especially related to species (Fig. 2). Most obvious is the high share of Scots pine samples with a severely decayed outer layer larger than 30 mm both for piles under buildings and for constructions in water. Spruce piles generally show a much thinner severely decayed layer, and in more than 60% of all samples in water constructions this layer did not exceed 5 mm (Fig. 2). This can be caused by unfavourable conditions for bacterial attack as described by Kretschmar et al. (2008). But also an influence of the sample protocol is suggested, while under buildings, according to the wooden pile guideline, only cores are taken from piles with a specific ratio between pile diameter, pile load and impact measurements. Whereas at water constructions, a specific percentage of the pile population has to be cored.

One of the limitations of the data set is that – especially for spruce samples originating from water constructions – the majority of the data has a severe decayed layer of less than 5 mm (62%). Contrary, for pine samples this category is underrepresented with only 11%. Nevertheless, this data set represents the actual situation in the Netherlands and the larger number of samples was a way to deal with this limitation.

In the next step, the entire Scots pine - spruce sample set (n=1207) was used to compare the depth of severe decay for each pile as determined from one increment core with the average penetration depth as measured with the impact hammer (3-4 measurements). The results gained by the two methods are only weakly correlated (R^2=0.31). The maximum penetration depth of the impact hammer is limited to 50 mm while the maximum of the severe decay depth can go even beyond 100 mm (Fig. 3). Whereas in the case of a small severely decayed layer (< 15 mm) there seems to be an overestimation of penetration depth but with increasing depth of severe decay, the penetration depth of the impact hammer underestimates the thickness of the severely decayed outer layer in a pile.

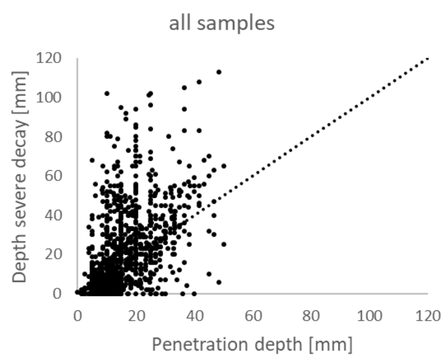
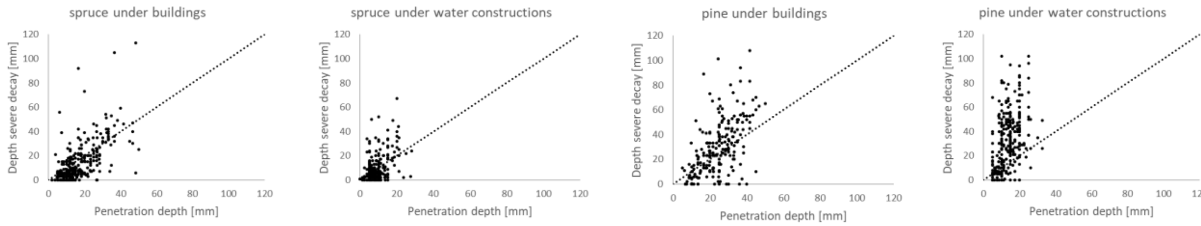


Fig. 3. Relation between mean penetration depth based on impact hammer measurements and the depth of severe decay as detected from an increment core from the same pile; results are shown for all 1207 piles; dotted line represents the 1:1 relationship.

The complexity of the relationship becomes clear if separating the entire dataset according to species, i.e., Scots pine and Norway spruce, and construction type, i.e., buildings and water constructions (Fig. 4).
For Norway spruce piles under buildings (Fig. 4a), penetration depth of the impact hammer and depth of severe decay are most strongly related (R^2=0.4), also because the range of the depth of severe decay and the penetration depth of the impact hammer, i.e., up to 50 mm are similar. However, for Norway spruce in water construction the relationship is weaker (Fig. 4b, R^2=0.25) and the range of the majority of samples for both, severe decay and penetration depth is restricted to c. 20 mm. In both construction types the impact hammer seems to overestimate the thickness of the severely decayed layer; i.e., most observations are located below the 1:1 line; Fig. 4a & b. Scots pine shows a less strong relationship (R^2=0.34) than Norway spruce for piles under buildings (Fig. 4c), largely caused by the greater susceptibility to bacterial attack and the limitation of penetration depth to 50 mm while not limiting the thickness of the severely degraded layer. For Scots pine in water constructions no relation can be seen (Fig. 4d), mainly due to the limited penetration depth of the impact hammer, which much like in the case of spruce, seldomly exceeds 25 mm, whereas the thickness of the severely decayed layer is high, as seen before in Fig. 2.



a b c d

Fig. 4. Relation between mean penetration depth based on impact hammer and depth of severe decay detected from an increment core from the same pile; dotted line represents the 1:1 for Norway spruce under buildings, n= 333 (a) and in water construction, n= 379 (b), Scots pine under buildings, n=216 (c) and in water construction, n=281 (d)

Variations in penetration around one pile at about 15 cm below the pile head for those piles for which not only the mean values, but also the indivual 2-4 impact hammer measurements were availeble (N=651), are shown in Fig 5. The figure shows that there is almost always at least some variation in the measurements and often with extreme deviations. Figure 6 shows the variation in the thickness of the severely degraded shell determine from 2-4 cores extracted from the same pile (N=22). The figure shows that the severely degraded shell can be evenly and unevenly distributed accros the pile.

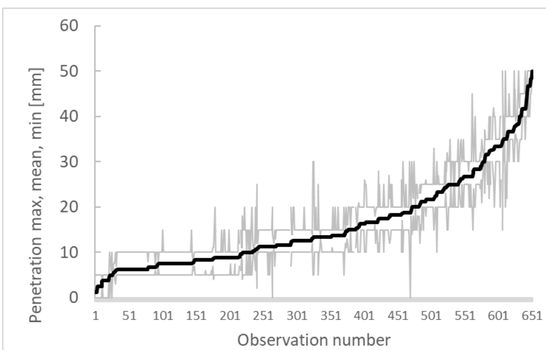


Fig. 5. Penetration measurements and the variation within one pile. The black line is the mean value and the gray lines the minimum and maximum values. Observations are sorted by the mean values.

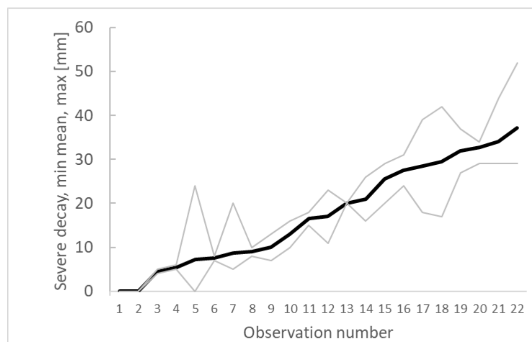


Fig 6. Thickness of the layer of severe decay and the variation within one pile. The black line is the mean value and the gray lines the minimum and maximum values. Observations are sorted by the mean values.

DISCUSSION

Impact hammer measurements differ from results of increment cores

The Dutch guideline for judging the quality of wooden foundations, relies strongly on pile inspections with the impact hammer. The impact hammer is used to measure the depth of the outer layer with severe decay of a pile, the so-called soft peel, which is a result of bacterial decay. It is assumed that this soft peel, does not contribute to the load bearing capacity of the pile. Microscopical analyses on increment cores confirm that in severe bacterial degraded wood no significant strength is left but they also reveal that the transition of severe degradation towards sound wood can be sharp but also gradual. In earlier studies it is seen that at sharp gradients, the penetration depth is almost equal to the layer of severe decay (Klaassen and Vosslamber, 2002) and that with increasing gradient, the depth of penetration decreases relative to the severely degraded layer. This explains the underestimation by the penetration measurements under buildings when the soft peel is thick (Fig. 4). In contrast, in the case of an intact pile, without soft peel or in the case of a superficial degradation, the penetration by the impact hammer will result in an overestimation of the thickness of the severely decayed layer. This is caused by the natural condition of the water saturated wood, which always makes the pin of the impact hammer penetrate at least several millimetres into the wood.

Differences between construction elements

The correlation between the penetration depth and the severe decay thickness for piles under constructions in water is weak but is often an underestimation of the depth of the severe decay. Likely the friction of the water in and around the impact hammer has too much influence on the measurements.

Variation in measurements with both methods and reasons behind it

The low correlation between the penetration depth of the impact hammer and the thickness of the severely decayed outer layer is – besides the above mentioned factors – caused by a variety of other aspects. First, it is impossible to guarantee that all data in this large data is collected in exactly the same way. For penetration measurements and collection of increment cores, we needed input from different companies that conduct foundation inspections. Although they all work according to the wooden pile guideline, decisions have to be made on, e.g., the number of impact hammer measurements and the specific location at the pile where these measurements are taken. Another decision considers whether increment cores are taken and if so at which exact position at the pile. Second, increment cores and impact hammer measurements are never taken at exactly the same position. Although in principle the guideline determines at which distance from the pile head the measurements have to be taken, the choice of the sampling position depends on a part of the pile circumference, which is exposed in the sometimes very small extraction pits. For piles under building and water constructions, only the mid front side is available for coring and a somewhat larger part of the pile surface is available for impact-hammer measurements. Although the exposed pile surface suitable for sampling is limited, taking of multiple samples results in a large variation in measurements, both for impact hammer and coring (Fig. 5 & 6). This variation in thickness of the soft peel even across relatively short, distances is mainly related to variation in wood structure around the stem circumference. An asymmetric pith in the pile indicates formation of compression wood, which has a higher lignin content (Panshin and de Zeeuw, 1990) and is therefore less sensitive to bacterial decay (Kretschmar et al., 2008). All these wood characteristics can vary across short tangential distances and explain variation in the detected thickness of the soft peel.

For the calculation of the bearing capacity of a pile based on impact hammer measurements and results from increment cores, it is also important to take into account that the specific environment may determine the development of deterioration and thus the loss of bearing capacity. For instance, in piles under quay walls the front side is in contact with open water whereas the back side is surrounded by soil. The variation in the thickness of the layer with severe decay, determined by core analyses from the same pile (Fig. 6), show the same pattern as seen for the penetration measurements (Fig. 5) and has the same causes.

Suggestions for improvement of detection of the soft peel

The results of this study give rise to proposals for improvements for the wooden pile guideline, which is specific for buildings.

The average penetration depth determined with the impact hammer is used to calculate the current pile load bearing capacity. In table 1 the actual and suggested formula are given. The actual formula is used independent of the height of the mean penetration. It is suggested to change from a static towards a dynamic interpretation of the mean penetration depth because of a structural under or overestimation.

Also, a structural combination of the impact hammer measurements with increment core analyses is suggested, which was also advised by Elam and Björdal (2022). Based on both the variation in penetration depths and the depth of the severe degradation in one increment core, the dynamic factor is specified for calculating the sound load bearing pile surface.

Table 1. Actual and suggested formula for calculating the load bearing pile diameter (legend: i= mean penetration depth [mm]; D = original pile diameter [mm]; d = remaining load bearing plie diameter [mm])

Calculation of the load bearing pile diameter	
formula	
Actual	d = D – 2 x (i + 5)
Suggested	
penetrations < 10 mm	d = D – 2 x (i - 5)
penetrations 10-30 mm	d = D – 2 x (i + 5)
penetrations > 30 mm	d = D – 2 x (i + 10)

On the other hand, the development of alternative assessment methods could improve the reliabilities of the actual and future pile strength. Klaassen et al. (2017) already offered alternative methods for calculating the remaining pile strength. Also, a combination of different assessment methods and the impact hammer is possible.

It is of key importance that the estimation of the remaining strength of wooden foundation piles is done with the highest possible accuracy. This enables the buildings' owners to take, if necessary, the proper interventions to maintain their properties in a sustainable way. Furthermore, it provides trust in the wooden foundation construction, which can result in more interest in building with wood including for foundation construction.

Contribution to carbon sequestration

Improvements in inspection protocols and estimating the current and future lead bearing capacity of piles will release more knowledge for improving and maintaining wooden pile foundations. This allows more structures to be preserved and will increase confidence in these wooden foundation structures, which will result in more new construction. In terms of carbon sequestration, wooden foundations can act as a large sink of CO_2. In order to estimate its size, mean values of pile length (variation between 2 and 20 m), pile diameter (variation 12 and 30 cm) and a taper of 7.5 mm/m (NEN 5491) were used (Klaassen 2014). Without loss of CO_2 by decay, the Dutch foundation piles store approximately 5.3 million tons of CO_2 (calculation of carbon content in wood according to EN 16449). Assuming that all piles originate from sustainably managed forests, their CO_2 footprint is nearly zero. If a mean weak peel of 2.65 cm (Klaassen 2014) is taken into account the total storage still count for 3.3 million ton of captured CO_2. It is unclear if the CO_2 emission of degraded wood is captured in the soil or released to the atmosphere. If a revival of the use of wooden foundation can be initiated this sink increases and can be doubled or more. Assuming that these new piles will also be sustainably produced. In order to reach this situation, it is important to restore trust in the use of wooden foundation and reliable measuring methods are crucial to reach this goal.

SUMMARY AND CONCLUSIONS

On the basis of 1314 field measurements and core samples from foundation piles all over the Netherlands, the reliability of impact-hammer measurements is investigated. Impact-hammer measurements form the basis of the load-bearing-capacity calculations and of the stability of wooden foundations, and are therefore crucial for maintenance of these constructions. Our analyses showed that the penetration measurements are not reliable for wooden foundations under water constructions. Under buildings the measurements with increasing decay give an increasing underestimation of the non-load-bearing outer peel of the foundation piles. Therefore, adaptations in the existing guideline for judging the quality of wooden foundation are suggested. These adaptations are important for a better maintenance of the construction as a whole and can be a stimulation for the use of wood in new foundations. Old and new foundations can play a significant role in carbon sequestration.

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