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Historical Wooden Pile Foundations in Amsterdam: An Integrated Approach for the Estimation of Structural Performance and Residual Service Life

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Abstract. Timber pile foundations are widespread in many areas around Europe and North-America. Especially in areas with weak soils, timber pile foundations have been a very good and economic solution. That foundations can be up to 500 years in service in cities like Venice, Amsterdam, Boston and many others. Degradation of the piles may occur over time which may influence considerably the residual service life. Residual service life is depending both on the time-to-failure behavior of wood, as well as the dead and live loads on the piles below buildings, quay walls and bridges. A good assessment method is required, as closing down infrastructure (bridges, quays) or buildings because of failing foundations causes considerable economical damage. In recent years in the cities of Rotterdam and Amsterdam failures occurs on such foundations. A comprehensive research program has been set up, that includes the development of underwater microdrilling equipment, so that an indication of the wood quality can be done in situ, without the need of bringing samples to the laboratory. The development of this microdrilling has been paired with a large scale campaign to determine the strength of new and recovered piles. In a next step, by applying a non-linear damage accumulation model, the remaining service life is estimated as a function of the decay level and decay rate, as well as the expected mechanical loads.

Keywords: timber · foundation piles · service life · non-linear modelling · micro-drilling · bacteria decay

1 Introduction

Timber as a structural material may be found in many buildings and structures around Europe, with a current age of sometimes more than 500 years. Already in the Roman era the foundations were made with timber, both in form of horizontal beams under brick walls and as vertical piles for deeper foundations. Timber can be found in foundations of famous heritage buildings such as the Royal Palace in Amsterdam, the Netherlands and bridges (Fig. 1). Timber foundations are in these cases true foundations of cultural

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heritage and therefore their economic and technical importance is large. A complication in the assessment is that pile foundations are difficult to inspect and maintain, and yet many thousands of buildings, bridges and quay walls depend on them.

Fig. 1. Bridge on wooden pile foundation in Amsterdam/Netherlands

Irrespectively of the applications, the assessment of these structures for their safety and serviceability requires models that take into account the history of the structure. Not only the timber species, also the loads on the structure over history and expected future loads are important in the assessment procedure. Although most of the timber foundations known worldwide are in very good condition, assessments of the quality and the load carrying capacity often have to be made.

There are various design and maintenance aspects that have to be taken care off, in order to assess the quality of the foundation. This deals with assessment of the current state of the foundation from both a mechanical as well as a durability point of view.

For that, a comprehensive research program has been set up, that includes the development of underwater microdrilling equipment, so that an indication of the wood quality can be obtained in situ by a trained diver, without the need of bringing samples to a laboratory. To determine the current loadbearing capacity in compression and stiffness of the piles, recovered piles have been analyzed using microscopy, FTIR, CT-scanning and longitudinal vibration, before full scale mechanical testing was carried out. These methods are not discussed further in this paper. The data obtained from these tests have been paired with micro-drilling readings, in order to estimate the cross sectional material strength properties of a partially degraded pile, as well as the remaining load carrying capacity of a full pile. A non-linear damage approach for the estimate of the remaining structural capacity and service life, will integrate biological degradation processes based on damage model.

2 Methodology and Material

2.1 Timber Foundation Piles

In order to develop a computational model for estimating the remaining service life, relevant parameters have to be identified and reliable input data have to be obtained.

Wooden foundation piles which have been investigated originated from bridges in Amsterdam. They vary between 150 mm and 280 mm in diameter and between 10 m and

14 m in length. The piles are normally tapered. The wood species is mainly spruce (*Picea abies* (L.) H. Karst). In total, 60 complete piles were retrieved from different locations. The piles under the bridges are below the water table, surrounded approximately by 1.5 m of free water before entering the saturated soil (more than 85% of the pile) where the pile is not accessible for inspection. The physical and mechanical properties of the pile such as density and compression strength vary along the height and the cross-section, because of the natural variability of the stem of the tree (Fig. 2). In a sound foundation pile, higher mechanical/physical properties can be expected at the top (bottom of the tree) and lower properties at the bottom of the pile [1]. This is because of the natural growth of a tree. The foundation piles are placed in the soil by turning the tree stem upside down (Fig. 2).

The mechanical properties of a sound cross-section depend on the diameter and the natural growth pattern with regard to the area of mature wood, juvenile wood and the pith. Heartwood and sapwood together is named mature wood (Fig. 3).

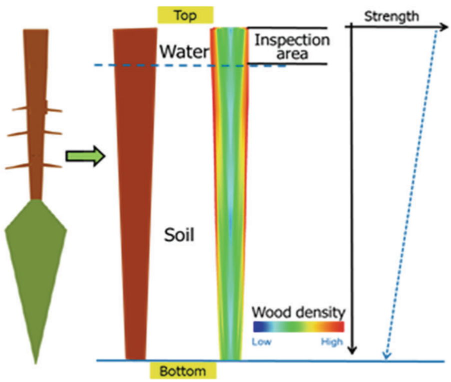

Fig. 2. Sketch of a sound tree stem as foundation pile upside down; possible density development along the length of the pile (colored picture); possible strength development along the length; accessible inspection zone at the top of the piles.

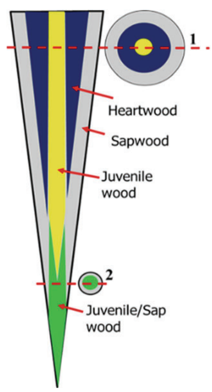

Fig. 3. Sketch of 2 cross sections (circular areas 1 and 2) of the pile at different heights of the pile.

In general, juvenile wood has lower mechanical and durability properties and densities compared to mature wood [2–4], resulting in lower load-bearing capacity of the pile. At the top of the pile cross-section, the portion of juvenile wood is smaller than at the bottom (Fig. 3). In addition, the whorls of the tree are also still present in the pile, and these are potentially areas with lower than expected compression strength, independent of decay.

2.2 Service Life Model

The prediction of the service life is extremely complicated, as it depends on a great number of influencing factors. As it is a time-dependent issue, the estimation of the (remaining) service life involves the assessment of the behaviour of wood under a mixture of loadings, which can be of mechanical, physical, biological and/or chemical in nature. The service life of structures can be determined using several approaches that have been classified by the Joint Committee on Structural Safety (JCSS). The most complicated approaches comprise of so-called level III calculations, where for each variable of the structure (e.g. strength, stiffness, durability and loads), the actual or an estimated statistical distribution of the parameter is used. For wood, such distributions are often unknown or have a high uncertainty level. The consequences of these uncertainties are that extremely high safety levels are aimed for, which often are not supported by practical evidence from existing structures.

Independent of the calculation level, reliability aspects have to be considered. In reality, both the resistance and the solicitation are varying in time and the limit state function can be written as Eq. 1 [5–7]:

$$Z(t) = R(t) - S(t) \tag{1}$$

where R = resistance (strength/stiffness), S = solicitation (external load).

Basically, strength and loads have to be far enough away from each other in order to avoid structural failures during the lifetime of the structure (Fig. 4). If the strength and loads are modelled as standard normal distributions, then Fig. 5 gives insight in the probability of failure. The greater the overlap between the two curves, the higher the probability of failure.

The strength R of the piles are dependent on.

- the wood species: spruce, pine
- the quality of the wood: strength grade
- the environmental conditions: in water, in soil
- the aging level: degradation by microorganisms, erosion
- the external load over time: dead load, traffic load
- the time in service.

An important feature is that timber has a time-dependent strength that is influenced by the load level. Consequently, the probability functions for the resistance and the solicitation are no longer independent from each other. This is expressed in the resistance

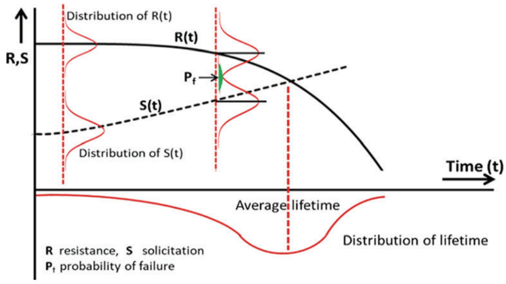

Fig. 4. Lifetime distribution of structures

function Z(t) = R(s(t),t) − S(t) [8]. A modified damage model is used considering degradation parameters that describe the time-dependent stress/strength ratio. This changes the standard exponential damage equation, as shown Eq. 2 [8–10]:

$$\frac{d\alpha}{dt} = exp\left(-a + b\frac{\sigma(t)}{f(t, T, \omega, \lambda, \mu \ldots\ldots)}\right) \quad (2)$$

where the strength of the timber element/pile $f(t, T, \omega, \lambda, \mu \ldots)$ depends on time in service and different aging parameters such as temperature (T), moisture content (ω) and λ describes the ratio of the cross section that is degraded as compared to the non-degraded section, whereas parameter μ describes the strength of degraded material, relative to non-degraded material. The damage α starts at 0 for a new structure (t = 0) and becomes 1 at the time of failure T_f, so 1−α is considered the residual strength.

In Fig. 5 an example is given for Service life calculation taking in consideration dead load, assumed live loads and biological decay with associated decay rates [8]. It can be clearly observed that the residual carrying capacity decreases over time while the accumulated damage increases (relative strength reduces).

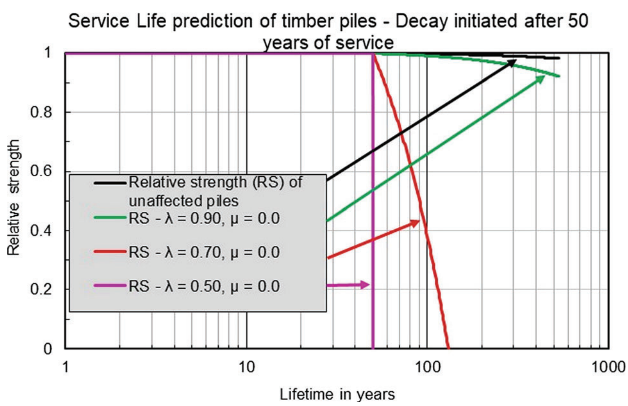

Fig. 5. Lifetime prediction of timber piles. Scenario: Biological decay initiated after 50 years, decayed wood has 0% strength of non-decayed wood, Cross section reduced by 10% (green line), 30% (red line) and 50% (pink line) [8]

In this example, it is assumed that the remaining strength of decayed wood is zero, which is a safe approximation, so $\mu = 0$. However, if that would not be the case, then the value of μ can be easily adapted in the model, and the remaining service life will automatically increase. By the way the model is formulated (Eq. 2), the stress on the remaining sound cross section will automatically increase when the decay progresses, so for each period Δt, the damage increase $\Delta\alpha$ will increase a bit more as the stress ratio $\sigma(t)/f(t)$ increases with the ageing process, see Fig. 6. From the analysis it follows that if half of the original cross section is degraded at $t = 50$ years, the residual lifetime drops to 0 almost instantly, but if it is reduced by 30% (so 70% remaining), the residual lifetime is still considerable with almost 100 years before structural failure. This shows that time to failure processes are really sensible for the load level on the one hand, directly influencing the remaining service life. These processes are logarithmic on the time-scale. For foundations the main load component is dead load. Variable loads from traffic are also present, but over the history of 100–300 years are less relevant. More important is to get an accurate estimate of the constant dead load over the pile's history. In that case the damage Eq. (2) is more straightforward to solve regarding the applied load. The failure process is then governed for long term static loading, without having the complexities of random variable loading. The assessment of parameters affecting the load bearing capacity is however, complex. Measurable assessment parameters are very limited, since only a very small 'window', approx. 10% of the whole pile at the top, is available for the assessment, and from this assessment, an estimate for the entire pile must be made.

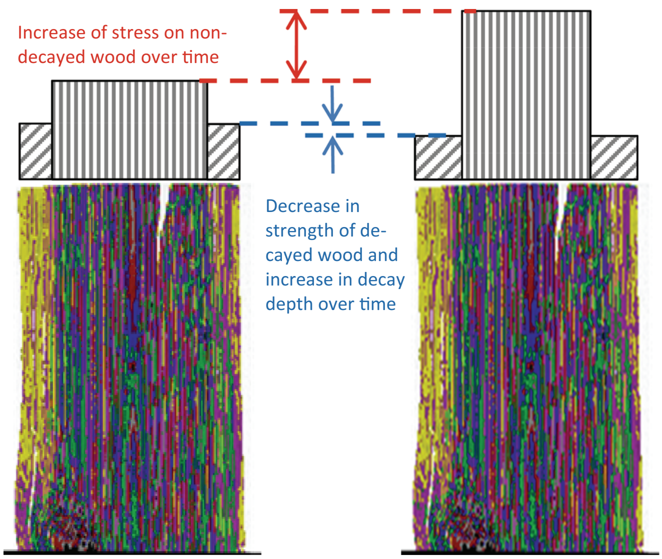

Fig. 6. Effect of stress redistribution over the pile cross section as a result of increasing decay, CT scan of a decayed pile section in longitudinal direction, low density: yellow, high density: blue)

Therefore a ‘pile-’model has been developed to estimate the load bearing capacity in compression along the whole pile, using input data retrieved from the measurements at the ‘assessment window’ for inspection of the top of the foundation pile and of course data from the load-history and installation period/situation. Measurements have been taken from parameters that can be correlated to the strength properties along the pile length. To find these correlations, an extensive test campaign has been set up at the TU Delft, the Netherlands, together with the municipality of Amsterdam.

From the cross-section of a pile different tissue areas can be district such as decayed wood caused by microorganisms, sapwood, heartwood, juvenile wood, compression/reaction- wood and early- and latewood within the growth rings. Furthermore, the position of the pith and the number of annual rings can be determined. These parameters have been investigated and correlated with the stiffness and load carrying compression capacity along the whole pile. The functions have been defined as followed:

Decay area of the pile cross section along the pile =	f (decay area of the cross section at the top, sapwood portion at the top of the pile, tapering of the pile, pile geometry, position of the pile cross section)
Wood quality (grade) =	f (at the top of the pile: wood density, juvenile area, knot area/dimension, cracks)
Load carrying capacity in compression of the pile at the relevant cross section =	f (at the relevant cross section: wood quality, decay area, load history)
Axial stiffness =	f (at the relevant cross section: wood quality, decay area, juvenile area, heartwood, sapwood, load history)

2.3 Degradation

The investigated foundation piles were 100 to 300 years in service under the bridges. The piles are subject to an aging process over time, which has both biological and mechanical causes. From our research, it appears that biological deterioration is mainly caused by bacteria and barely by soft rot fungi. As far is known to the authors, deterioration of wooden foundation piles under water by bacteria was indicated for the first time about 90 years ago by Varossieau in old foundations in Rotterdam, the Netherlands [11]. The severity and the development stages of the decay are shown in Fig. 7.

The decay by bacteria propagates over time from the outside (high concentration of bacteria) to the inside of the pile (Fig. 8). In general, sapwood is the part of the stem cross-section with the least resistance to microorganisms [12]. Highly decayed parts have a low density and less decayed vice versa (Fig. 4). From the CT (computer tomography) scans in Fig. 4 it can be observed that the decay is not equally distributed along the height of the pile. In the cross-section at the top of the pile (large diameter) the width of the decayed ring is smaller than at the bottom (small diameter). It can be assumed that the decayed area over the cross-section is mostly sapwood. The decay rate is often expressed in term of loss of mass per time. However, loss of mass is different from loss of strength.

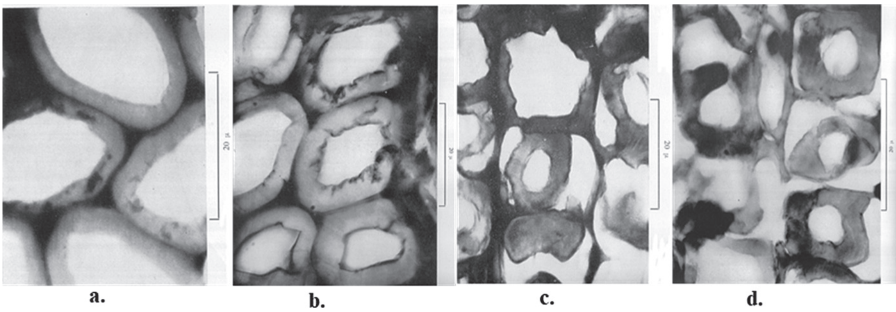

Fig. 7. a. Onset of bacterial decay in the cell wall, b. S3 layer decayed and S2 layer affected, c. Cell wall collapse visible, d. Cells completely decayed and collapsed [11].

Often, a small percentage of mass loss is causing a considerable loss in strength [13], does not concern the engineer when assessing an existing structure. An engineer needs values for strength and stiffness of decayed timber, and he needs information about the distribution of decay in a cross section.

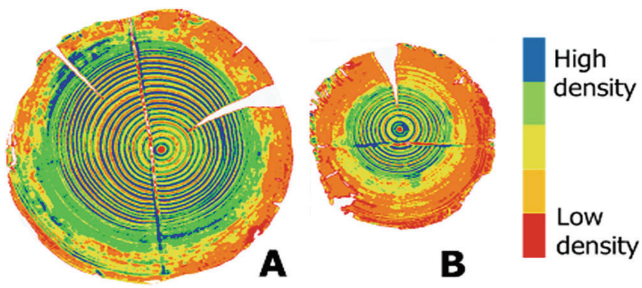

Fig. 8. CT scan of a pile cross-section at the top (A) and bottom (B) of the pile. Low density (orange) at the outer circumference indicates decay, green color at the inside means high density.

The piles are primarily loaded in compression by dead weight of the upper structure and, especially during the last 100 years, by increased traffic loads. Mechanical loads can lead to creep and ultimately to failure. In this context, historical loads are essential to estimate the time to failure. Experience shows that the relative load level can be around the 50% load level, indicating that the long term strength of the wood may have been reached after being in service for one or more centuries service for one or more centuries. The load bearing capacity of the pile depends mainly on the decayed cross-section area, the not decayed heartwood and the juvenile area.

2.4 Test Campaign

Full Scale Pile Testing. In order to understand the influence of long term loading in compression in combination with the effects of biological decay, existing piles are being retrieved from foundations of old bridges in the city of Amsterdam/Netherlands. Mechanical testing on full scale pile sections is performed to determine (residual) compression strength and the static modulus of elasticity. For that, extracted piles are divided in three pieces (head, middle part and tail), debarked and prepared for the compression test.

Before testing, the piles are submerged to reach the wet condition for the compression test, which means a moisture content higher than 70%. Figure 9 shows the compression test set-up with pile sections up to 1800 mm length. LVDT sensors are place between the plate heads and on the piles themselevs to determine the static modulus of elasticity. In order to obtain both global and local strength and stiffness information, LVDT measurement devices are placed over the length of the section, over the section with the largest knots (location of whorls) or the section that is expected to fail in compression first. Because of eccentricities of knots in the cross section, failure may concentrate on one side of the pile only. Apart from compression wrinkles, longitudinal cracks also develop at later stages.

Fig. 9. a. Set-up for compression tests, b. LVDTs are mounted around knots.

With these test results a possible relation between load carrying capacity of the pile section at the top and the other parts of the pile can be investigated.

Microdrilling in-situ. Depending on the technology, in-situ measurements can be done, or material from the limited inspection area under water at the top of the pile can be brought to a laboratory for more in-depth analysis. Taken samples can be analysed in the laboratory for the mechanical properties and type and state of degradation. Taking wood samples under water is very costly and gives information only at one spot of the pile. Common practice is to taken out a wood sample of half radius of the pile with diameter of approximately 10 mm with an increment drill.

One of a few semi-non-destructive and in-situ methods that is available for wood inspection is micro-drilling, such as IML-RESI PD. An IML-Resi for underwater use (hereinafter RPD), is currently developed and in a trial stage on timber foundation piles under bridges and quay walls in Amsterdam/Netherlands (Fig. 10.). In [14] an extensive analysis of microdrilling resistance and some of the pros and cons of the technology have been presented. The drill is equipped with a needle, which is injected through the cross section of the wooden pile in question (Fig. 11). As the needle passes through the material, the amount of energy needed to drive the needle through the medium is recorded/captured as drilling resistance. The needle is 3mm diameter at a tip and 1.5 mm diameter at its shaft.

Fig. 10. RPD deployment underwater by a diver.

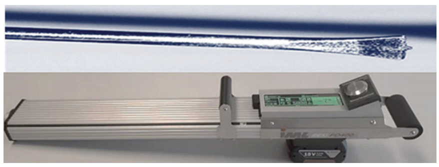

Fig. 11. Microdrill (upper picture), drilling device below.

The spectrum of the microdrilling measurements along half of the cross-section of the piles show annual ring profiles, with maximum amplitudes marking latewood and minimum amplitudes pointing towards earlywood (Fig. 12). There are also extreme maximums and minimums. Those with higher values can be associated with the knots and other high-density anatomical variations, and lower value extremes pointing towards piths and cracks. Figure 12 shows a not evenly decayed cross-section of a pile where 2 microdrillings were applied at different locations. The blue line (drilling amplitude) in Fig. 12. a. shows a considerable low density area at the outer layer of pile which is recognised as decay, in comparison to the red line shows a higher density which is recognised as less decayed. Both lines are confirmed by CT scans of the cross-section where high and low density areas can be identified. The blue and green colour indicates lower densities. Lower density areas towards to the pith of the pile indicates the juvenile wood and not decayed by bacteria.

The degree of decay is defined by the relative density differences compared to sound wood, which can be assumed in the centre part of the pile cross-section. For very severe decay areas the term ‘soft shell’ has been introduced. In Fig. 13. a microdrilling is carried out along the whole diameter of the pile. A ‘soft shell’ of around 18 mm is indicated from the outside towards the centre of the pile. Also here, the area of the juvenile wood can be identified.

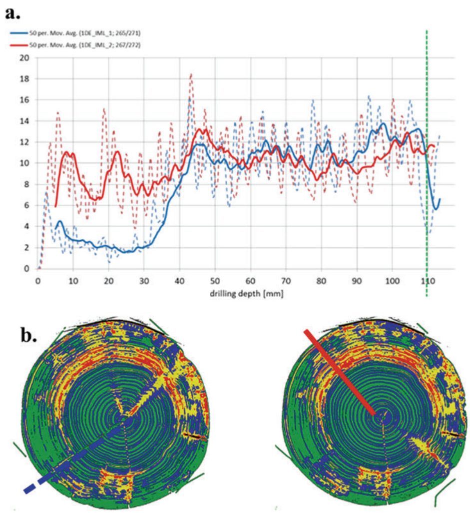

Fig. 12. a. microdrill measurements over half of the cross-section of the pile a 2 different spots of the circumference, b. CT scans of the cross-section confirming the density map (high density: red, low density: green).

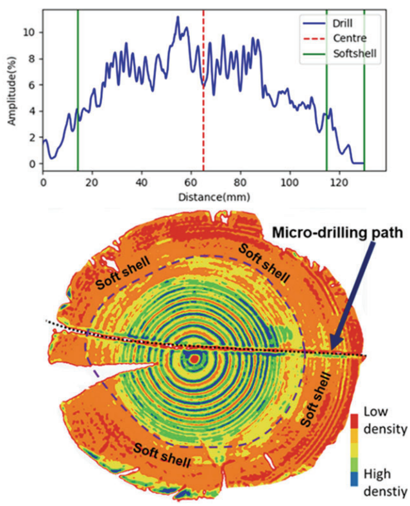

Fig. 13. Microdrill measurement along the whole diameter of the pile with a severe decay (soft shell) at both sides: left and right, blue line in the graph is the drilling amplitude.

3 Discussion and Outlook

A service life model is as reliable as the reliability of the input data. The unique pile material aged between 100 and 300 years old and different degradation levels allows developing a reliable service life prediction model for the timber pile foundations for the population of Amsterdam/Netherlands. For other populations of timber pile foundations, the soil conditions and also the external loads can be different so that the wood properties along the pile height have changed in a different manner.

Even if the inspection area at the pile top in-situ is very restricted, with the 'new' development of the RPD for under water use, relevant information about the state of the piles can be obtained. With these data a 'pile model' has been developed to determine the state of the wood along the whole pile length with regard to the decay, sapwood, juvenile wood, density and pile shape (taper). The 'soft shell', identified through micro-drilling at the top of the piles, can have a considerable influence on the remaining load carrying capacity and the average modulus of elasticity (MOE) of the pile cross section as shown Fig. 13. Also, the overall specific gravity shows a high correlation with the MOE ($R^2 = 0.70$) (Fig. 14).

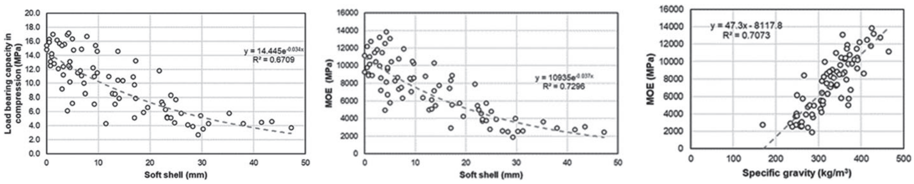

Fig. 14. Correlation between soft shell width and load carrying capacity in compression (left graphic) and the MOE (middle graphic) and the correlation between specific gravity and MOE (right graphic).

The project is still ongoing and further parameters will be analyzed in depth so that the model can be completed in the near future. Items that are under consideration are the development of the decay over time, delay times with respect to decay of sapwood and heartwood, wood species, as well as the questions whether the residual strength of decayed wood is such that load carrying capacity can be attributed to that. In addition, so far the focus has been on piles that are predominantly loaded in compression. However, applications of piles in quay walls are loaded in a combination of compression and bending, which requires a more elaborated approach.

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