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Renovation of Buildings with Timber Pile Foundations in Europe

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Abstract

The maintenance and renovation of buildings with wooden pile foundations is an important part of European real estate management. As Europe turns its focus on greener and more sustainable methods in construction, renovation and reuse of wooden foundations can play a role in reducing unnecessary constructions. The thesis aims to serve as a guide for homeowners and facility managers (FMs) to make informed decisions when it comes to when, how and why wooden foundations under a building should be assessed, preserved and renovated. To achieve this, literature review is conducted. Diagrams and flowcharts are used to visualize the knowledge about wooden foundations that the owner of the FM should know. A case study and a cost calculation of it is also conducted.

Firstly, the topics which the owners ought to know are written in this report. These include the history, types and current situation of wooden pile foundations in Europe, how they get damaged and their significance. The assessment and restoration methods are reviewed; their benefits and challenges are discussed. Some innovative maintenance and repair techniques are also investigated. A case study on the Berliner Schloss (Berlin Palace) is also conducted. An alternative proposal for the foundation of the Humboldt Forum is proposed and the cost estimation is carried out for the alternative calculations.

The renovation and maintenance of the wooden pile foundation are important to the overall health, stability and safety, serviceability, maintenance, operation and value of the building. Owners can face both internal and external difficulties, like the lack of knowledge and experience, government funding, and external threats. Innovative/sustainable renovation and maintenance can be achieved by a groundwater monitoring and replenishment system and perhaps the use of eco-friendly composites in wood repair. A flowchart for decision making for the owner or FM is also given.

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List of Abbreviations

AD	*anno Domini* or the Common Era
BC	before Christ or Before the Common Era
COVID-19	Coronavirus disease 2019
DATU	Database on Turku Underpinning Projects[1]
DDR	former East Germany, the German Democratic Republic (*Deutsche Demokratische Republik*)
DIN	German Institute for Standardisation (*Deutsches Institut für Normung*)
EM	electromagnetic
EN	European Standard (*Europäische Norm*)
EU	European Union
FM	facility manager
FMs	facility managers
GIS	Geographic Information System
GPR	Ground Penetrating Radar
NDT	non-destructive testing
PE	polyethylene
UK	United Kingdom of Great Britain and Northern Ireland
WPCs	wood-polymer composites
WPCNs	wood/polymer/clay nanocomposites
WWII	World War II or the Second World War

[1] See Footnote 6 on page **Error! Bookmark not defined.**.

1. Introduction

Renovations are a very important goal of the European Union (EU) in the future, as highlighted in the European Green Deal published in 2019. In this deal, the EU wants to promote the renovation of public and private buildings. Their aim is to at least double the current rates of the renovation of public and private buildings. (EUROPEAN COMMISSION, 2019) In other words, renovation in buildings will play a key role in the sustainable development of tomorrow's Europe.

A healthy foundation supports a healthy building. One of the challenges faced by the owners in the maintenance of a building (especially historical buildings) in Europe is the preservation and renovation of timber piles. The purpose of this paper is to discuss the repairing of timber foundations of historical buildings in Europe from the owner's or facility manager's perspective. Research questions such as follows will be investigated:

- Are owners willing to preserve these buildings with failing foundations? If not, why not?
- What are the difficulties in the renovation of historical buildings with wooden pile foundations?
- What are the benefits of preserving or renovating these piles?
- What innovative/sustainable ways are there to renovate these piles?

The foundation of a building is often unseen and does not receive enough attention. However, a faulty foundation can cause a myriad of problems ranging from serviceability problems of the building to financial problems for the owner. In Europe, many foundations are wooden pile foundations, and a poorly maintained foundation can cause problems like settlement and cracks in the building. This thesis aims to give the owner and FM the knowledge they need to manage a building with a wooden pile foundation and to manage any potential renovation project therewith.

The benefits of preserving wooden pile foundations are highlighted from both the owner's point of view and society's point of view, since inherently the maintaining a building, as opposed to building a new foundation, is a more sustainable way towards real estate management. Finally, the future of wooden pile preservation and its opportunities and challenges are investigated.

2. Methods

Research questions are answered by conducting literature review and comparison. Diagrams are drawn to visualize the knowledge that an owner or FM should know about the historical wooden foundations. A flowchart is proposed to help owners and FM maintain an old building that may be supported by a wooden foundation. GIS is used to map the known cases of wooden foundations supporting buildings against the maps of coarse fragment distribution in Europe to study the effect of topsoil type on the choice of wooden foundations.

A case study is conducted on the Berlin Palace to take a deeper look into the history of the renovation of the wooden foundation of the building. Both qualitative and quantitative methods are used: 1) the history and condition of the wooden foundation are studied by reviewing existing literature, 2) an alternative renovation proposal is suggested in the report and 3) a cost estimation is conducted on the alternative proposal and that is compared with the cost of the actual construction carried out.

3. Knowledge Owners Ought to Obtain

A lot of the topics regarding the maintenance of wooden piles have already been covered by previous literature. In this section, these topics are summarized in order to increase the owner's and facility manager's knowledge from the maintenance and renovation point of view. The topics range from the history and purpose of wooden piles to the maintenance techniques and the life cycle of wooden piles. At the end of each topic, a recommendation or a key-take-away note is given to the owners or facility managers (FMs).

3.1 History of Wooden Pile Foundations

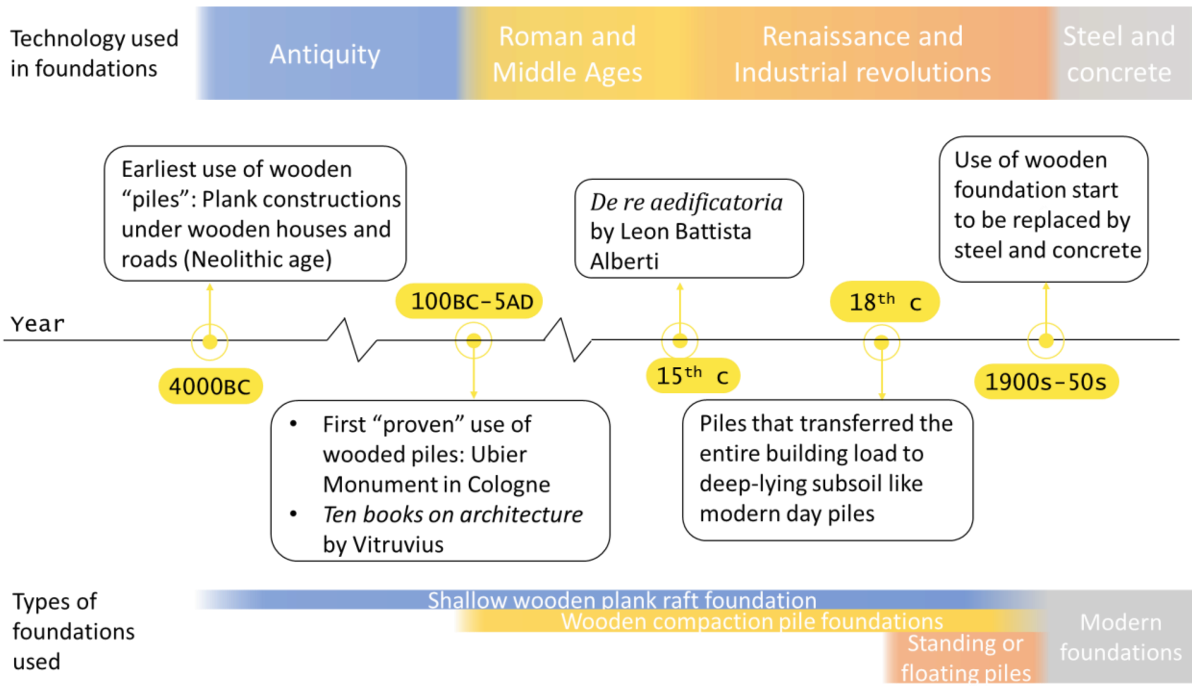

Figure 1 Timeline of use of wooden piles in European history

The earliest use of wooden piles was found in the plank constructions under wooden houses and roads in Central European regions during the late Neolithic age which was about 4000BC. (Jovanovic, 2002) This marks the beginning of the use of wooden piles in Europe. Ancient civilizations settled near river valleys and other bodies of water. However, with bodies of water come floods, high groundwater tables, soils that are geologically young, silty, clayey, or organic soils. The soils are therefore soft and not unstable and not suitable for shallow foundations. Wood planks were used to reinforce weak soil layers underneath buildings and bridges and were common throughout Europe, according to archaeological records. During this period, antiquity technology was used to construct wooden foundations.(Jovanovic, 2002; Ulitskii, 1995) However, the understanding of these constructions as “piles” is debatable, because while the wood used in the foundation certainly did increase the bearing capacity and served the purpose, the building load is not entirely transferred to the bottom layer of the soil like modern-day piles and there were written design or calculations for these “piles”.

The first proven use of wooden foundation under stone building was found in Central Europe during Roman antiquity dating back to 100BC. It was the Ubier Monument in the city of Cologne in modern-day Germany. (Jovanovic, 2002) The Ubier Monument marks the edge of the Roman colony. Its foundations were laid on the old Rhine flood plain, which was 6 meters below the street level during Roman times. A grid of oak piles was used in underlying gravel to support a “Pile cap” built from “opus caementitium”[2]. A tower made of massive tuff blocks was built on top of this. The wood in the pile grid was analyzed and the construction was dated to AD 4/5. (Römisch-Germanisches Museum, 2014)

From the year 33 to 22 BC, *The Ten Books on Architecture*, was written by the Roman architect Marcus Vitruvius Pollio, or simply Vitruvius. This was the first written record of the use of wooden foundations. Vitruvius recommended the use of prepared oak piles or alder or olive wood piles that have been previously thermally treated, in order to achieve a strong founding. Simple machines with mechanics of winches and blocks were described to be used to install these wooden piles. Also, the word “pilius” is first used to describe piles during this period. (Jovanovic, 2002; Ulitskii, 1995)

These two events were monumental to the usage of wooden piles in European history, and they marked the beginning of the use of Roman technology. The same Roman technology continued to be used for the foundation (and even for architecture in general) up until 15th Century or even 18th Century. (Jovanovic, 2002; Ulitskii, 1995) It was not until mid-15th Century that another book on architecture and foundations was written, *De re aedificatoria*, written by Italian author Leon Battista

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[2] This term is sometimes referred to as “concrete work”, due to its cement like nature. The technique used here is simply mixing aggregate and lime mortar as a binder.(Rossi & Russo, 2016)

Alberti. The *Ten Books* were modelled after Vitruvius' *The Ten Books on Architecture*, and in it, the understanding of piles was increased. For the first time in history, the relationship between building loading and pile dimensions is drawn. (Jovanovic, 2002)

During the renaissance period, more and more texts were written about foundations. The understanding of both pile foundations and soil mechanics continued to increase. Near the end of the renaissance, the length of piles gradually increased and surpassed the limit of 6 meters. In the mid-18th century, the piles that transfer their entire building loading was into the deep more stable load-bearing subsoil layer, like the modern-day piles, were invented and implemented for the first time. (Jovanovic, 2002; Ulitskii, 1995)

After the renaissance, studies into pile installation and understanding of soil mechanics exploded. Fuelled by the industrial revolutions, new pile installation techniques and tests for bearing capacity of clayey soil, like the metal auger tests were invented and recommendations on how to make wooden pile foundation safer and more reliable were made. The connection between the lowering of the groundwater table and the loss of bearing capacity in wooden pile foundations was also made during this period. These new technologies and understanding of piles laid the foundation of our modern understanding of pile foundation engineering and made the modern-day reinforced concrete piles and steel piles possible. (Jovanovic, 2002; Ulitskii, 1995)

However, with the rise of modern piles also came the inevitable replacement of wooden foundations at beginning of the 20th century in Europe. Wooden piles continued to be used up until the mid-20th century in Europe. (Klaassen & Creemers, 2012) Compared to wooden piles, modern-day piles can be designed to much deeper lengths that are required to transfer building loading to much more stable soil or even bedrock layers, which makes modern-day skyscrapers possible. The use of wooden piles was side-lined but still found uses in special applications and pockets of Europe. For example, in a 1928 publication, it is recommended the wooden piles be used for buildings on marshes and bogs because the acidity of the water is known to cause damage to the lime and cement mortar in the concrete. (Schultze, 1928) In Turku, Finland, wooden piles continued to be used as building foundations until the 1970s.(SSAB, 2020)

The development and understanding of wooden piles throughout history are truly foundational towards today's tall buildings and skyscrapers. Without the history of wooden piles, none of them would have been possible.

For the owners and facility manager of an old building, the take-away is as follows:

- Wooden pile foundations have been used in Europe throughout history.
- Modern-day concrete/ steel piles did not start to become popular until the early 20th Century. Wooden piles were used exclusively before this period and continued to be used up until the 1950s.
- Wooden piles are used in soft, clayey, and unstable soils.
- Wooden piles are associated with high groundwater tables.
- Wooden piles are found near bodies of water (rivers, lakes, coasts).

If an owner has a building that fulfils one or more criteria of these points, it is possible or likely that the building in question is with a wooden pile foundation and would require maintenance and special attention.

3.2 Types and Mechanisms of Wooden Foundations

As the owner or facility manager, it is important to understand the foundation, on which the building sits. These have implications on the building condition evaluation techniques, maintenance and repair techniques and their costs. Hence it is important for owners and FMs to understand. For the purpose of understanding historical wooden foundations, there are two types of foundation, according to the difference in mechanisms.

- Shallow foundation, or spread foundation
- Deep foundation, or pile foundation

Shallow foundation refers to the building foundation that carries the building load to soil near the ground surface and not to the deep subsoil layer. Shallow foundations can include structures in the shape of pads, strips, and rafts. (EN 1997-1, 2004) Modern-day shallow foundations are usually made of reinforced concrete. Historical foundations, however, are made of layers of wooden planks in a grid or piles lying next to one another horizontally. The diameter of the piles is about 30 – 40 cm and they are installed at a depth of about 2 – 3 m below the ground surface. (Jovanovic, 2002; KÖPPL, 2012; Wigger, 2000)

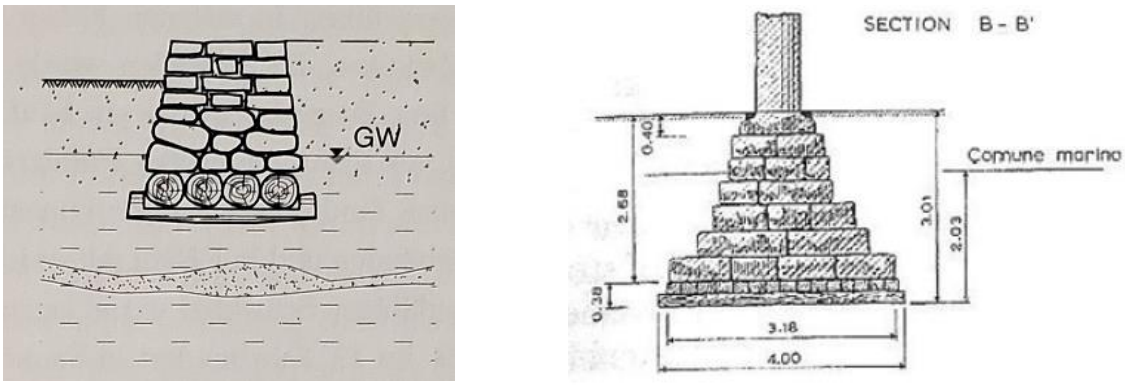


Figure 2 Examples of wooden shallow foundations, left: Schwellengrüdung (Jovanovic, 2002)**; right: wooden plank foundation of Palazzo Ducale by Malvezzi (1874)** (Ceccato, 2011)

On top of this sits the stonemasonry. This type of construction is called *Schwellengründung* in German and was most commonly found in buildings with a foundation built in the Middle Ages. This construction method is also used in lighter and simpler buildings and when the founding level is thick, soft soil layers, where the load-bearing layers were so deep that they could not be reached by piles (e.g. in 19th Century Saint Petersburg). Only after the Middle Ages were real pile foundations with longer and stronger piles employed as mentioned in the previous section. (Jovanovic, 2002)

Deep foundations are understood today as the type of foundation which transfers the building load to the subsoil further down than a spread foundation. The pile in this case is used as a vertical element to support the building above, as opposed to the piles used horizontally in wooden shallow foundations. In modern days, these vertical piles are made of reinforced concrete or steel, and they are installed by "driving, jacking, screwing or boring with or without grouting". In deep foundations, the building load is carried by a layer of soil at the toes of the piles through the entire pile (end-bearing piles) or they are carried by the soil surrounding the pile through skin friction (floating piles). They can also be tension piles and transversely loaded piles. According to DIN 4026, driven piles should be at least 5 m embedded into the load-bearing soil layer. (Bowles, 1996; EN 1997-1, 2004)

In historical wooden foundations, especially since the 18th Century, these two types of piles are known as:

- Standing pile foundation (or *stehende Pfahlgründung*): piles that penetrate through soft soil layers and are extended into a firmer layer of soil and carried the loads into the firmer layer mainly with pile toe areas. These piles are supported at the end of the pile toe as well as by the skin friction. This corresponds to today's end-bearing piles.
- Floating pile foundation (or schwimmende Pfahlgründung): piles that penetrate the soft soil layers, but the toes did not end in a firmer layer of soil and carried the loads mainly by skin friction of the piles. This corresponds to today's friction piles.

  (Döhner & Antkowiak, 2013; Jovanovic, 2002)

Both the standing piles and the floating piles have to be deep enough to penetrate into the lower soil layers. Longer pile foundations over 3.00 m were only possible when longer piles into the ground by ramming or driving. Until the invention of the steam-powered pile driver, installation of piles was not always easy and was done by primitive pile drivers, where a weight is dropped from a height onto the pile to drive it into the ground. Examples of pure deep foundations can only be found in the recent history 18th to 20th Centuries. (Döhner & Antkowiak, 2013; Jovanovic, 2002; Wigger, 2000)

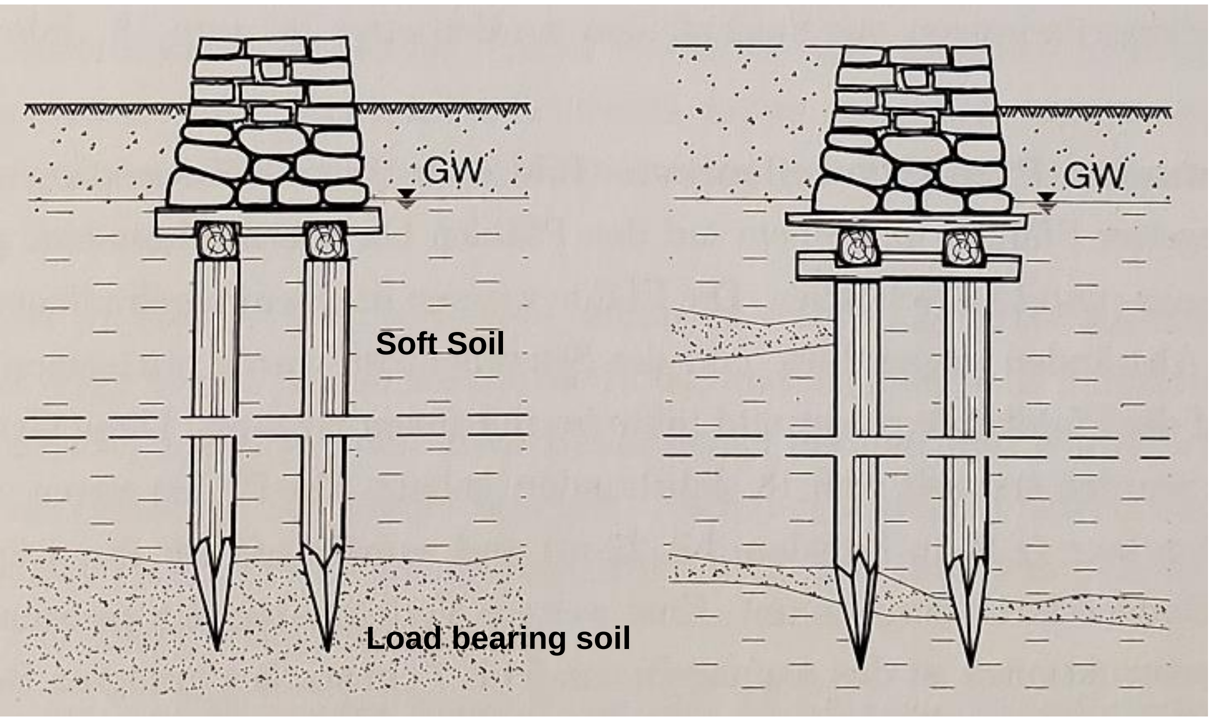
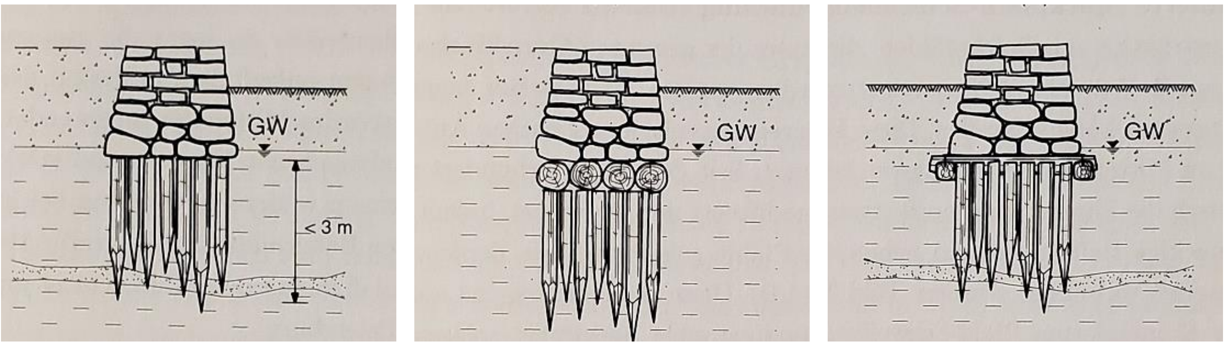


Figure 3 Schematic diagrams of deep foundations (Jovanovic, 2002)

For the most part of history, however, a special type of wooden foundation, called *Spickpfahlgründung*[3] in German and *pali di costipamento* in Italian, was most commonly used. (KÖPPL, 2012; Wigger, 2000) These wooden compaction piles are less than 3 m long and 10 – 20 cm in diameter. They are short, sharpened at the tip and driven vertically into the ground, closely packed together or at small intervals, regularly rows or simply randomly scattered. The piles do not reach a lower layer of firmer soil. On top of it sits the foundation masonry. The pile is usually found 30 cm below the lower known groundwater level, since it has been known since the ancient time that this is the only method back then to prevent the rotting of wooden piles in soil. This type of wooden foundation is most common in historical buildings and was used from Roman antiquity to the mid-18th Century and was used even well into the beginning of the 20th Century. (Jovanovic, 2002) (Figure 4a).



a) b) c)

Figure 4 Schematic Diagrams of Wooden Compaction Pile Foundations, a) Pure wooden compaction piles underneath masonry footing, b) & c) wooden compaction piles underneath horizontal wooden piles or planking underneath the masonry footing (Jovanovic, 2002)

A combination of a wooden shallow foundation, *Schwellengründung,* and the wooden compaction piles, *Spickpfahlgründung,* is also possible. An example of this is the Foundation of the new San Marco bell tower in Italy (Figure 5). This type of foundation consists of three components: masonry footing on top of layers of wooden planks on top of wooden compaction piles (Figure 4 b) and c)). Because of how tightly packed the compaction piles are installed next to one another, sometimes wooden compaction pile foundations are regarded as simply soil improvement underneath a shallow foundation. According to modern-day understanding, the primary goal of the wooden compaction piles is to improve the mechanical properties of the soft soil and it does not aim to transfer the building load to deeper layers of

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[3] For the lack of an English term, here the Author will coin the term "wooden compaction piles" for this purpose, similar to sand compaction piles.

firmer soil, as what we understand as deep foundations or “pile foundations” today. (KÖPPL, 2012; Wigger, 2000)

These historical deep foundations or “pile foundations”, whether they are the compaction pile foundation or the floating pile foundation, do not effectively transfer the load to a deeper soil later. The building load is transferred into masonry footing and only part of the load travels through those piles into deeper soil while part of it is transferred directly into the soil by the masonry footing or the horizontal wooden plank or raft. There is an overlap of loading between the soil supporting the plate and the piles, which the bearing capacity and the load-settlement behaviour must account for. In this sense, the historical pile foundations should be understood as combined pile-plate foundations or piled raft foundations according to the definition of Eurocode 7 (EN 1997-1, 2004) The load-settlement behaviour is statically indeterminate and is calculated with elasto-plastic material mechanics. (Jovanovic, 2002)

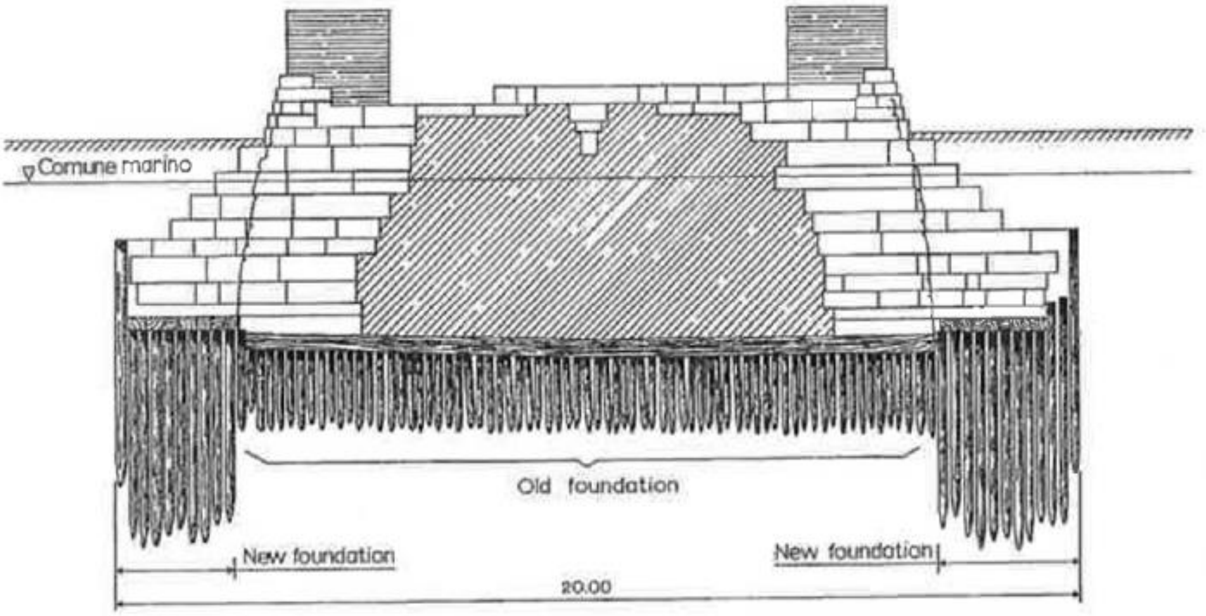


Figure 5 Foundation of San Marco bell tower by Donghi (1913) (Colombo & Colleselli, 1997)

For the owners and facility manager of an old building, the take-away is as follows:

- Wooden pile foundations come in different types, shapes, and dimensions.
- The wooden foundation is often found below the historical groundwater table.

- There were wooden raft foundations, wooden compaction pile foundations, wooden pile foundations (standing piles and floating piles). Combinations of these are also possible.
- In buildings founded before the mid-18th Century, only wooden compaction piles and the length of which is only 1 – 3 m long.
- In buildings founded after the mid-18th Century, piles longer than 3 m were possible and popular (standing and floating piles). However, short wooden compaction piles continued to be used until the early 20th Century.
- Wooden compaction pile foundations were used in lighter and simpler buildings and when there is a thick layer of soft soil.
- Wooden pile foundations were used for thinner layers of soft soil.
- Wooden compaction pile foundations can be understood as raft foundations with the wooden compaction piles as soil improvement work.
- Historical wooden pile foundations can be understood as piled raft foundations according to modern-day understanding.

This information is important for the owner or the FM to know the likelihood and the type and shape wooden foundation underneath the building, and also the understanding of the mechanics and physical properties of the building.

3.3 Current Situation of Timber Piles in Europe

There is no systematic database for wooden foundation piles in entire Europe but nevertheless, the usage of wooden foundations is widespread. (Klaassen & Creemers, 2012) The map in Figure 6 shows locations of known wooden pile foundations used under buildings and show the city and geographic location in Europe.

Among Nordic countries such as Sweden, Finland, Denmark and Norway, the use of wooden foundations is well known. These buildings are mostly built from the 19th to early 20th century and can be found in cities like Gothenburg, Malmö, Stockholm, Helsinki, Turku, and Bergen. In Turku, Finland, wooden piles are even found from underneath a building built in 1957 and the use of wooden pile foundations continued until even the 1970s until it was replaced by reinforced concrete. (Klaassen & Creemers, 2012; SSAB, 2017, 2020)

Figure 6 Locations of wooden pile foundations for buildings in Europe

Location Index in Figure 6	Reference
1 – 11, 13-29	(Klaassen & Creemers, 2012)
12	(Lehtonen et al., 2010; SSAB, 2017)
26	(KÖPPL, 2012)
30	(Keller & Lee, 1866)
31	(Jovanovic, 2002)

Table 1 Reference for indexed pile locations in Figure 6

In Eastern Europe, wooden foundations were also common the Baltic states (e.g. Tartu, Pärnu, Haapsalu, Kuusalu), and Russia (e.g. St. Petersburg and Moscow). In central Europe, wooden foundations were common in Poland and they are also found in the German cities of Hamburg, Cologne, Bremen, Berlin and Leipzig as well as the western parts of the Netherlands (e.g. Amsterdam Rotterdam, Haarlem and Hague).

In Berlin, Germany wooden foundations are found under the Reichstag and the old Berliner Schloss. In Cologne, Germany wooden foundations were used since Roman times. In the western Netherlands, wooden piles can be found in many cities like Amsterdam, Rotterdam, the Hauge etc. According to Dutch building inspection records, there are as many as 25 million wooden piles still in use today in the country, half of which are used under buildings. These pile foundations have started as early as Roman antiquity and continued to be used throughout the subsequent centuries. In Switzerland, wooden piles were used as foundations under buildings located in communities known as the Swiss Lake Dwellers in lakes around Zürich, Switzerland.[4] (Jovanovic, 2002; Klaassen & Creemers, 2012; KÖPPL, 2012)

In the rest of Europe, wooden foundations under buildings were less common, with the exception of some buildings in the cities in the UK (Hull, Bristol and other cities of UK) and some buildings in Paris (like the Grand Palais and parts of the Louvre), in the cities of Bordeaux and Nancy. In Southern Europe, they are even rarer, and this could be because, in southern Europe, buildings are usually founded on stone or hard ground surfaces, which means wooden piles are not a necessary building element.[5] The exception for this is the historical city of Venice as almost all historical buildings in this water city are founded on wooden piles. (GUDIĆ, 2019; Klaassen & Creemers, 2012)

The owner takeaway in this section is that wooden pile foundations are all over Europe. They are mainly found in Northern, Eastern and Central Europe, in buildings before the 1950s but with the oddity of Turku, Finland, which only phased out wooden piles with modern concrete and steel piles in the 1970s. There is no centralized database for wooden piles for Europe except for in the Netherlands[6]. Owners will have to investigate their buildings individually to know if they have wooden piles under their buildings.

[4] As described in reference (Keller & Lee, 1866)
[5] See Appendix E for the mapping of known wooden foundation against distribution of coarse fragment of topsoil in Europe
[6] There used to be also a database of underpinning projects in the year 2007, based in Turku, Finland, commissioned by Turku AMK, but the website is no longer running (accessible only by Wayback Machine) (Turku AMK, 2007)

3.4 Mechanism of damage of wooden piles

Wooden piles foundations are common throughout Europe and can have a lifetime of hundreds of thousands of years, but they are can also get damaged during their service lifetime that will negatively affect their serviceability. It is important for the owners or FM to understand these damage mechanisms, in order to assess and mitigate the problems and maintain or renovate the wooden piles, when needs be.

According to literature there are four kinds of possible ways for wooden piles to get damaged and they are as follows:

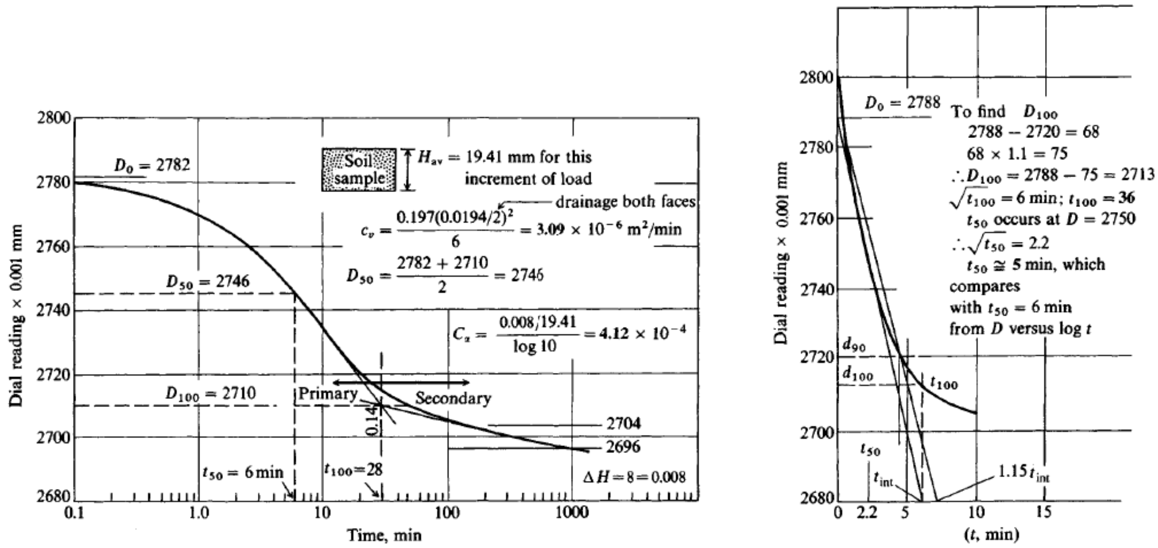
- Old or new primary settlement and continuous secondary settlement
- Shear failure of soil or loss of bearing capacity
- Bio-degradation: fungal and bacterial
- Other controllable forces

  (Jovanovic, 2002; van de Kuilen, 2007)

This section will give a brief summary of the mechanics of each of these elements and suggest the common real-life situations that cause these conditions to occur, that the owner might face.

3.4.1 Primary and Secondary Settlements

Settlement refers to the lowering of ground level. Usually, settlements are caused by a process called consolidation. Consolidation starts when a load is added onto a soil porous soil and the water in the soil drains away. This results in a reduction of excess pore water pressure and the reduction of volume of the same soil over a period of time. Over time the excess pore water pressure is completely dissipated and the effective stress of the soil increases. At the end of the primary consolidation, the entire load is borne by the structure of the soil and primary settlement stops. The speed of primary consolidation depends on the physical properties of the soil. The more porous the soil is (e.g. sand and gravel), the faster the process is. On the other hand, clay and silt have a slow consolidation process. The time also depends on the thickness of the porous material, the thicker it is, the longer it will take. Also, the consolidation process depends on drainage conditions. If the soil is allowed to be drained sideways, consolidation will finish faster. (Bowles, 1996)



(a) Casagrande's semi log method of presenting time–settlement data. Method is required if it is necessary to obtain a secondary compression coefficient C_α as shown.

(b) Taylor's $\sqrt{time}$ method to directly obtain d_{90}

Figure 7 Two common methods of representing time-settlement from consolidation

In the case of historical buildings, if there has been no recent load increase or reduction of the groundwater level, it is reasonable to assume that the primary settlements have long since been completed. Settlement is natural and usually an unavoidable process of building construction. Even settlement of the entire building is of great concern to the building itself. At most, it can negatively affect the neighbourhood building. However, uneven settlement, or differential settlement, can occur when the soil condition is uneven or if the loading is uneven. A substantial differential settlement can cause stress and curvature to the superstructure of the building and cause damages in the form of cracks. These cracks to the particular elements of the historical building often have occurred in the past, during or shortly after the construction of the building. (Bowles, 1996; Jovanovic, 2002)

In practical applications, there is would happen when additional loading is added to the soil. This can include the increase of loading, due to alteration of the superstructure, change of use of the building. This can increase the direct loading onto the pile and transfer it onto the soil and induce additional primary settlement. Another way the additional primary settlement is induced could be adjacent building load from an adjacent shallow foundation that is too close to the piles, and this induces stress onto the pile increasing the pile load or the adjacent building load is acted directly on the soil underneath the historical building.

After primary consolidation and the excess pore water pressure has been dissipated, the settlement starts to stabilize. However, usually more settlement is observed after primary settlement and that is known as secondary consolidation, secondary compression, secondary settlement, or *creep*. This settlement rate is not determined by the permeability of the strength of the grain structure anymore. This process can continue for many years and is approximately at a logarithmic rate. Therefore, in the logarithmic time-settlement representation (Figure 7 a), secondary settlement in time is represented as a straight line. This means the secondary settlement of a foundation happen at a much lower rate than the primary settlement and gets slower and slower. (Bowles, 1996)

There is no universally agreed-upon understanding of why secondary settlements happen, but traditional teaching in engineering classes says that it is due to gravity, as the grains move into gaps to settle into a more compact state and hence reach a lower potential energy state. There is no clear-cut delineation of time between the primary and the secondary phase of the consolidation because the complete excess pore water pressure is dissipated only asymptotically and because creeping takes place from the beginning. Essentially, the strict separation of primary and secondary phases with different settlement coefficients and different causes in the delay of settlement is not a correct understanding, but for the purposes of settlement calculation, these traditional coefficients and equations are accurate enough. (Bowles, 1996; Jovanovic, 2002)

In historical buildings, the foundation load and the groundwater level have remained unchanged for several decades, and there are still ongoing settlements, then it is usually caused by creep settlement of clay or organic layers. In soil layers prone to creeping, creep settlement can result in noticeable settlement rates even centuries after the construction of the structure and be the cause of damage. The kind of settlement is of particular concern to historical piles that are considered standing piles. As the toe of the pile rests in a solid load-bearing layer of soil, any creep settlement that occurs in cohesive soils (such as clay and silt) surrounding the pile will generate negative skin friction on the pile (see Figure 8). This will add to the pile loading or may lead to additional settlement of the pile, sinking deeper into the ground, which may affect the building. This settlement behaviour of historical piles is observed in standing piles during secondary consolidation in Holland. (Bowles, 1996; Jovanovic, 2002)

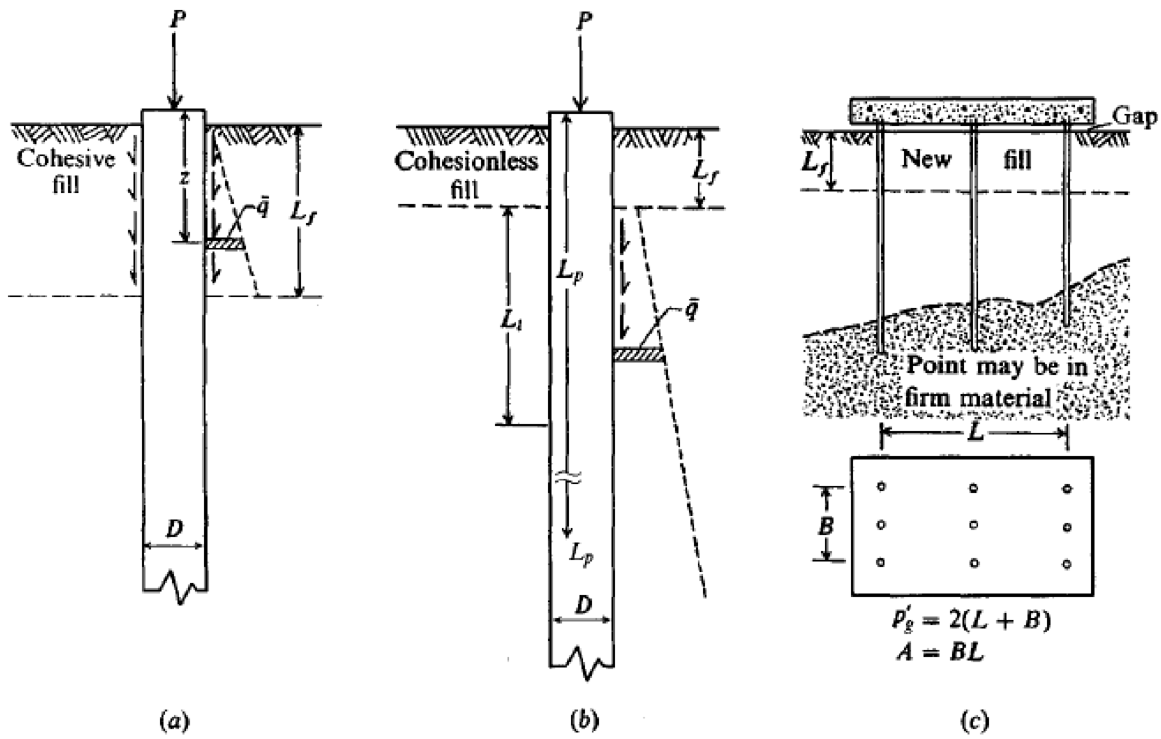


Figure 8 Diagrams showing the development of negative skin friction on a pile or pile group in cohesive soils(Bowles, 1996)

3.4.2 Shear failure of soil or loss of bearing capacity

When the shear resistance of soil is overcome under a foundation body, shear zones form in the subsoil and the foundation body sinks swiftly. This is known as a soil failure. Soil failures do not just happen over time. In the case of historical buildings, it is indicated by a quick, violent reaction to unfavourable changes in loads, dynamic loads, or influences in the nearby buildings. (Jovanovic, 2002)

There are three types of common reasons for this type of ground failure:

- Shear strength of soil overcome by increased loading or by the removal of a supporting lateral load
- Decrease of shear strength of soil due to influences in soil or dynamic load (vibrations)
- Hydraulic ground failure, also known as piping failure[7] (Jovanovic, 2002)

[7] Piping failure refers to when a mixture of water and soil flow from the bottom to the top in a "pipe" formed in the soil, because the counteracting downward pressure is

The loss of bearing capacity is one of the most dangerous forms of damage for a foundation. In this case, the foundation would suddenly sink into the ground, and the neighbouring soil bulges up. The sinking and uplift of soil is a result of soil moving and the soil surfaces slip and slide along each other in the shear zone in the ground. The movement of soil depends on the stratification of soil, shear strength parameters of the soil and the dimension and structure of the foundation itself. Figure 9 shows three types of common shear failures. (Jovanovic, 2002)

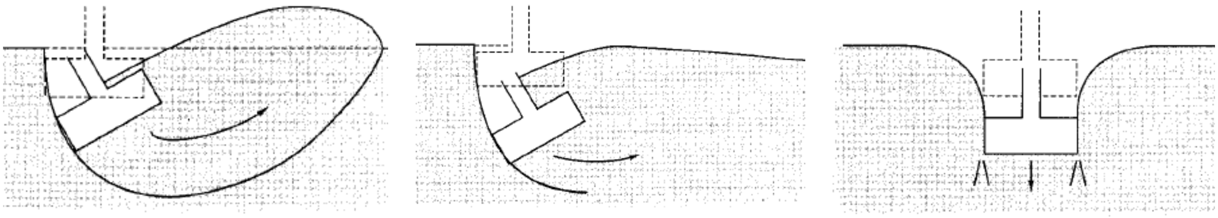


Figure 9 Representations of different modes of bearing capacity failures a) general capacity failure; b) local shear failure; c) punching shear failure (Bowles, 1996)

The damage caused by the bearing capacity failure cannot be calculated in advance. However, the bearing capacity of a foundation can be calculated in advance given the parameters such as the shear strength of the soil, the geometry of the foundation and so on. For conservative purposes, the most unfavourable soil condition is usually assumed and on top of that, a safety factor of 3 is usually applied. The formulae and the factors are regulated by engineering standards. In Europe, this is stipulated by Eurocode 7[8] and their respective national indexes for each country. The principles of these calculations of bearing capacity are based on the equations developed by Terzaghi's Method (see Figure 10). (Bowles, 1996; Jovanovic, 2002)

In ancient times, however, builders did not have these methods to calculate the bearing capacity available to them and they could only learn from experience, and cope with the risk of bearing capacity failure with caution. The biggest risk of such an event happens during the construction phase of the project, during which the builder had to constantly monitor any settlement or bulging in the soil. They had to react quickly to any sudden movement by halting the construction all together or slowing down the construction to allow for sufficient time for the dissipation of the excess pore water pressure. It was only because of the slow and low-vibration methods of

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not enough to suppress the flow. This happens most often during an excavation and there is a hydraulic pressure difference between the excavated surface and unexcavated surface.

[8] See reference (EN 1997-1, 2004; EN 1997-2, 2007)

operation that large building loads could be applied to the lower soil. (Jovanovic, 2002)

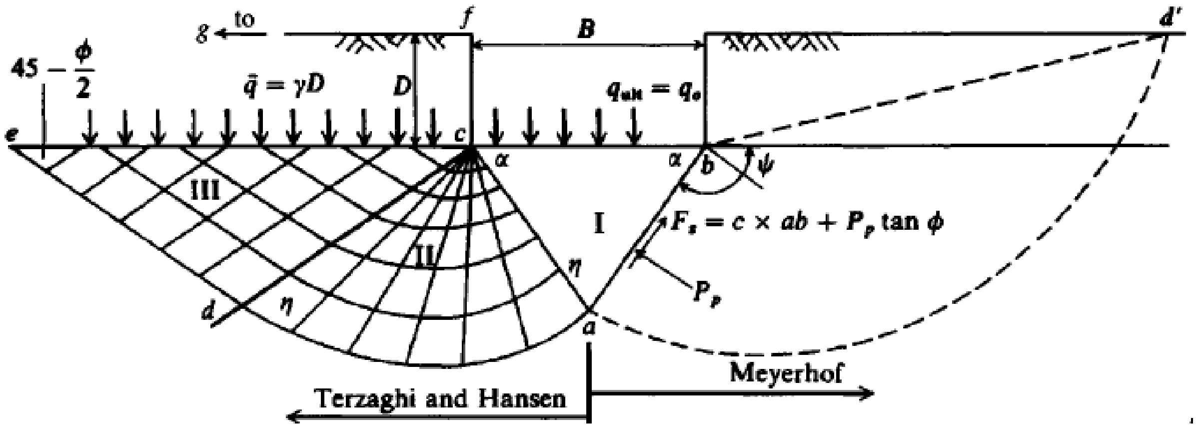

Figure 10 General footing-soil interaction for bearing capacity equations based on Terzaghi, Hansen and Meyerhof methods (Bowles, 1996; Hansen, 1970; Meyerhof, 1951; Terzaghi, 1943)

Historical buildings that have withstood the test of time, are not susceptible to bearing capacity failure under their normal constant loading, even if, when evaluated under modern standards e.g. Eurocode 7, they do not meet the safety coefficients that are set for new buildings. However, the bearing safety of such buildings has been proven by their long service lifetime and has only increased due to the secondary consolidation of the soil over a long period of time. (Jovanovic, 2002)

Major threats towards the bearing safety of historical piles mainly come from a reduction of bearing capacity due to changes to the structure or change to the surrounding. These can be damages to the foundation itself or removal of lateral support loading due to a nearby excavation. Heavy construction machines or increased traffic can also induce damage to the historic foundation, by collapsing the structure of the saturated and poorly drained clayey soil or the liquefaction of sandy soil with cyclical loading.

3.4.3 Bio-degradation: fungal and bacterial

Since wood is an organic material, wooden foundations are susceptible to various mechanisms of degradation and destruction. The greatest damage to wooden pile foundations buried underground is caused by microorganisms: fungi and bacteria. What type and extent of biological degradation the wooden piles are subjected to is heavily decided by whether the wood is above or submerged under the groundwater table. (Jovanovic, 2002)

The part of the wooden pile which is above the groundwater table is in an aerobic environment which will allow oxygen (in minimal amount) to reach the wood, creating an ideal environment for fungal attack. Fungal attacks are also called “Pile rot”[9]. Fungal attacks can happen regardless of the type of wood used. All softwoods are equally susceptible. The fungal infection generally causes quick wood rotting, a significant loss of strength, and even the eventual disappearance of the wood component. Brown rot, white rot, and mildew rot are the three most prevalent forms of fungi that break down wood in the soil, there three groups of rotting are classified based on the damage they leave behind. During fungal degradation, enzymatic reactions break down lignin and cellulose, in the wood cells. The fungal threads (also known as hyphae) weave their way through the wood, growing until the wood becomes fully fibrous and brittle. (Jovanovic, 2002; van de Kuilen, 2007; van Etten et al., 2007)

The lowering of the groundwater level is the main cause of pile rot in historical buildings. Wooden piles should be at least 10cm below the lowest known groundwater level to ensure the ideal anaerobic situation for the preservation of piles. The result of pile rot might not be immediately obvious. A cumulative dry period of 10 to 20 years often leads to a loss of load-bearing capacity in the foundation and structural damages to a building, such as cracks in the façade and wall due to differential settlement. Several short dry periods like cyclical groundwater fluctuations must be added together. This is because many types of fungi can survive the harshest anaerobic conditions and underwater in a dormant state, even after decades, and they can continue to break down wood once better living conditions, such as the resupply of oxygen, happen again. (Boston Groundwater Trust, 2018; Jovanovic, 2002; van de Kuilen, 2007; van Etten et al., 2007; VROM, n.d.)

The other type of biological attack piles face is bacterial decay. Bacterial decay of piles is also called “pile plague”[10], likely due to the dark appearance of the piles under attack. Bacterial decay is perpetrated by anaerobic bacterial and that is why it can also happen underwater but is less common and slower than fungal decay, because

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[9] *paalrot*, in Dutch (VROM, n.d.)
[10] *palenpest*, in Dutch (VROM, n.d.)

of the breakdown of cellulose in the so-called secondary walls of the wood cells. This process slowly reduces the wood strength and increases the water content. The structure of the pile can be assumed to remain stable for 70 to 90 years or even up to centuries until the damage finally set in. (Jovanovic, 2002; van de Kuilen, 2007; van Etten et al., 2007; VROM, n.d.)

Bacterial decay mainly occurs in the sapwood, which is the outer edge of the wooden pile. Therefore, unlike fungal attacks, different types of wood have different resistance to biological degradation. According to DIN 68364, teak wood and green hearth are very resistant, then comes oak and then comes spruce and Pine. Spruce has a narrower sapwood edge and therefore has fewer problems with this form of attack. Pinewood has a wide sapwood edge and is therefore sensitive to bacterial attacks. (Jovanovic, 2002; van Etten et al., 2007; VROM, n.d.)

Nutrients, moisture and temperature conditions, oxygen and pH values in the wood and soil all influence the growth of microorganisms, both fungal and bacterial, as well as the degree of wood degradation. Nitrates and phosphates speed up the decomposition of wood by fungus. This also applies to bacterial damage, since most bacteria also require the same nutritional salts, thus. And as mentioned about oxygen is vital for the amount of damage fungus can cause on the wood. (Jovanovic, 2002)

In real-life applications, fungus and bacteria are everywhere and a lot of the factors determining the degree of damage by bio-degradations has already been determined by the environment. However, some common reasons for the fluctuation of groundwater and changing of chemical conditions of the soil are: 1) lowering of the groundwater table by groundwater pumping in a nearby excavation; 2) leaking sewage system and misaligned drainage below the groundwater table that lead to contamination and draining of groundwater; 3) drainage of groundwater in the fields for agricultural uses.

In this section, the owner and the FM understands:

- The three main mechanics of wooden pile damage: Primary and secondary settlements, loss of bearing capacity, and fungal or bacterial attack;
- Different factors and real-life situations that can lead to damages, both internal and external, are given.
- Owners and FMs should look out for these situations and monitor if they are causing damage to the building

3.5 Problems of a damaged wooden foundation

All the damages to piles mentioned in the previous section can also have severe negative effects on the superstructure of the building. This will affect the safety, serviceability, operation, lifetime and value of a building. In the paragraphs below, the problems for the building when the wooden piles underneath are not properly maintained are discussed.

The most concerning effect of the damaged wooden foundation is of course concerning safety. As discussed above, the safety of historical buildings under their own constant loading is all but guaranteed, what with the test of time and the secondary settlement over the years increasing the stability of the foundation. However, there are still internal and external factors to the foundations which can threaten the safety of the foundation and hence the building. (BAKA Bundesverband Altbauerneuerung e.V., 2020) The most dangerous external threats are settlements due to cyclical or dynamic effects from outside influences. It has been demonstrated in experiments that construction operations that produce vibrations, impacts or pressing of displacement pile can negatively impact the historical foundation, by means of producing an undrained soil condition and a sudden softening of soil (liquefaction) Owners ought to be aware of neighbouring construction activities, like installation of sheet pile, excavation of a construction pit (with dewatering) and installation of piles, because these activities are most threatening to the safety of the historic building during the construction phase. The finished product usually does not impose any danger to the building. (Jovanovic, 2002) Whereas internally, there is the threat of additional building load, change of structure and chance of fungal and bacterial attack.

All the internal and external damages mentioned in 3.4 can lead to safety problems to various extents. The most threatening is the loss of bearing capacity mentioned in 3.4.2. The loss of bearing capacity can happen suddenly, and this will seriously threaten the stability of the building and may even threaten to collapse the building. The loss of bearing capacity can happen due to neighbouring construction activities and increased traffic load, and also the reduction in the shear strength of the cohesive soil because of the change in consistency due to water absorption, in the event of water leakage from sewage or pipes. (BAKA Bundesverband Altbauerneuerung e.V., 2020)

The other threat to the safety of the building is fungal, and to a lesser extent, bacterial attacks. If no foundation repair takes place, a house will not immediately have to be declared uninhabitable. However, over time the piles will lose their load-carrying capacity[11] and even the failure of the wooden pile themselves. The building will increasingly become more unbalanced and lean on adjacent houses. This will threaten the safety of the building and its neighbouring building. At this point, the building must be declared uninhabitable. (BAKA Bundesverband Altbauerneuerung e.V., 2020; van Etten et al., 2007)

The foundation problems that do not lead to immediate safety or stability problems can also so negatively affect the serviceability of the building and hence its operations. It is typical for the foundation of historical buildings to be classified as soft and sensitive to settlement. The stiffness of the foundation is usually not sufficient to prevent differential settlements. The above mentioned outside influences such as changing soil conditions and dynamic loading can lead to the loss of bearing capacity and differential settlement, which in turn causes defects of the building. (BAKA Bundesverband Altbauerneuerung e.V., 2020)

The typical defects in buildings with bad wooden pile foundations are cracks in the walls and ceilings. Apart from cracks, there are other signs of defects, such as the skewed position of the house, sloping floors, window and door frames that warp and jam, a level difference between the building and the street level. (VROM, n.d.) When uneven settlement sets in, eventually it can even lead to the bursting of pipelines. [12] These defects have petty negative effects on the users, from being mildly annoying to look at, to creating day-to-day challenges like doors and windows being hard to open and close. But they can affect the serviceability, operation, and lifetime in a major way.

[11] The change of load-carrying capacity over time due to fungal infection is an important indicator of the expected remaining service lifetime of the pile itself, which will be discussed further in 3.6.3.

[12] See reference (Hämäläinen, 2006)

Figure 11 Pictures showing cracks on the inside and outside of the building (VROM, n.d.)

Firstly, when windows and doors do not shut properly, it means the indoor environment such as noise from outside and indoor temperature will be hard to control. This means the users will feel hotter in the summer and colder in the winter. The building's thermal envelope is broken. Secondly, Cracks in walls can create seepage and can lead to moisture in the building and moulding. Moulding in the indoor environment is bad for the user's health, both mentally and physically. The whole user experience of the building will be affected by these defects. Thirdly, the cracking and bursting of pipelines will affect directly the serviceability, as, for example, water pressure can be affected or sewage pipes can be broken. The broken sewage and water pipes can also lead to the contamination and fluctuation of groundwater, which will exacerbate the wooden foundation problem, forming a vicious cycle. All these will eventually affect the commercial operations that take place inside the building.

Having a historical building with foundational problems can have cost implications. Firstly, since the building envelope is broken by openings of the building. This will increase the heating cost. There will also be an increase in maintenance costs when the owner has to repair the defects in the building, filling the cracks, cleaning the mould, fixing the doors and windows, fixing the burst pipelines and other broken infrastructure. Eventually, the owner of the building will have to also fix the foundational problem, and this will incur a renovation cost. Finally, having a building with visible cracks on the walls is an open invitation to vandals, swatters and people with intentions. This means additional security might need to be hired and that increases operational costs. On the other hand, if the building can no longer perform its function or perform at the required standards by the commercial operations in the building, this might also affect the quality of the commercial operations the building hosts. For example, a boutique hotel in a renovated historical building may suffer from moisture problems because of the cracks caused by its bad wooden pile foundation. And will lead to dissatisfied end-users and a loss of income. Also, during the renovation of the wooden foundation, occupants may have to move out and this means a loss of income.

The defects in the building also decrease the value of the building. First of all, the defects will lower the aesthetic value of the building. It creates a bad image for the owner of the businesses. Secondly, the cracks in the walls will also damage the superstructure of the building, as water seeps into the walls. This decreases the lifetime of the structure.[13] And finally and most importantly, it will affect the willingness of any potential buyers who would buy the building. In many countries, the seller is obliged to disclose any foundational problems to the buyer, while the buyer will, of course, carry out their due diligence before buying the property. This will lower the price of the building the buyer is willing to pay, as they will have to pay for the renovation to fix the myriad of defects. The same goes for the valuation by the bank, who will be more cautious when deciding a large amount of mortgage with lower interest rates on this building.

3.6 Assessment of Wooden Piles

In this section, the owner and FM will learn about when the assessment of piles should be performed and what are the assessment techniques of the wooden piles to know their condition and serviceability.

3.6.1 When do we need an assessment of piles?

The most obvious situation in which an assessment of wooden piles is necessary is, of course, when there are signs of defect. If any of the defects mentioned in 3.5, such as cracks on the walls, doors and windows not closing properly because the door/window frames have deformed, the building or walls has tilted, the floor of the

[13] Service lifetime of the pile itself will be discussed further in 3.6.3.

building is slanted, the ground becomes uneven and any other signs of damages to the superstructure, then further investigation is probably warranted. (VROM, n.d.)

The second reason when a foundation assessment is warranted is when there is a change of use in the superstructure. This can lead to a change in the design loading of the building and hence the pile loading. When additional loading is added to the wooden foundation, both the pile capacity and the bearing capacity of the soil have to be checked against the new loading. Otherwise, it might need to pile failure or more commonly more building settlement or even bearing capacity failure. For example, according to the loading design guide in Europe, the design loading for offices is 1.8-2.5 times that of residential loading (see Table 2). (van de Kuilen, 2007)

Categories of loaded areas	q_k [kN/m^2]	Q_k [kN]
Category A		
- Floors	1.5 to 2.0	2.0 to 3.0
- Stairs	2.0 to 4.0	2.0 to 4.0
- Balconies	2.5 to 4.0	2.0 to 3.0
Category B	2.0 to 3.0	1.5 to 4.5
Category C		
- C1	2.0 to 3.0	3.0 to 4.0
- C2	3.0 to 4.0	2.5 to 7.0 (4.0)
- C3	3.0 to 5.0	4.0 to 7.0
- C4	4.5 to 5.0	3.5 to 7.0
- C5	5.0 to 7.5	3.5 to 4.5
Category D		
- D1	4.0 to 5.0	3.5 to 7.0 (4.0)
- D2	4.0 to 5.0	3.5 to 7.0

Table 2 Imposed loads in buildings, according to Table 6.2 Eurocode 1 Part 1-1; Category A refers to domestic and residential loading, Category B office loading, Category C areas where people may congregate, Category D Shopping areas; where a range is given, national index refers. (EN 1991-1-1, 2002)

The same goes for any alteration in the superstructure. This includes alteration that will add loading to the foundation: for example, an additional floor is added, the timber floor is reinforced with concrete, walls are added to the building etc. (van de Kuilen, 2007) In the superstructure, any alteration in the flow path of the building will also warrant a re-evaluation of the foundation capacity, for example, any removal or addition of beams, or opening at the ground level. This will change the distribution of loading on individual piles and may lead to an uneven settlement or bulging of the soil as the original loading is lifted. (Mandala, 2002) In modern concrete and steel piles, usually, an allowance of pile loading is given, and engineers only need to check that the new pile loading in a renovation is within the given capacity. However, in historical buildings founded on wooden pile foundations, no such provision is given, and pile assessment is necessary.

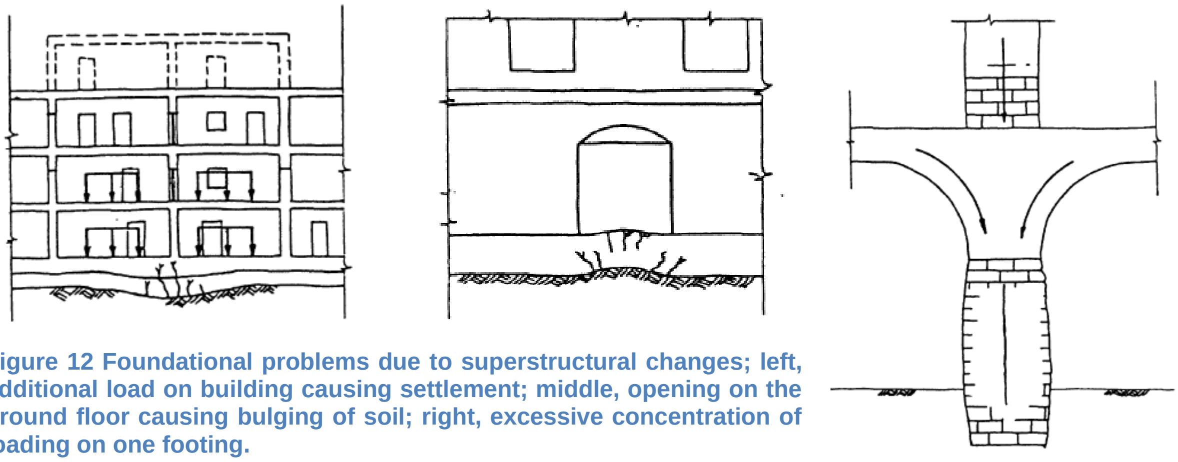


Figure 12 Foundational problems due to superstructural changes; left, additional load on building causing settlement; middle, opening on the ground floor causing bulging of soil; right, excessive concentration of loading on one footing.

The second reason that calls for an assessment of wooden piles is underground or neighbouring construction activities. Since historical buildings are oftentimes located in historical centres and densely populated areas, the demand for infrastructure, transportation and new housing is high. As mentioned in 3.4 and 3.5, building problems can arise from nearby constructions. In coastal areas where wooden piles are often found, the buildings are often founded on soft soil. Any underground activities may cause settlement on the ground. Excavation can cause a loss of lateral support of soil which leads to a loss of bearing capacity, any dewatering activities in a construction site may cause the drawdown of groundwater table which is necessary for the protection of the wooden piles. When these nearby activities cause structural damage to the building like cracks and tilting, this might lead to disputes between the two parties. An assessment of the wooden pile condition might be necessary to ascertain the damage and support claims or litigations for reparation. (van de Kuilen, 2007)

Another situation in which wooden pile assessment might be necessary is after the cleaning of contaminated soil. The soil underneath a house might be contaminated by old factories or brownfields in the vicinity. As mentioned in 3.4.3 groundwater contamination might be a factor that exacerbates bacterial and fungal growth. When soil is temporarily removed, the wooden piles might also be exposed to the open air, and they need to be assessed for strength and for if they can withstand the temporary exposure. In addition to that, removing soil directly below the foundation and near the foundation could lead to the loss of bearing capacity. (van de Kuilen, 2007)

The assessment of the foundation can also be a part of the strategic maintenance planning. There is a synergic benefit when many types of infrastructure are maintained concurrently. For example, maintenance or replacement cables, sewers, road and pavement surfaces can be done together with the maintenance of the piles this can save cost and time in terms of the excavation work and they can share the same excavation pit at the same time. Also, the associated nuisance, such as construction noise, redirection of traffic and loss of revenue from maintenance downtime can be shortened or minimized. (van de Kuilen, 2007) In a survey carried out in Turku, Finland, a response suggested that residents received new plumbing, sewers, surfaces, washroom and cellars after the underpinning project of the building with wooden piles. (Hämäläinen, 2006)

3.6.2 Assessment Techniques

There are many ways to assess the timber structure. Traditionally, visual inspection and sharp tools are used. (van de Kuilen, 2007) Visually inspection can be carried out by digging observation pits underneath the foundation. The most important observations are 1) to see whether pile heads are exposed above the groundwater table, and 2) if the pile heads have become rotten with visible mould.

The second type of method is so-called non-destructive testing or *NDT*. NDTs usually make use of ultrasounds and stress waves to determine the condition of the piles. In addition to these methods, pilodyn hammers are also used to determine the density of the wooden piles. This method is also used to determine the density of living trees, sawn timber logs and logs suffering from decay. (van de Kuilen, 2007)

Figure 13 Photo of a rotten exposed wooden foundation in need of repair (Algemeen Dagblad, 2020)

As opposed to NDT are methods like drilling and coring. For core testing, a part of the wood is bored out and the bore core itself is tested for strength in the laboratory. The method has the benefit of being highly accurate because the correlation between the strength of the test core and the strength of the pile is high, and this enables the measurement of pile residual strength without causing so much destruction to the pile that it must be replaced. Other drilling methods are based on torque resistance and are in situ tests. They are preferable in dry conditions of the building. However, since these types of tests are wood species-specific, they must be cared out with caution. (van de Kuilen, 2007)

The third type of tests is full-scale pile tests (see Figure 14). However, piles tests are costly and not always feasibly. This is a method that directly measures the capacity of a pile under certain settlement requirements and studies the settlement-load behaviour. It is the only test that can tell the direct residual strength of the existing piles. For a large-scale renovation, this test might be worth it, as the effort of testing a few chosen test piles can increase the understanding of the existing foundation by a lot and the renovation project can benefit from it. In addition to that, the tests also tell the engineers about the change in the strength of the piles over time and it tells the owner and facility manage the characteristics of their building. It also has the added benefit of facilitating future uses of the foundation as well as giving data to other projects of a similar scale. (van de Kuilen, 2007)

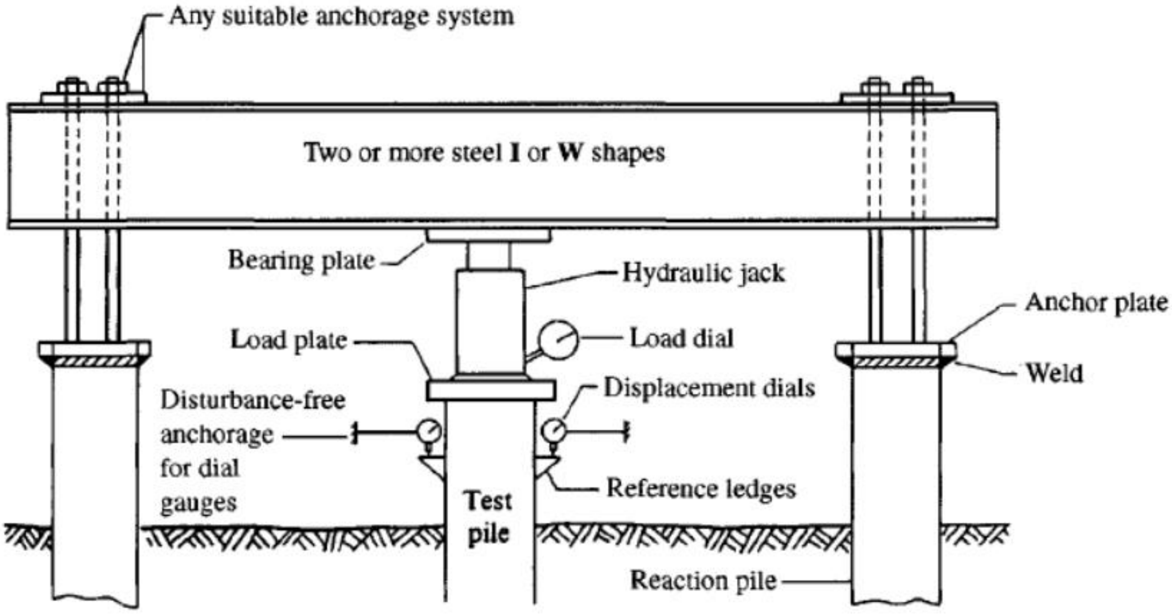


Figure 14 Typical set-up for a pile load test(Bowles, 1996)

For non-testing assessment methods, flow charts are also a tool that engineers can use to reliably determine the residual strength of the piles. For the analysis, engineers will require the inputs of the original structure of the building, its usage, the location and types of defects or degradation. By analyzing the load history, age of the structure estimated historical files, the result of visual inspection, and the future use of the building, the residual lifetime can be estimated, and the need for renovation can be determined. (van de Kuilen, 2007)

In contrast to the more invasive methods such as excavation and exposing the pile head, an alternative method of assessing wooden pile foundation, as well as groundwater condition, has been proposed. The proposed ground penetrating radar (GPR) method makes use of electromagnetic (EM) waves to which are reflected by "reflectors", such as piles and groundwater, in the underground environment to infer the depth to the reflector, based on the velocity of the EM pulse and the travel time of the reflected pulse. The GPR method does not directly reflect the condition of the wooden piles, but it reflects the depth of the wooden pile heads and the depths of the groundwater table. In this way, GPR can be used to find out if the pile is at risk of getting fungal attacks. (LeFrançois, 2003)

The proposed GPR method however heavily relies on existing data, such as recent observation excavation pits, groundwater elevation in monitoring wells and the resistivity survey, in order to verify the GPR finding. In contrast to owners digging up observation pits one by one by the wooden pile building owners, this method can find application in the screening of potentially at-risk buildings in a neighbourhood.(LeFrançois, 2003) As the technology matures and the resolution increases GPR should find more uses in wooden pile assessment and groundwater detection, even though a recent meta-study states that GPR methods are still not very prevalent in the field of groundwater-dependent ecosystems, and GPR is still used as a secondary tool.[14] (Paz et al., 2017)

3.6.3 Service Lifetime of Wooden Piles

The service lifetime of wooden pile depends heavily on the residual strength of the wooden piles for it carry its intended loading. In this section, the different factors affecting the residual strength are discussed. According to a study carried out on historical foundation pile specimens, the residual strength of wooden piles over time depends on the decay sustained. The location of the decay is usually at the top of the pile and also only located at the sapwood, whereas the plinth can still retain a relatively high strength, and the pile section just 1 m below could suffer no decay at all. (van de Kuilen, 2007)

Another potential factor is the effect of temporary drying of wooden piles. This can occur during excavation for any reason from rerouting and maintenance of building services, removal of contaminated soil etc. However, from this study was concluded that decay-free timber can be left in a covered open-air climate for up to 9 months without additional treatment and not lose strength. Also, any potential development of longitudinal fractures as a result of drying has no negative effect on the compression strength of the material. (van de Kuilen, 2007)

Both loading and decay will decrease the strength of a pile over time. Since the load history of a building foundation is not always known, the level of decay is what is measured in the study. The results of the load test on cross-sections of historical piles indicated that the amount of heartwood in the cross-section of a pile determines

[14] See 3.10.2, for more non-invasive monitoring methods.

its residual strength. Figure 15 indicates the decrease of wooden pile strength over time. The strength at relative strength = 1 is determined from the average strength of new spruce piles in wet conditions, which is 20MPa. The speed of decrease of piles strength over age is assumed to be exponentially decreasing. From the graph, it can be concluded that piles on average have 30% - 40% of their original strength after 100 years of service, while the heartwood can retain about a bit less than 80% of its original strength after 100 years. The whole pile strength half-life[15] can be inferred to be 30 years, while the strength half-life of the heartwood can be as high as 400 years. (van de Kuilen, 2007)

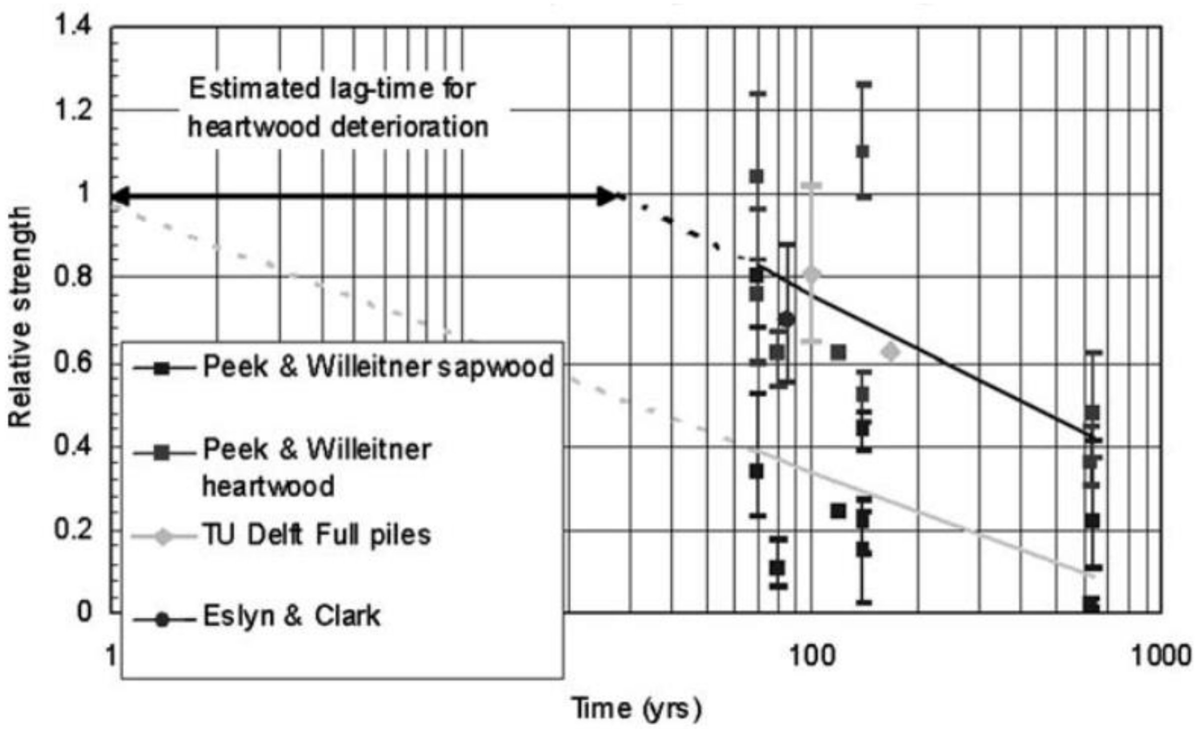


Figure 15 Change of wooden pile strength as a function of time(van de Kuilen, 2007)

A big factor in the decrease in strength is fungal and bacterial decay. And the change in average strength and loss of mass over time can be drastic. For example, the strength of timber can be reduced by 30–100% within a time of just 3000h or 125 days, after being infected by fungi. (van de Kuilen, 2007)

[15] The time it takes for the strength to decrease to 50% of the original.

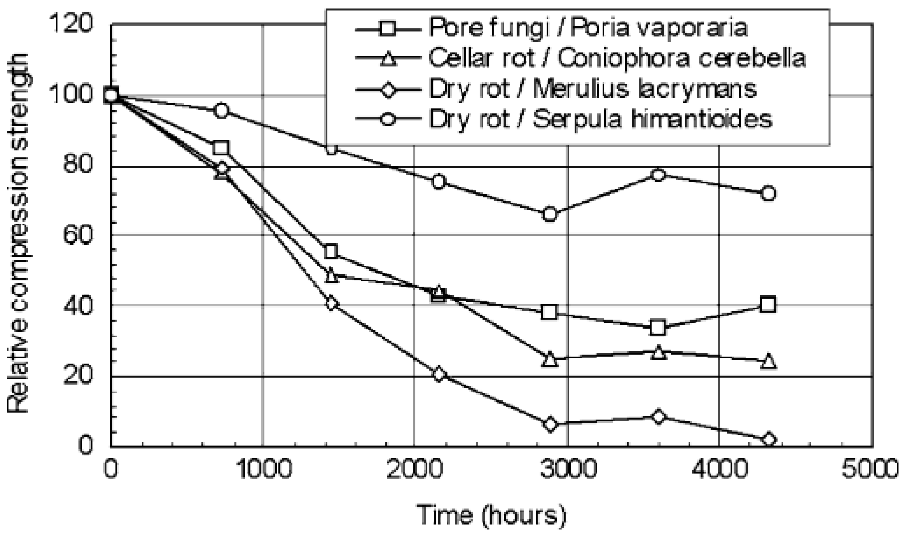


Figure 16 Change of wooden pile strength over time after fungal infection (van de Kuilen, 2007)

After the assessment of piles is carried out as mentioned in 3.6.2, the residual strength and residual lifetime of the wooden foundation should be determined. This can be achieved by using damage accumulation models. One such model focuses on two inputs 1) the amount of healthy cross-section as a ratio of total original cross-section *δ,* and 2) the assumed strength loss ratio of infected versus healthy wood *β*. (van de Kuilen, 2007)

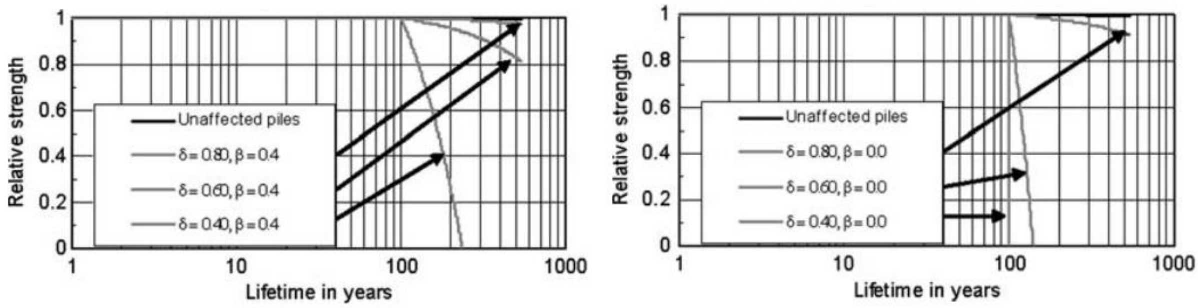


Figure 17 Service life prediction for different levels of *δ* and *β* (van de Kuilen, 2007)

As shown in Figure 17, the service life is heavily dependent on the assumption of the ratio of *β*. For conservative purposes, *β* should be assumed to be 0, but this leads to a rapid drop off the relative strength after decay has set in[16] and the affected cross-section area is larger than 40%. (van de Kuilen, 2007)

In the Netherlands, the service life is also estimated using the degree of decay of the pile with respect to the pile diameter. Piles are categorized into 4 classes, each with its respective estimated service life and recommended course of action, according to Figure 18. (Lehtonen et al., 2010; Stichting Platform Fundering, 2006)

[16] Assumption: decay initiates after 100 years of service.

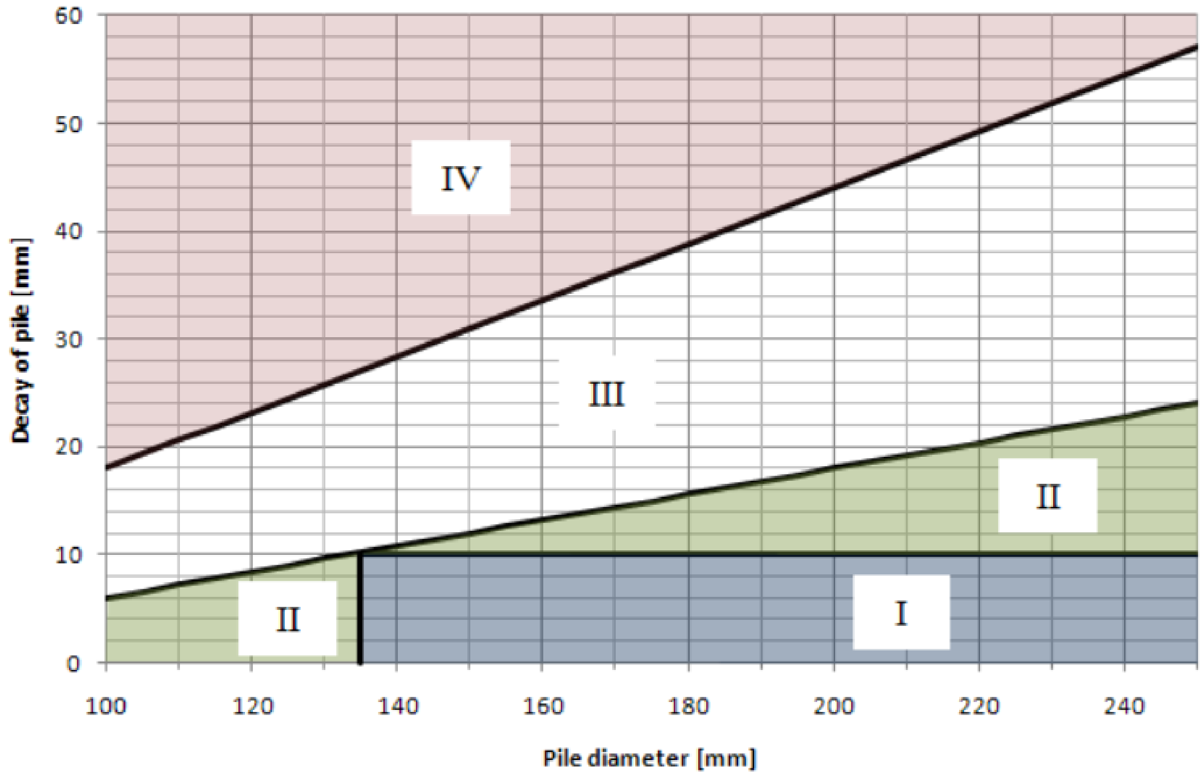


Figure 18 Classification of piles according to extent of decay of pile and pile diameter (Lehtonen et al., 2010; Stichting Platform Fundering, 2006)

The description of each class is as follows:

- Class I: No bio-degradation is present. There is no need for action. Predicted service life: 50 years.
- Class II: The pile is damaged, but it is still so minor that there is no observable effect on the strength of the pile. No sample is required to investigate the pile strength, but samples can be taken to investigate the cause of the damage. Predicted service life: 25 years.
- Class III: Laboratory test is necessary to investigate the strength of the pile shaft. Bore core samples should be taken. Predicted service life: 15 years.
- Class IV: Large extent of infestation relative to the diameter. The strength of the pile shaft is clearly insufficient here. Sample taking is only necessary if the cause of the damage has to be determined. Underpinning action is immediately necessary. Predicted service life: 1years.

(Lehtonen et al., 2010; Stichting Platform Fundering, 2006)

3.7 Restoration Methods

When a wooden pile foundation is found to be in need of restorations, the aim of restoration of piles is usually to restore building functionality which is showing signs of damage in the superstructure or to support a new usage of the building with a much more intense loading. These methods should be combined with other renovations of the historical building in order for the building to be fully functional with the intended usage. (Mandala, 2002) There are three general ways to strengthen a foundation:

(1) Underpinning
(2) Base Enlargement
(3) Soil improvement

By underpinning, it is meant that an additional structural element is installed between the existing structure and the foundation soil with the aim to reinforce the foundation, by means of transferring the building load to a deeper firmer soil. The second method, base enlargement, aims to spread out the building load and reduce the stress experienced by the soil in order to reduce settlement. The third method, however, aims to improve the mechanical properties of the founding soil itself, to make the soil firmer and be able to carry a larger bearing capacity. (Mandala, 2002)

In practical applications, four commonly used methods are proposed in the Netherlands, which are combinations of methods (1) and (2). In the following paragraphs these four methods will be discussed:

- Pile head lowering (Method 1)
- New pile foundation “Board Construction”[17] (Methods 1 & 2)
- New pile foundation with edge beams (Methods 1 & 2)
- New pile foundation pressed from the wall (Methods 1)
  (van Etten et al., 2007)

Pile head lowering

In order to lower the pile head, the soil is excavated, to 50cm below the lowest known groundwater level or below the level of the bottom of any nearby sewer pipe to prevent future drained conditions, to expose the pile heads. After that, either the top

[17] *tafelconstructie*, in Dutch (“Table Construction”)

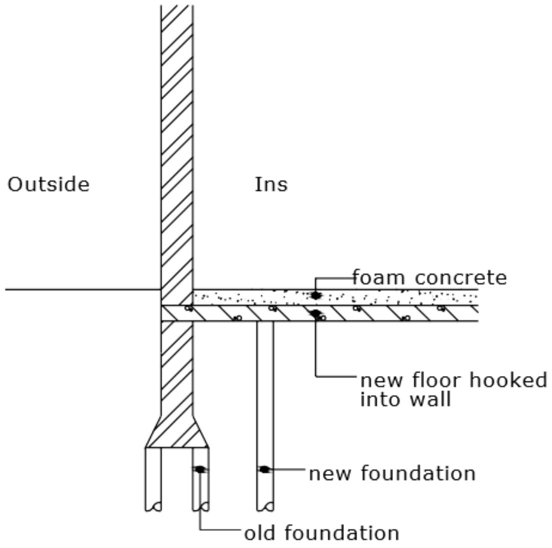
of the rotten pile head is sawm off and a jacking device is placed between the new pile head and the load-bearing structure above, and then steel reinforcement and formwork are placed and ready for concrete to be poured in individually for each pile; or after the pile head shad been sawn off, a beam of reinforced concrete is poured for the underpinning of an entire row of piles. Finally, bricks are laid in the gap between the concrete and the bottom of the masonry foundation, after the concrete has cured. (van Etten et al., 2007)

For this repair method to work there are a few preconditions: 1) the correct pile must be founded on a firm load-bearing sand layer (standing pile); on soft cohesive soil, the foundation would experience unacceptable settlement. 2) Only the top part of the pile is damaged as a result of fungal infection. 3) the infected pile is of spruce and not pine wood, as pinewood piles are also susceptible to bacterial attack even under the pile head. Also, this method does not raise the allowable bearing capacity of the foundation, other methods must be used for that purpose. (van Etten et al., 2007)

Figure 19 Left: buildings on wooden piles before and after pile head lowering; right: reinforcement of underpinning concrete structure ready to be cast (Photo: CJ Smith) (van Etten et al., 2007; VROM, n.d.)

New pile foundation "Table Construction"

In this method, new piles are constructed right next to the old piles on the inside of the building. A new floor is constructed on the ground floor or in the basement floor inside the building. For this method to work, there must be enough headroom at the level at which the construction is carried out. For pressed pipe piles, at least 180cm is required and for driven pipe piles, 230cm is required. (van Etten et al., 2007)



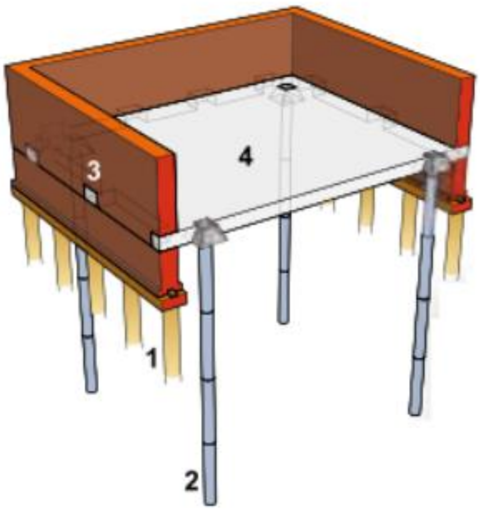
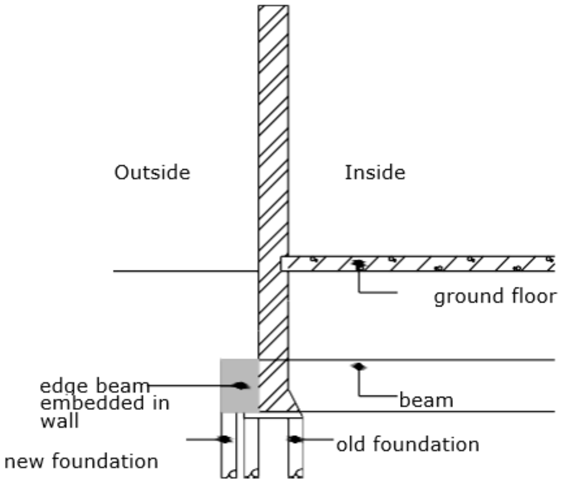


Figure 20 Left: schematic section of Board Construction; right: 1) old wooden piles, 2) new piles, 3) support for the new "board", 4) new reinforced concrete floor (van Etten et al., 2007; VROM, n.d.)

New pile foundation with edge beams

As the name of the method suggests, edge beams on the load-bearing wall are utilized. First, a trench is dug on the outside of the house around the load-bearing foundation wall. A row of new piles is then installed right next to the old wooden piles. On top of the new piles, a reinforced concrete beam is constructed with construction joints inside the foundation wall. The concrete beam can be precast or cast in-situ as well as prestressed. Instead of reinforced concrete, sometimes steel is also used for the edge beam. The edge beam can also be inside the building, provided there is enough headroom for installation. If the beam is installed outside then there needs to be enough space from the wall to the lot boundary.(van Etten et al., 2007)



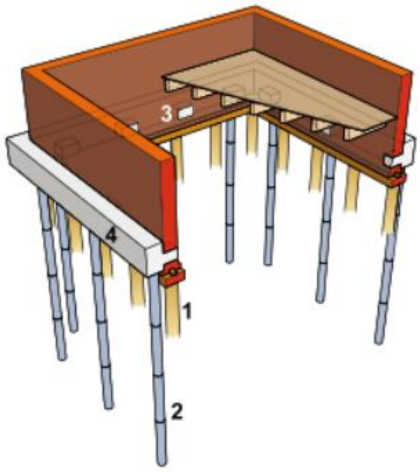


Figure 21 Left: schematic section of edge beam; right, 1) old wooden piles, 2) new piles, 3) support for the new edge beam, 4) new edge beam (van Etten et al., 2007; VROM, n.d.)

New pile foundation pressed from the wall

This method is developed relatively recently. In this method, piles are installed into the ground, directly supporting the existing load-bearing walls wall openings. These openings are carved into the load-bearing walls in dimensions of about 0.3 x 0.2 m x 1.2mH, at an interval of about 1 to 2 meters. From these cavities, a hole is drilled downwards through the masonry footing and then into the ground and well into a firm loading-bearing sand layer. A pipe pile 80-160mm in diameter is pressed into the hole segment by segment, coupled together welded or screwed together until it reaches the sand layer. Finally, the pipe pile is filled with concrete and the wall opening is filled. (van Etten et al., 2007)

The method can be carried out either inside the building (provided enough headspace) or outside the building with minimal disturbance to load-bearing walls. Other pre-requisites for the implementation of this method are 1) the masonry must be enough stiff and strong to press down the pipe without suffering damage and 2) the house must provide enough counterweight for the pressing of the piles. (van Etten et al., 2007)

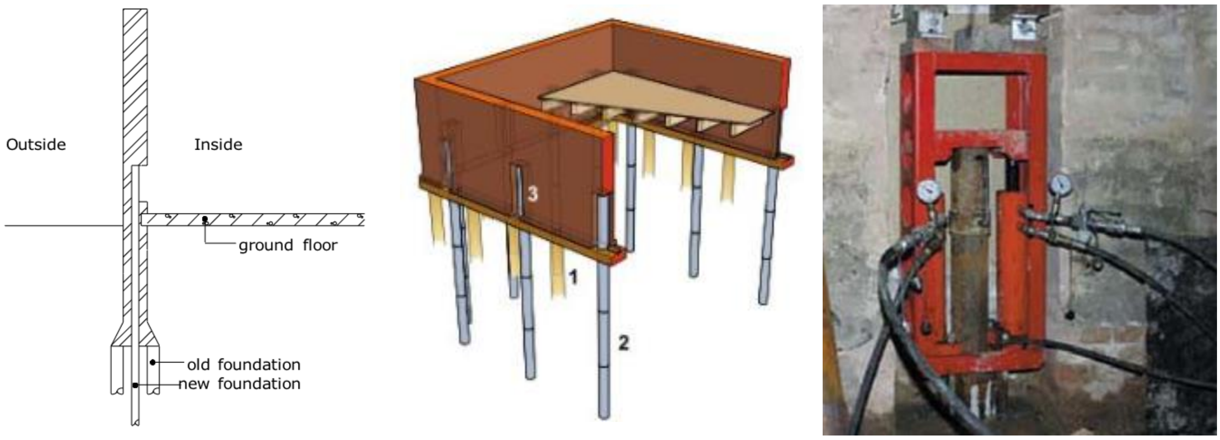


Figure 22 Left: schematic section of piles pressed from the wall; middle, 1 old wooden piles, 2 new piles, 3 wall opening of new foundation; right: set up of pipe pile pressing in the wall opening (van Etten et al., 2007; VROM, n.d.)

Finally, there is the method of jet grouting which aims to directly improve the soil properties and increase the bearing capacity and reduce settlement. Jet grouting is based on the execution of drill holes in the soil. After the execution, the hole is injected with a high-pressure grout (cement-based), which is released forcefully from the bottom of the drill hole all the way to the top, through the nozzles at the end of a drilling perforation rod. The grout mixes with the weak layer of sand. At the end of the process after the grout cures, there is a hard impervious grout column, which is also called a grout pile. When implemented underneath a historical building, this grout pile can be used to reinforce the historical building and can also be considered as underpinning. It can also be implemented as a soil improvement, where multiple closely packed small diameter shafts, called root piles, improve the bearing capacity of the founding soil. This method is reminiscent of the historical wooden compact piles mentioned in 3.2, but instead of wood cement grout is used. (Bowles, 1996; Mandala, 2002)

The choosing of the type of reinforcement to carry out is very much technically constrained firstly by the intended future use of the building. As mentioned, only the method of pile head lowering cannot increase the bearing capacity of the foundation. If the future use has a larger design loading, one of the other methods must be chosen. The second deciding factor is the site constraints of the building. As mentioned, the headroom of the crawlspace or ground floor decides if the piles can be installed indoors. The distance of the building to the site boundary decides whether or not the excavation can be carried out outside the building. Lastly, the extent of damages also restrains the choosing of methods, for example, only foundations with wooden piles rotten only at the top can be reinforced with pile head lowering. (van Etten et al., 2007) Jet grouting can also be implemented into some of the four Dutch renovation methods mentioned. For example, in “table construction” the pipe piles installed can easily be replaced by grout piles or root piles, when site restrictions allow.

Other determining factors of the method chosen concerning the owners or FM are risks of future settlement, cost of renovation, length of time, noise and disturbance to the user, renovation downtime, influence on adjacent ground, and dirt and damages to the building inside. And these factors are discussed here to help the owner understand how the decision.

Pile head lowering has the highest risks as the wooden foundation needs to be exposed through excavation, which in itself is risky, and the piles may develop more defects in the future. Also, the additional load capacity can be added. “Table construction” and jet grouting, on the other hand, have the lowest risks because they are the most extensive, do not require excavation and the bearing capacity of the soil can be optimized to almost any required stiffness for any future loading. Because of the level of benefits of these methods, it is not surprising that the least versatile method (pile head lowering) is the cheapest, while the most versatile ones jet grouting and table construction are the most expensive. (Bowles, 1996; van Etten et al., 2007)

It is also not surprising that the renovation that takes the longest time is “table construction” since it is the most extensive and an entire rebuilding of the ground floor is necessary, whereas the shortest construction time goes to piles pressed through wall openings. In addition to the renovation, the construction time also depends on the size of the foundation area, site constraints such as headroom, depth of excavation and refurbishment such as pipes and ground. (van Etten et al., 2007)

The renovation with the most noise and vibration is table construction, whereas the one with the least amount of vibration and noise is pile head lowering, with almost no vibration or noise (except if of course excavation and sheet piling for excavation is needed). Pressed piles through wall openings will also produce almost no vibration or noise, except for the noise when the wall openings are carved. (van Etten et al., 2007)

Another factor of concern to FM and owners is the indoor renovation downtime. Both pile head lowering and “table construction” will render the ground floor unusually if there is no basement or the construction cannot be carried out in the crawlspace. Part of the ground floor will also experience downtime in the method of piles pressed through wall openings when carried out indoors. Renovation downtime can be completely or mostly avoided if the edge beam method or the wall opening method is used and carried out outside the building. The trade-off of this is if the edge beam or pile head lowering is carried out outside the building, the impact on the nearby ground is very big and sufficient space outside needs to be reserved for the excavation work. Meanwhile, renovation work carried out indoor will have almost no impact on the neighbouring ground. There will also be no renovation downtime if jet grouting is carried out diagonally and locally from outside the building to reinforce the identified weak layer of soil underneath the edge of a building. (Joostdevree.nl, n.d.; van Etten et al., 2007)

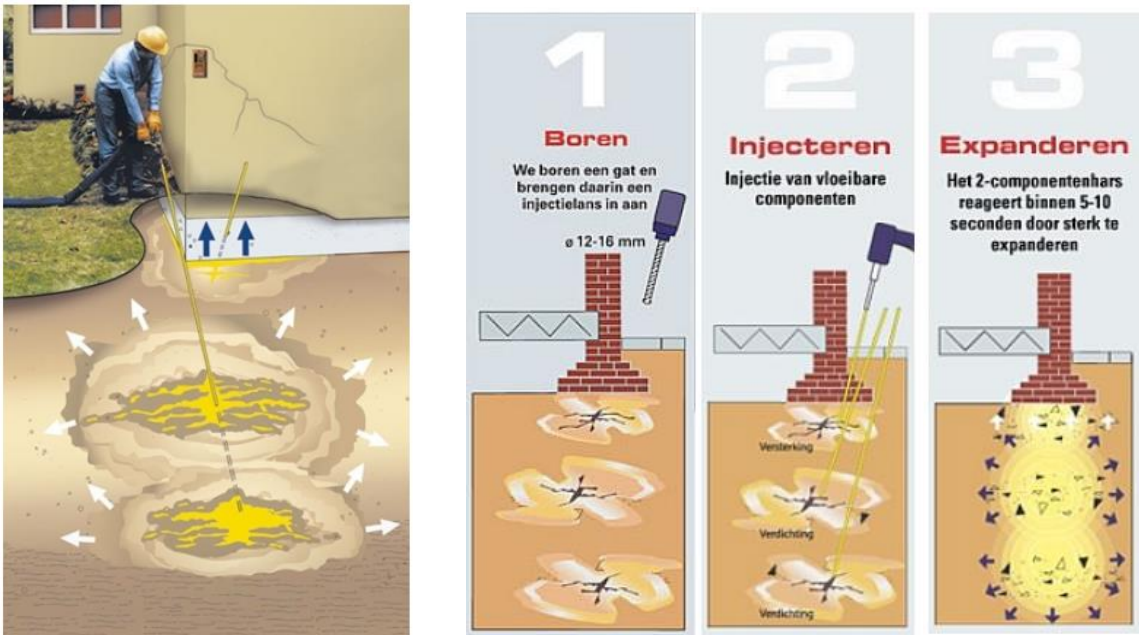


Figure 23 Left: diagram of localized jet grouting; right: procedure of 2 component resin grouting (Joostdevree.nl, n.d.)

In conclusion, the method of restoration is technically restrained by site conditions and the planned future use of the building. It is also a balancing act among different desirable factors, such as low construction time, cost and disturbance, no construction downtime and long serviceability of the reinforced foundation. The project manager or owner must balance the needs and wants of different stakeholders to make the most suitable decision for their building.

3.8 Preservation and Reuse of Historic Wooden Piles

In this section, the owner and FM will find out the arguments for preserving historical wooden piles, what might the legal requirements be and the benefits and significance of reusing historical wooden piles under a building.

3.8.1 Legal Matters

In many countries, monuments of historical values are protected under the law. Owners of buildings are obliged to preserve some parts of the building of particular historical value, even in capitalistic societies where private ownership is guaranteed. In Germany, the legal basis for obliging the owner to preserve the building can be found in its Basic Law Article 14 Paragraph 2 "Ownership obliges. Its use should also serve the public good.” According to Basic Law Article 30, the exercise of state powers is a matter of the federal states. Monument protection laws is thus a matter for the individual federal states in Germany. (Grundgesetz Für Die Bundesrepublik Deutschland, 1949)

In Berlin, the law for the protection of monuments is the “Denkmalschutzgesetz Berlin”. In it, four types of monuments are stipulated: architectural monuments, monument areas, garden monuments and ground monuments. In particular, ground monuments, refer to any objects, movable or immovable that are found in the ground or water, and the preservation of which is of public interest. According to the law, any ground monument found during the implementation of a building project must be notified to the authorities and the construction work must stop and the site must be preserved for further archaeological evaluations. It is in the category that the preservation of historical wooden piles might be mandated by law, such as the example of the wooden foundation of the Berliner Schloss. (Gesetz Zum Schutz von Denkmalen in Berlin, 1995)

There are many reasons why the public and hence the government might want to preserve historical piles in the name of public interest. Firstly, archaeological wood can be conserved in the anoxic and wet environment of the underground soil for thousands of years. Not only do they perform their structural functions throughout these years, but they are also an archive of history, as they tell us the history of construction technology in building. It is a record of past timber trade and craft. Special markings made by tradesmen and traders can sometimes be found on the tip of the piles. In addition, the climate changes throughout history are encoded in these wooden piles as chemicals and isotopes. Climate information can be extracted from the piles and the complete view of the development of the tree throughout its lifetime. (Klaassen & Creemers, 2012)

3.8.2 Benefits and Significance

Apart from the cultural benefits of conserving wooden foundations for the interest of the public, as discussed in 3.8.1, there are benefits to preserving and reusing wooden foundations after a building renovation for the owners as well. As mentioned in 3.6.3, wooden piles can be preserved in the ground for hundreds and thousands of years. A well-preserved wooden foundation can serve its intended purpose (support the superstructure of the building) for the owner for years and years.

Firstly, wooden piles foundations are usually found in early human settlements and historical centres. These historical centres tend to remain influential and the economic and cultural centre of the city and even country that they are located in nowadays, despite the fact that the historical towns suffer from wears and tears of times and damages from wars. In Germany, these historical parts of the cities are referred to as the *Altstadt*, meaning “old town”. There are even efforts to reconstruct old towns in Germany. Their old towns remain the economic centre and the demand for prestigious buildings in the central locations is high, and the availability of undeveloped virgin land in this area is very low. This means the buildings on top of these old piles are inherently valuable to the owners and also the operation time is of financial value to the owner. Preserving and reusing the wooden pile can reduce the downtime of the building due to the implementation time of a renovation project or restoration project. (Ramm, 2019)

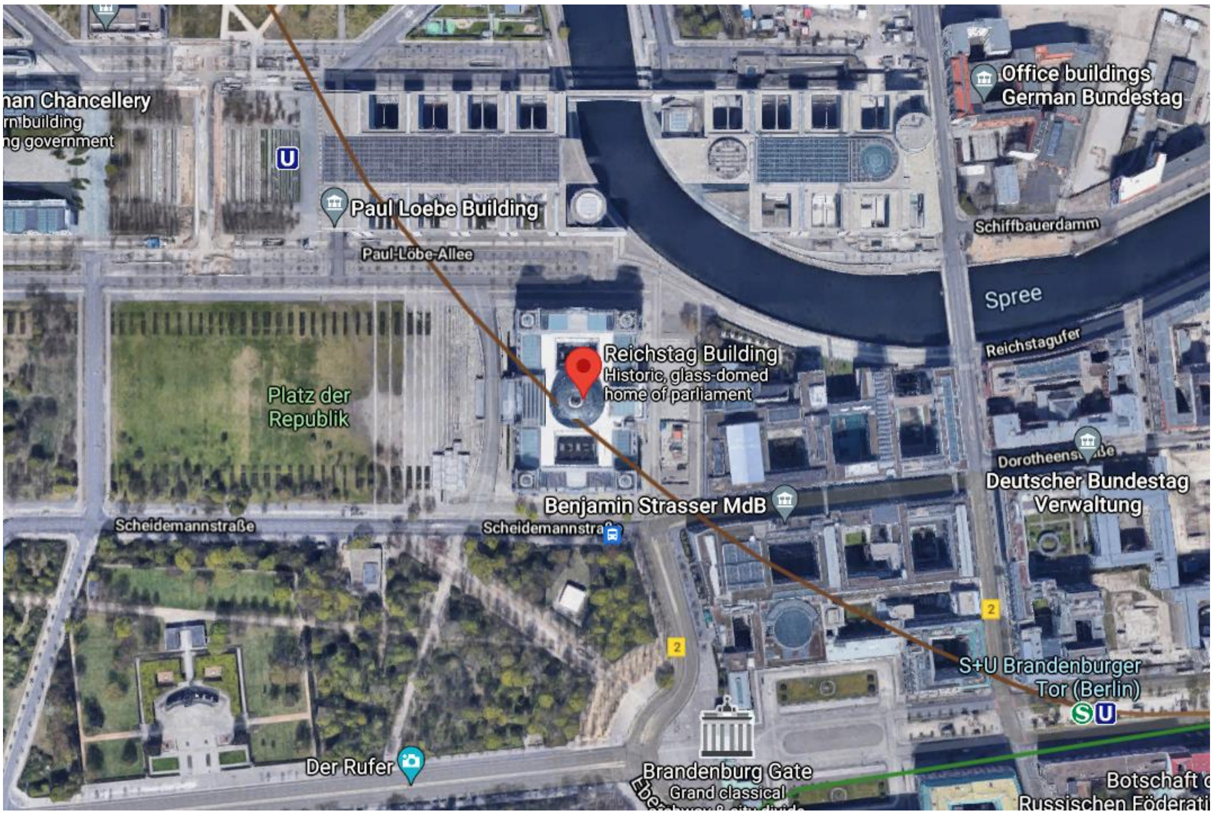


Figure 24 Location of Reichstag Building on top of U5(Google Maps, 2021)

The second reason for the reuse and preservation of foundations is also related to the location of the historical building. Usually, centrally located buildings are located in a crowded built environment, meaning it is likely a lot of services and infrastructure are required. In the underground space of the building, it is likely that it is crisscrossed by various structures such as tunnels for traffic routes, underground garages, canals and lines or sheeting walls from a neighbouring site. With all these obstacles underground, the production of new foundation elements is made more difficult, and it might be more practical and economical to reuse the wooden foundation of the building as much as possible even if there is renovation or alteration in the superstructure of the building. (Ramm, 2019)

One such example of a historical building with a wooden foundation and underground structure underneath is the Reichstag Building in Berlin, Germany. The Reichstag building is located in the heart of Berlin next to other important buildings and the river Spree. The underground railway U5 runs underneath it (see Figure 24). 5 m long wooden piles are present underneath the building’s north tower and have been previously damaged due to groundwater table lowering. During the renovation work of this building in the 1990s, laboratory tests, load tests and deformation evaluation was carried out to prove the serviceability of the historical wooden piles. Only micro piles and jet grouting was necessary in other parts of the building. The wooden piles were preserved and continued to be used underneath the then-new renovated Reichstag. (Ramm, 2019)

The third reason for reusing and preserving wooden piles is to do with the difficulties removal of old piles and installation of foundation. Not only can a new modern foundation be expensive and (sometimes) unnecessary, as in the case in the Reichstag, but the removal of the existing deep foundation could come as a technical challenge and often impose obstacles on the renewal projects. (Ramm, 2019) Technical challenges of the removal of the wooden piles could mean increased the project cost and time. Also, there might be a legal challenge on top of this. As mentioned in 3.8.1, historical wooden piles and their surrounding foundation can be declared as a ground monument. And this would oblige the owner to stop the construction work for archaeological exploration and even the preservation of the monument.

Finally, renovating and maintaining the pile can also avoid all the negative impacts of a faulty wooden foundation on the building, discussed in 3.5. It avoids building defects due to foundation problems, ensures the building is in a good running condition to avoid high operation costs and loss of income due to a bad indoor environment and renovation downtime. And conserving the wooden foundation also increases the building price any potential buyers would pay and the willingness of the bank to grant a loan based on the mortgage. From the end user's point of view, they can get better building services such as plumbing, sewers, surfaces, cellars.[18] This can be a win-win situation for all stakeholders involved.

3.9 Challenges of Conservation of Buildings with Wooden Piles

There are a lot of reasons to conserve wooden piles under buildings as discussed in 0. However, there are also challenges when it comes to conserving and renovating buildings with wooden piles. In this chapter, these difficulties from the owner and FM’s point of view will be discussed.

Firstly, since wooden piles are buried underground and hidden from view in our everyday life, they might be perceived by some as unimportant. And people might believe what they do not see is not worth preserving or maintaining or being proud of. (Klaassen & Creemers, 2012) According to a survey, there is also a difference in the perception of foundation between what is visible and what is invisible. Designers consistently view the visible part of the foundation more favourably and hence more deserving of preservation than the part of the foundation hidden in the ground. (Hesso, 2005) The lack of visibility also makes the assessment of the wooden piles difficult as engineers will have to depend on historical files, using GPR, or simply digging up the piles in order to get an accurate assessment of the condition of the piles.

The second problem is of the renovation of wooden piled is their bad image. Wooden piles in modern times evoke bad experiences of rotten piles and collapsed buildings. Wooden piles are seen as irrelevant or old-fashioned as far as modern-day buildings are concerned. A misconception about wooden piles is that their conservation is about craftmanship and not innovation. (Klaassen & Creemers, 2012)

[18] Response from a survey on underpinning projects in Turku (Hämäläinen, 2006)

Another problem is that investors of the building might not see the need for the restoration of wooden piles or the reinforcement of the wooden foundation, as necessary. From the investor's point of view, their objective is to make as much profit as possible in as little time as possible. Foundation strengthening is one of the biggest and most costly renovation projects for a housing company to take on. The investors of the company may not see any immediate benefits as a result of the strengthening or restoration project. This may lead to hesitancy from the investor's point of view to pursue the project. It was reported in a survey in Turku that FMs and investors can sometimes find themselves on opposing sides of whether or not to pursue the renovation project, where the FM has to act as the salesperson. In addition to that, long-term settlement monitoring can also help with the understanding of the problem and lead to the investor being convinced. Government credit is also important in convincing the investor. (Hämäläinen, 2006)

From the perspective of facility management, another problem lies with the facility managers themselves. The educational background of the FM is most likely not in construction. They may not have any training in the construction industry at all. According to a survey conducted in Turku in 2006, it is more likely that they have an educational background in commerce and trade. And it is also very likely that these FMs who are put in charge of an underpinning project of a building with a wooden foundation may not even have previous experience in foundation strengthening. For this reason, it is reported that FMs heavily valued the importance of good consultants and partners. The FM will have to rely on the expertise of the consultants to produce convincing arguments for the necessity of the pile renovation project so that they can effectively play the role of the salesman of the project and convince all any hesitant stakeholders to get on board. (Hämäläinen, 2006)

Another challenge to repairing wooden foundations is financial. As mentioned in 3.7, many of the renovation methods will lead to a renovation downtime when tenants have to temporarily move out. This may lead to a loss of income due to the place being vacated. Also, it is reported that owners may be less motivated to renovate the foundation due to a lack of government funding. Since the underpinning of the wooden pile foundation is a very specific renovation, there might be a lack of competition in the choice of contractors, especially if the building is located not in a big city, and this would drive up the renovation cost. (Hämäläinen, 2006)

3.10 Other Pile Conservation Issues and Innovative Methods

In this section, factors determining the conditions of wooden pile foundation which are outside of the owner's control and require cooperation with external parties are discussed. Also, the possibility of some innovative repair methods is discussed.

3.10.1 Fickle Nature of Groundwater Control

In maintaining the wooden pile, another challenge comes from the fickle nature of trying to maintain enough groundwater to protect the wooden piles from exposing to air and rotting. Groundwater as an element of nature is not always within the control of engineers, the FM, property owners, or even the local authorities. In the experience of the city of Boston, historical buildings with wooden piles suffer from both leaky underground pipes draining away groundwater as well as pipes *not leaking enough* water into the ground to resupply the groundwater level. (Snow, 2003)

No one agent is in society is able to completely maintain groundwater at a healthy level, but it only takes one malicious or inconsiderate actor to pollute or deplete the groundwater to harm an entire community with a building founded on wooden piles. In the 19th century, this was the “Big Pump Theory”, whoever had the most powerful pump could legally own the right to pump an entire neighbourhood dry of groundwater, under the absolute ownership model of real estate, with no legal repercussions. It was not until at late as 1972 in the United States that polluters of groundwater are legally required to pay and until the 1980s that the absolute ownership of groundwater is gradually regulated and abolished in the state of Massachusetts. (Snow, 2003)

In order to maintain the groundwater level, it takes all actors in society to cooperate and sometimes the intervention of law is necessary. In Boston Bay, Massachusetts in 1986, after lawsuits over the construction of a dam which caused the groundwater lowering and historical buildings cracking, the Boston Groundwater Trust was founded, to promote welfare “by monitoring groundwater levels and making recommendations to raise the water table in areas where it is low to protect wood pile foundations.” The Trust was given the privilege of accepting and spending donations to safeguard wood pile foundations by monitoring groundwater levels and offering recommendations to raise the water table in places where it is low. However, legal regulations can also cause their own problems. As now parties can be held individually responsible for the lowering of groundwater table, parties are not willing to divulge the monitoring or testing data, in fear of potential litigations. This might lead to groundwater problems not being identified early to prevent the rotting of wooden piles. (Snow, 2003)

In addition to individual actors, groundwater flows and levels are also determined by natural and manmade ecologies. In Boston, centuries of human activities, such as taming, fouling, filling, levelling, diverting groundwater for city use, and infrastructures such as transportation tunnels and dams, has transformed the Boston Basin from what was once a peninsula of “fountains of living waters” to place where wooden pile foundation struggle to have enough groundwater cover to prevent rotting, as groundwater is being depleted away. (Snow, 2003)

Different stakeholders have different and often contradicting motives when it comes to issues related to the groundwater table. In the case of Boston, owners and residents of the building on wooden pile foundations were, of course, eager for the groundwater table to be restored, but other parties who have the influence to do so have other objectives. For example, the Boston Water and Sewer Commission wants to provide a good quality sewer system and reduce leakage from their pipes but by fixing the pipes they also reduce the amount of water leaked from their pipes that was replenishing the groundwater used to protect the wooden piles. The Boston Redevelopment Authority wants to reduce flooding and abate pollution of the Boston Harbor, but replenishing the groundwater table is not on their agenda. As shown by this example, water management is multifaceted, and there is a fine balance to be struck between preventing flooding by better drainage and preventing the excessive drawdown of the groundwater table. (Snow, 2003)

The condition of wooden piles which is heavily tied to the groundwater table of the neighbourhood is not always something the FM or owner can control. The environment and trends that can affect the wooden pile foundation are something owners and FMs need to be constantly vigilant about.

3.10.2 Constant Vigilance for Changing Environment

As a continuation of 3.10.1, this section discusses what constant maintenance of wooden piles and monitoring of groundwater requires, actions that should be taken by different stakeholders when there is an unhealthy drawdown and what was the experience of residents and homeowners of the Boston Metropolitan Area.

In Boston, the groundwater today is meters below the level of the nearby Charles River, which is where the natural groundwater table should have been, and this is detrimental for the maintenance of wooden piles in the entire area and at a steep cost to homeowners. The main cause is the leaking and draining of groundwater into man-made underground structures such as pipes and tunnels. The sewer pipes in Boston act as both sewerage and storm drains and is designed to have such great capacity that it is almost always empty. Through the ages, cracks have started forming in these century-old brick structures and started draining the groundwater away. The problem is exacerbated by the impervious cover and lack of green space in the city and the deliberately placed under-slab drains in developments such as underground car parks in condominiums. This prevents the infiltration of precipitation into the ground and the replenishment of groundwater. (Lambrechts, 2008)

The first proposed method of fixing the groundwater table problem is the fix the cracks in the old brick sewer structures. However, these cracks are all over the place and it is practically impossible to find them all. Fixing these cracks would only rise the groundwater by a few centimetres much less than what is required to protect wooden piles and cracks can form again in the future. The task of fixing older sewers is never-ending. Other preventative methods are also proposed, such as legislation against underdrains in new developments that do not take into account the groundwater needs of the wooden piles of the buildings in the vicinity. (Lambrechts, 2008)

Another route towards fixing the groundwater table problem is proactively recharging and raising the groundwater levels. Recharge systems have existed in Boston as early as 1929. A system of perforated pipes embedded in gravel was used to let surface drainage infiltrate directly into the ground in Copley Square in front of Trinity Church, Boston. After the installation of the system virtually no precipitation needs to run off to the street drains again. In addition to this, Trinity Church also used the roof drainage to recharge the groundwater through recharge pits, in order to protect the

4500 wooden piles that the church is founded on. More sophisticated systems would monitor the groundwater level and only activate when the level falls below a certain level to protect the piles. (Lambrechts, 2008)

Such recharging systems had been local and voluntary installed at the discretion of the owners. This is until 2005 when the Boston Redevelopment Authority took an interest in recharging groundwater and enacted the Groundwater Overlay District designation of areas affected by the drawdown of groundwater. When district-wide groundwater recharging is incorporated into public policy, it is possible to legislate to require any new development and buildings undergoing large renovations to install groundwater recharge systems to redirect rainwater collected at the roof into dry wells in the ground (see Figure 25). Such endeavours will require hydrogeology investigations beforehand and should see results of rising groundwater levels in decades to come. This spreads out the economic burden of repairing wooden piles to the entire community and will also lower the burden of city drains and the possibility of floods in the long run. (Lambrechts, 2008)

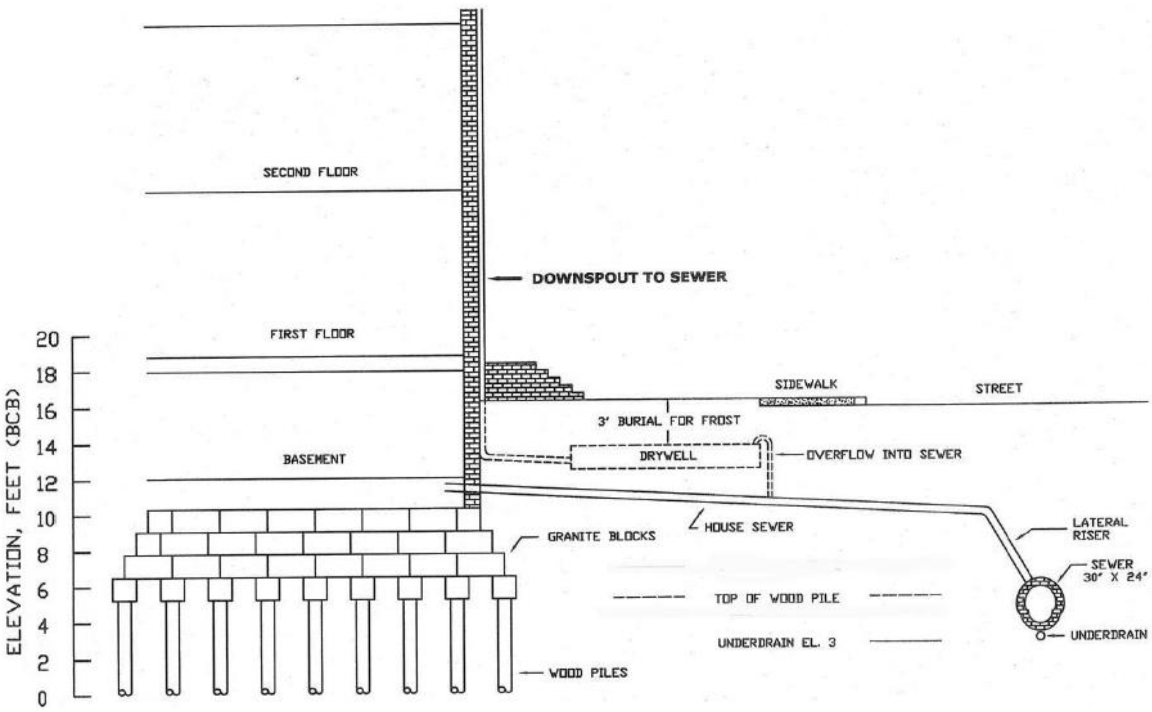


Figure 25 Cross Section of a Building Connected to an Existing Underdrain and Proposed Recharge Drywell (Lambrechts, 2008)

3.10.3 Innovative Repair Methods

In Turku, Finland, a new model is proposed to determine the need, the extent, the timing of micropiles necessary for the underpinning of wooden pile foundations, based on the settlement behaviour of wooden piles. According to the DATU database, the settlement speeds of both standing piles (end-bearing piles) and floating piles (skin-friction piles) are categorized into three stages of the life cycle of the pile. By monitoring the speed of settlement of the foundation, the owners in Turku can compare it to that of the average in the city (see Table 3) and estimate at which stage of the life cycle the building foundation is and when underpinning will be necessary. (Lehtonen et al., 2010)

Stages of life-cycle and types of piles	Annual settlement s on average mm/year
C1, skin-friction wooden piles	s < 4
C2, skin-friction wooden piles	4 ≤ s ≤ 6
C3, skin-friction wooden piles	s > 6
E1, end-bearing wooden piles	s < 2
E2, end-bearing wooden piles	2 ≤ s ≤ 4
E3, end-bearing wooden piles	s > 4

Table 3 Average speed of settlement of wooden pile foundations before renovation in Turku according to DATU (Lehtonen et al., 2010; Turku AMK, 2007)

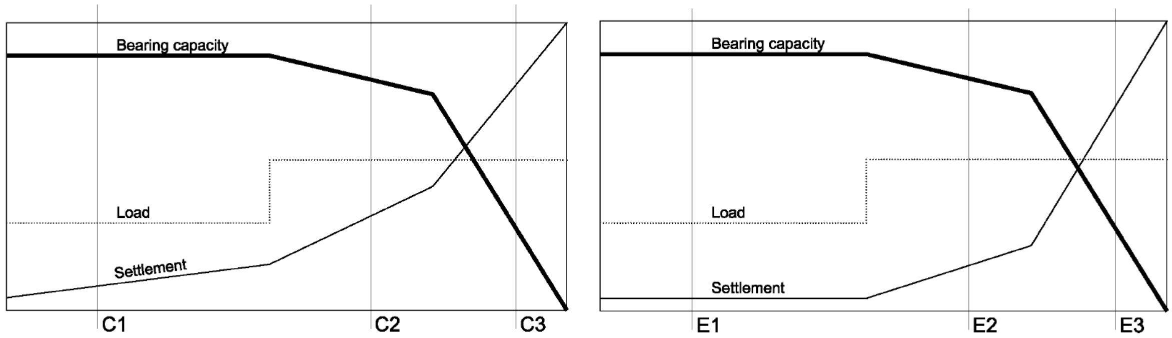


Table 4 Graphical representation of bearing capacity and expected settlement in different stages of the life-cycle of, left, skin-friction wooden piles and right end-bearing wooden piles.[19] (Lehtonen et al., 2010)

For this method to be implemented, the owners should have an idea of what type of piles is underneath the building to find out the level of the expected settlement. Also, the owner or FM will have to monitor the settlement in the long term, and this should be incorporated in the routine maintenance or part of the strategic maintenance planning.

[19] End-bearing piles at the beginning of the life cycle, E1, should experience little to no settlement at all, whereas skin-friction piles at the beginning, C1, already have more expected settlement.

Another repair method is to use composites to repair the damaged wooden foundation. Composites are materials made of a matrix and a reinforcement. The matrix is usually a type of resin, such as epoxy or vinyl ester, while the reinforcement bound by the matrix is a type of fibre such as Kevlar and aramid. (Petrescu et al., 2021) In the following paragraphs, two types of material and their use in repairing damaged wooden pile foundations are discussed.

The first of these materials is the Wood-polymer composites (WPCs) is a kind of composite material with the matrix of a plastic (usually made of Polyethylene (PE)) and reinforcement material which is made of wood fillers (flour and fibres). WPCs can be quickly and continuously produced. They are durable and require minimal maintenance. Also, the wood filler is a more sustainable alternative to traditional inorganic fillers, since it is reusing waste wood. Since PE is not a very adhesive material to wood, a coupling agent or compatibilizer is required. This agent is proposed to be maleic anhydride grafted polyethylene (MAPE) or polypropylene (MAPP) to make the material more compatible with wood. In addition, clay nanoparticles are also added to the mix to improve the deformation behaviour of the material and form the Wood/Polymer/Clay Nanocomposites (WPCNs). These WPCNs are found to have a Young's (tensile) modulus high enough and comparable to that of wood, meaning the material is stiff enough and does not deform excessively under stress. In the report, it is stated that decaying wood specimens simulating decaying conditions of foundation wooden piles will be treated with WPCNs and tested in the future. (de Kee et al., 2008)

Another such material is the so-called "Liquid Wood", which is a biocomposite material developed in Germany. A biocomposite is a composite material whose matric is completely biodegradable and whose reinforcements are made of natural fibres. "Liquid Wood" is made of a naturally occurring matrix, lignin, which is what gives plants strength and a reinforcement of natural fibres such as hemp and straw. The result is a completely biodegradable and eco-friendly material, which is more sustainable than traditional composites made of PE, derived from petroleum products with a large energy footprint. "Liquid Wood" is tested to have comparable tensile strength like traditional wood. It is stated that it could be used to repair existing decaying wooden structures. (Petrescu et al., 2021) Both these materials deserve further investigation as repair methods of wooden piles.

4. Case Study: Berliner Schloss (Berlin Palace)

The history of the Berliner Schloss or the Berlin Palace is a story full of twists and turns as the palace lived through its many lives. Most fittingly, the story of its wooden pile foundation is just as interesting and almost as controversial. In this case study, a brief history of the palace is given, with a focus on its wooden foundation. And then a deeper look is dived into the most recent reincarnation of the palace. When the new Humboldt Forum was built, a new foundation was built. In this section, an alternative proposal is looked into, and the renovation cost of the alternative renovation is calculated and compared to that of what was carried out for the Humboldt Forum.

4.1 Brief History of the Site

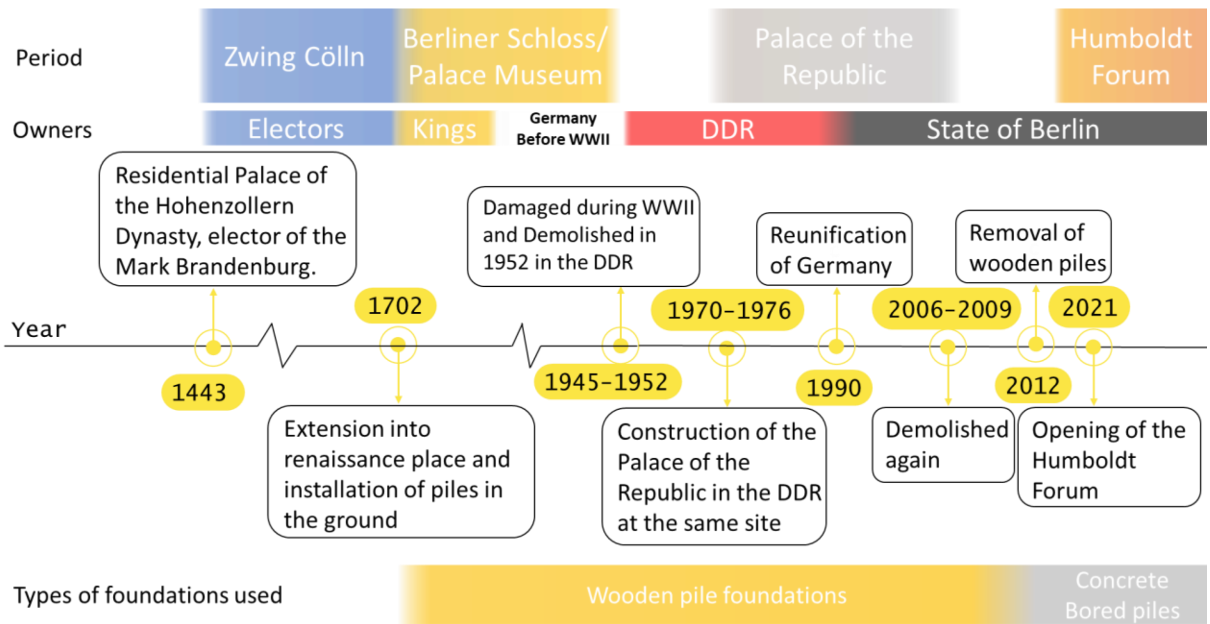


Figure 26 Timeline of the Berliner Schloss, major events and type of foundation used

The palace known as the Berliner Schloss today was founded in 1443 and ordered by the Elector of Mark Brandenberg, Friedrich II, as the Zwing-Cölln Castle. It was used as the residence of the Hohenzollern-Dynasty. Located at the edge of the twin-city of Alt-Kölln and Alt-Berlin, on today’s Museum Island in Berlin, the castle was also used as a city defence. (berliner-schloss.de, n.d.; Malliaris & Wemhoff, 2016)

For the next 260 years, the castle has gone through wars and the castle has changed hands from elector to elector. Major renovations and expansions were also carried out. Most notably, in 1536 the Dominican Monastery, on what is today's Schlossplatz, was dissolved and the building was remodelled and the palace expanded into the church area. In 1608, the palace expanded yet again at the expense of rendering the church smaller (see Appendix A Plans of the Berliner Schloss from 1451 – 1936). (Malliaris & Wemhoff, 2016)

In the year 1701, however, Elector Fredfrich III because the first King in Prussia Friedrick I and the castle has now become the primary residence of a king and the political centre of the new Prussian kingdom. This means that the palace needed an upgrade and be transformed into a renaissance palace, and Architect Andreas Schülter was ordered to do that. In 1706 however, the Mint Tower catastrophe happened, which was a botched extension due to a geotechnical error that led to the tilting and eventual demolition of the new Mint Tower. Schülter was sacked for that and replaced by Johann Freidrich von Eosander who completed the planned building of the "Neuen Schloss" (new palace). (berliner-schloss.de, n.d.; Malliaris & Wemhoff, 2016)

It was this renovation that gave the Berliner Schloss that has remained almost unchanged until WWII and this was when the wooden pile foundations were installed. Throughout the next two centuries, the building has changed hands from king to king and the state of Germany was founded in this period. The palace served as the main residence of the monarch at the time, until the Weimar Republic was established in 1918. The Berliner Schloss was turned into the Palace Museum and then was also used by other academic associations like the Kaiser Wilhelm Society (present-day Max-Plank Institute). (berliner-schloss.de, n.d.; Malliaris & Wemhoff, 2016)

However, the life of Berliner Schloss would soon come to an end. The Nazis took over the control of the country and the building to carry out propaganda events. In 1945, the Berliner Schloss suffered severe bombings and was almost completely burned down. The Nazis were then defeated and Berlin was captured by the Soviet Union. The ownership of the ruins of the building was transferred to the then-established DDR, former East Germany in 1949. And in 1950 the DDR decided to demolish the building altogether. (berliner-schloss.de, n.d.; Malliaris & Wemhoff, 2016)

The Palace would find a new life again as the new Palace of the Republic that was built at the same site between 1974-1976.

and looked nothing like the old Berliner Schloss. After its opening, it was used by the general public and officials alike. However, the Palace of the Republic was also short-lived. As Germany re-unified in 1990, asbestos was found in the Palace which had to be closed, and in 2006-2008, the building was demolished. (berliner-schloss.de, n.d.; Malliaris & Wemhoff, 2016)

In 2002, the Federal Republic of Germany decided to reconstruct the Berliner Schloss which is based on the exterior look of the Berliner Schloss in 1900 and that the Humboldt Forum, what is proposed to be “Germany’s equivalent of the British Museum”, will be hosted in it. The construction of the “new old Berlin Palace” began in 2012, and in 2021 after delays due to the COVID-19 pandemic, the Humboldt Forum is finally open to the general public. (berliner-schloss.de, n.d.; Humboldt Forum, 2021; Malliaris & Wemhoff, 2016)

Figure 27 Opening of the Humboldt Forum (Photo: Author, 2021)

4.2 When, where and why were the wooden piles used?

When Friedrich von Eosander took over the project of expanding the palace for the Prussian King in 1707, it was just one year after the Mint Tower catastrophe. He planned to double the palace in size to the west, which made Eosander’s Portal (the later Portal III) do directly on top of where the remains of the demolished Mint Tower had been. Since the cautionary example of Schlüter's design had only been removed in 1708, Eosander feared that his portal would suffer the same fate on top of the weak soil. To strengthen the foundation, Eosander laid a foundation so solid, “the likes of which no one has seen before”. (Malliaris & Wemhoff, 2016)

The wooden foundation consisted of three parts: at the bottom, thousands of tightly packed pine piles up to ten meters in length were driven into the subsoil with low-lead rams; on top of it was a precisely leafed wooden grate made of 30 cm thick pine beams; and on top, an 11 cm thick planking made of horizontal oak beams fixed with 30 cm long iron nails. Essentially, the foundation is a mix between a wooden compaction pile foundation and a deep foundation, with a *Schwellengründung* on top (see 3.2). The wooden foundation was protected underneath the high groundwater table of the nearby Spree River. On top of the wooden foundation sits the stone foundation, several metres thick. The western wing and the Eosander’s portal were completed by 1713, but the foundation works of the southeast of the portal had only just begun. (Döhner & Antkowiak, 2013; Malliaris & Wemhoff, 2016)

Eosander was replaced when the first King of Prussia Frederick I died. He was succeeded by Martin Heinrich Böhme in 1714, who completed the 116 x 192 metre square of the palace by closing out the southern segment of the Eosander wing and the Schlossplatz wing.[20] It was also under Böhme, that all the buildings within the church area fell victim to the expansion of the palace and were removed. (Malliaris & Wemhoff, 2016)

During the excavation of the palace in 2011 and 2012, the remaining wooden foundation of the Berlin Palace on the northwest was examined in 2012. The archaeological exploration was carried out on the former mint tower, parts of the Eosander wing and the former Lustgarten. The wooden foundation mentioned was discovered and 42 cubic metres of samples were taken. (Döhner & Antkowiak, 2013)

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[20] For the locations of different wings, please see Appendices A3 and A4.

4.3 What happened to the wooden piles?

The fact that the old Berliner Schloss was demolished in 1950 was very controversial. It was criticized by many today. The Association Berliner Schlosses e.V. even went so far as to say it was an act of barbarism. (berliner-schloss.de, n.d.) However, most of the wooden foundations of the 1706 Eosander renovation did survive the 1950 demolition. It was during the construction of the new Humboldt Forum of the new Berliner Schloss that the wooden foundation was completely destroyed. (Loy, 2012)

Before the foundation of the Humboldt Forum was laid, about 3000 historical pine and oak piles, up to 10 meters long were pulled out and transported away for recycling. According to reports, the piles that were dug up were all well preserved by the groundwater and the anaerobic soil conditions. The piles have been petrified over the years under these conditions. This protects the pile against rotting even better. (Loy, 2012)

Figure 28 Removal of historical wooden piles in the Berliner Schloss site (Loy, 2012)

As discussed in 3.8, there are many benefits in preserving and reusing historical wooden piles in a building under renovation. This sentiment is echoed by Wilfried Wolff from the Monument Committee of the Baukammer Berlin who said that new concrete piles did not have to be constructed at the expense of the old wooden piles. The Humboldt Forum Foundation, however, refers to the difficult building site and the U5 Tunnel, which is expected to run underneath the construction site and the piles must be removed there. A part of the historical foundation will be preserved in a history window in the Historical Basement of the Humbodlt Forum where the wooden piles will be on display (see Appendix C). (Loy, 2012)

A brand-new concrete foundation was used for the new Humboldt Forum, with a large concrete slab sitting on top of 40 m deep concrete piles. The reasons cited for the preference of concrete foundation was cited the new U5 underground tunnel as well as the layer of peat underlying the foundation. It was reported that the piles did not penetrate the soft layer of soil deep enough. (Berliner Schloss e.V., 2013)

However, this is not the end of the controversial story of the historical wooden piles of the Berliner Schloss. The piles were removed and then taken away for auction. According to reports, about 2000 piles were purchased at a price of around 500 Euros If the numbers are correct, this would generate a proceed of about 1 M Euros. However, the State of Berlin will not see a Eurocent of this because they all went directly to the recycling company that cleaned up the building site. The salvage and clean-up cost was 65 Euros for each pile. On the other hand, some wooden piles are being turned into wooden flooring by a wood wholesaler, who said they can provide a totally of 8,000 square metres of palace floorboard at a unit price of 189 Euros per square metre. This can amount to 1.5 M Euros of income. The company bought 9 truckloads of wooden piles a total cost of 50,000 Euros at the auction in 2013. It is no wonder that Berlin was accused of auctioning its history away. (COLMENARES, 2015; JAUER, 2013; STOLLOWSKY, 2013)

Figure 29 Promotional Brochure for Berliner Schlossdiele: the Floorboard with History (Berliner Schlossdielen, n.d.)

4.4 Estimation of Alternative Renovation Costs and Comparison

An alternative proposal could have seen the historical wooden piles preserved. Similar buildings in the vicinity have been renovated in such a way. For example, when the Neues Museum was rebuilt, the wooden piles were preserved and reused.

In this cost calculation the following assumptions are taken:

- The entire historical foundation will be preserved.
- The renovation method for the foundation is “table construction” over the entire footprint of the building, the courtyards in the middle included: 116 x 192 square metres.
- Construction cost is estimated to 2013 value according to the construction index (see Appendix D1)
- The unit prices are given in the Dutch TNO report and the paper by Lehtonen (see Appendix D2 and Appendix D3)
- The cost includes the implementation of the work as well as the project management costs.

The calculated cost of the proposed alternative foundation for the Humboldt Forum is 40 million Euros (2013 costs) (see Appendix D4). The total construction cost of the Humboldt Forum im Berliner Schloss, which is reported to be about 680 million Euros. (SCHÖNBALL RALF, 2021) Compared to the total construction cost, the renovation of the wooden foundation is only 6% of the total cost, which is much lower than the 11.6% average percentage of foundation cost in total construction cost.(Taylor, 2015) As this cost estimation shows, not only does preserving the foundation have cultural benefits it can also be a financial benefit as money can potentially be saved.

5. Discussion

Decision-making for Owners

In Section 3 Knowledge Owners Ought to Obtain, different topics regarding wooden foundations are brought to the attention of the owner and FM. As mentioned in 3.9, one of the challenges of maintaining the wooden foundation is that the FM or the owner may not come from an engineering background and may lack the technical know-how. This section serves to increase the knowledge of the owner and FM. In addition, a flow chart is also proposed, based on the knowledge in Section 3 to help the owner or the FM make decisions about a building that potentially have a wooden pile foundation. The flowchart is given in Appendix F Flow Chart of Wooden Building Foundation Maintenance.

Factors Owners Cannot Control

There are also other stakeholders in society that can affect the outcome of a wooden foundation. Namely, the most important factor is the groundwater level in a neighbourhood full of buildings supported by the wooden foundation, like in the case of the Boston Metropolitan Area, as disused in 3.9 and 3.10.1. In this case, legislation and coordinated management of groundwater are needed. It is also in the public’s interest when the burden of maintaining wooden piled buildings is spread across the whole society. In addition to that, government subsidy is also important in helping owners decide to keep and renovate the wooden foundation.

Renovation of Wooden Foundation as Part of Sustainable Development

The benefits of preserving and reusing the wooden pile foundation have been thoroughly discussed in 3.8, especially from the owner’s point of view. However, it should also be highlighted that these benefits are also in line with the Sustainable Development Goals of the United Nations. In terms of reducing the need for a new foundation or superstructure renovation, preserving and reusing wooden pile foundation can be seen as being aligned with Goal 12 Responsible consumption and production. As the production of concrete that would otherwise be needed is a big contributor to greenhouse gasses in the building industry, preserving and reusing wooden pile foundations is also in line with Goal 13 Climate Action. Strengthening the building to improve the building infrastructure and building envelope can also be seen as in line with Goal 9 Industry, Innovation and Infrastructure. In line with this goal are some innovative ways of implementing wooden pile foundation repair also discussed and they should be further investigated. (United Nations Department of Economic and Social Affairs, 2021)

Life-Cycle Lessons from the Berliner Schloss

The life cycle of wooden pile foundations can vary a lot. As discussed in 3.6.3, when kept in optimal conditions, a wooden pile can have a service life of thousands of years, outliving the building that was built on top of it. Such was the case of the wooden foundation underneath the Berliner Schloss which had been in service for 300 years surviving the bombing of WWII and twice the demolition of the building on top until it was taken out to make way for the new Humboldt Forum. The controversial point about this case study is that the historical wooden piles were auctioned away, and the State of Berlin was accused of auctioning away its history, even though the state of Berlin did not see on Eurocent of this income as it went to the recycling company. It can also be argued that this is an innovative way to dispose of and create value from what would otherwise be “construction waste”. But the fact that the piles generated about 1M Euros in proceeds of sales and one company could potentially make 1.5M Euros from the products that are produced from the piles that they bought from the auction, could also speak to the argument that they perhaps the piles are seen as valuable by the public and should be preserved in-situ. After all, can you put a life-cycle cost on 300 years of history and culture?

Future outlook of wooden pile foundations

As for the future outlook of wooden pile foundations, many current trends may affect the value of wooden foundations and hence the owners' willingness to maintain them as well as challenge the long term preservation of wooden pile foundations that owners need to look out for. In the medium term, Europe is experiencing a rise in timber and construction prices right now, especially after the COVID-19 pandemic. This might be a motivating factor for the owner to maintain and repair the wooden foundation in order to avoid an increasingly expensive construction cost. As part of the NextGenerationEU programme, the 800-billion-euro recovery programme to help Europe recover from the COVID-19 pandemic, owners may also get more government funding for repairing foundations under the regional development programme. (European Commission, 2021) In the medium to long term, there is also the housing crisis and the shortage of land, especially in city-centre locations. This will also act as a motivating factor for the owner to preserve the wooden piled building as usually historical buildings are located in historical centres and are still economically important today.

On the other hand, however, the continued development and densification of city centres would pose a challenge to the preservation of wooden piles. As overdevelopment will lead to increased excavation activities, increased traffic vibration, increased underground utilities and tunnels as well as a depletion of groundwater. As discussed in 3.9 and 3.10, all of these factors are detrimental to the preservation of wooden pile foundations. Another challenging factor is the ongoing climate crisis as well as groundwater crisis worldwide (Famiglietti, 2014). The global groundwater crisis is not good news for the preservation of wooden pile foundations as wooden piles need wet conditions in soil to be protected and long-lasting. The climate crisis and the overdevelopment of city centres are only making matters worse. Their impact on wooden pile foundations should be evaluated and owners and the government should be prepared to take preventative measures for it.

Limitations of this Thesis

Admittedly this thesis relies heavily on literature review. This is mainly due to the lack of a database on wooden piles in Europe like the now-defunct DATU. Even though the FM and owner's perspective is supplemented in this thesis by the interview carried out by Hämäläinen (see footnote 18 on page 45). Further research could be benefited from a more first-hand response from owners and FMs to further verify the claims of this research.

Secondly, the lack of material in English and the author's little knowledge of German are also an obstacle in trying to obtain the relevant information required to complete this thesis. At some point, the author had to coin an English term because there simply is not a term for it in English. Hopefully, in completing this thesis, the lack of English material in this subject matter can be improved.

Finally, due to the lack of data from Berliner Schloss construction, the alternative cost estimation is only that, an estimation. Further research could benefit from more investigation in the justification of removing and selling the 300 years old wooden piles.

6. Conclusion

In summary, what is hidden in the underground can nonetheless be very important to the overall health, stability and safety, serviceability, maintenance, operation and value of the building. However, since the foundation is not seen, it is often not given enough attention.

The formulated questions at the beginning of the thesis are answered. It turns out that many owners are willing to preserve buildings with failing wooden pile foundations, even though sometimes they need a push from the FM and the FM needs to sometimes take the role of the salesperson to promote the renovation of wooden foundations, as building problems arise. Owners can face many difficulties in preserving or renovating wooden pile foundations, both internal and external. These difficulties are a lack of knowledge and experience, a lack of government funding, and external threats like excessive groundwater drawdown from city densification that the owner cannot control. A building with a well maintained or renovated wooden pile foundation can have many benefits. First, it avoids and mitigates the problems of a poorly maintained foundation. Also, it creates value in both increasing the serviceability of the building as well as avoiding an ever-increasing construction cost of a new foundation, not to mention the inherent cultural value of preserving a historical artefact. Some innovative and sustainable ways of renovating and preserving wooden piles are looked into, such as the use of a groundwater monitoring and replenishment system as well as the use of eco-friendly composites in wood repair. In addition to this, this thesis hopes to serve as a guide for owners and facility managers in maintaining a wooden piled building and managing a renovation project of a wooden pile foundation. For that purpose, a flowchart for decision making is given in Appendix F.

There future outlook of wooden pile foundations has both opportunities and threats. On one hand, the rising timber and construction prices, shortage of land and housing crisis, and future EU funding might motivate the preservation and renovation of wooden piles. But on the other hand, the overdevelopment of cities, climate change, and the groundwater crisis might threaten the future wooden pile foundations in Europe.

Declaration of Authorship

I hereby declare that the attached Master's thesis was completed independently and without the prohibited assistance of third parties, and that no sources or assistance were used other than those listed. All passages whose content or wording originates from another publication have been marked as such. Neither this thesis nor any variant of it has previously been submitted to an examining authority or published.

Berlin, 30 July 2021

Location, Date

Lau Siu Kong

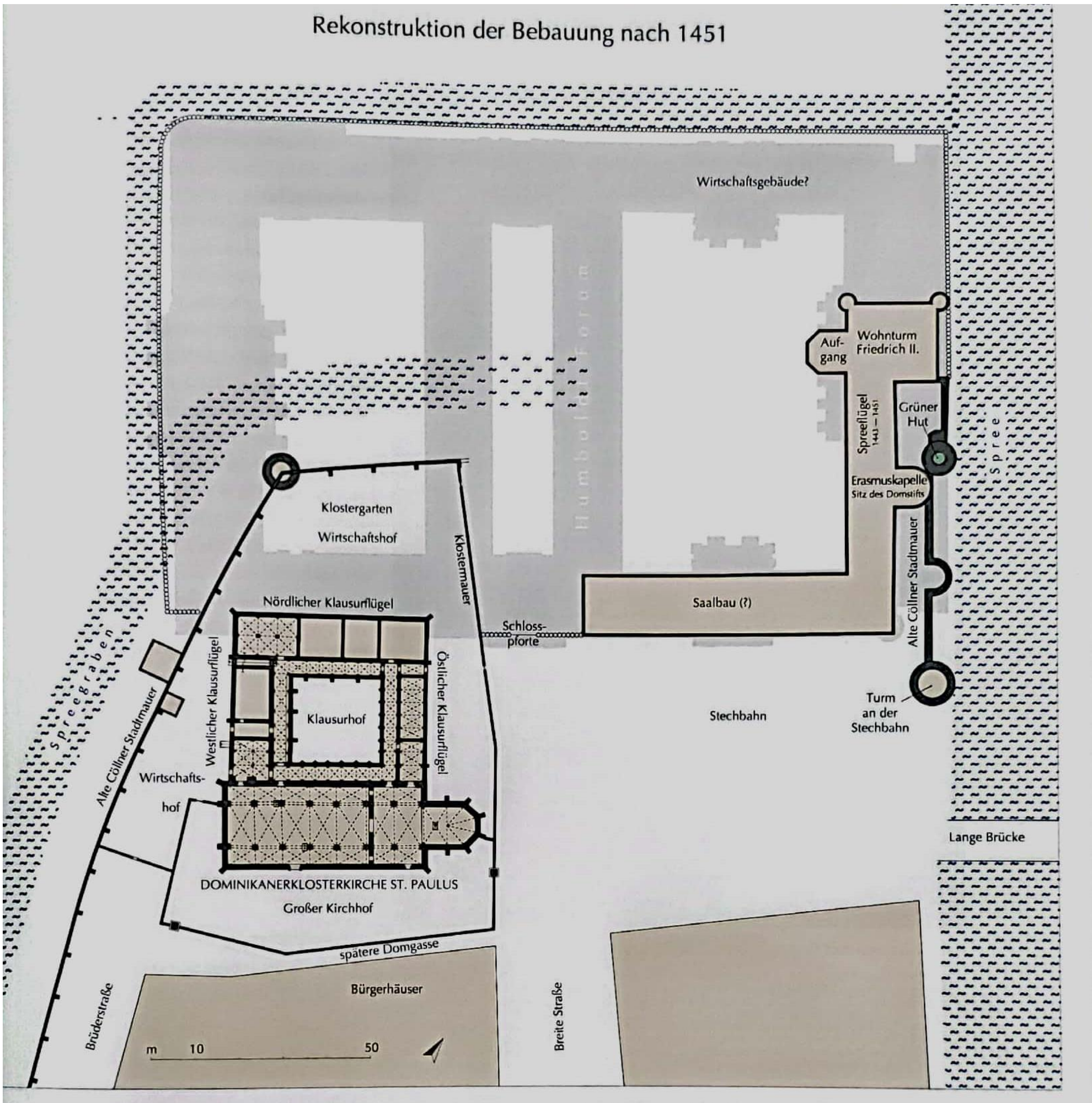
Signature of the student

Consent of publishing the Master`s Thesis

(Document redacted for the public version)

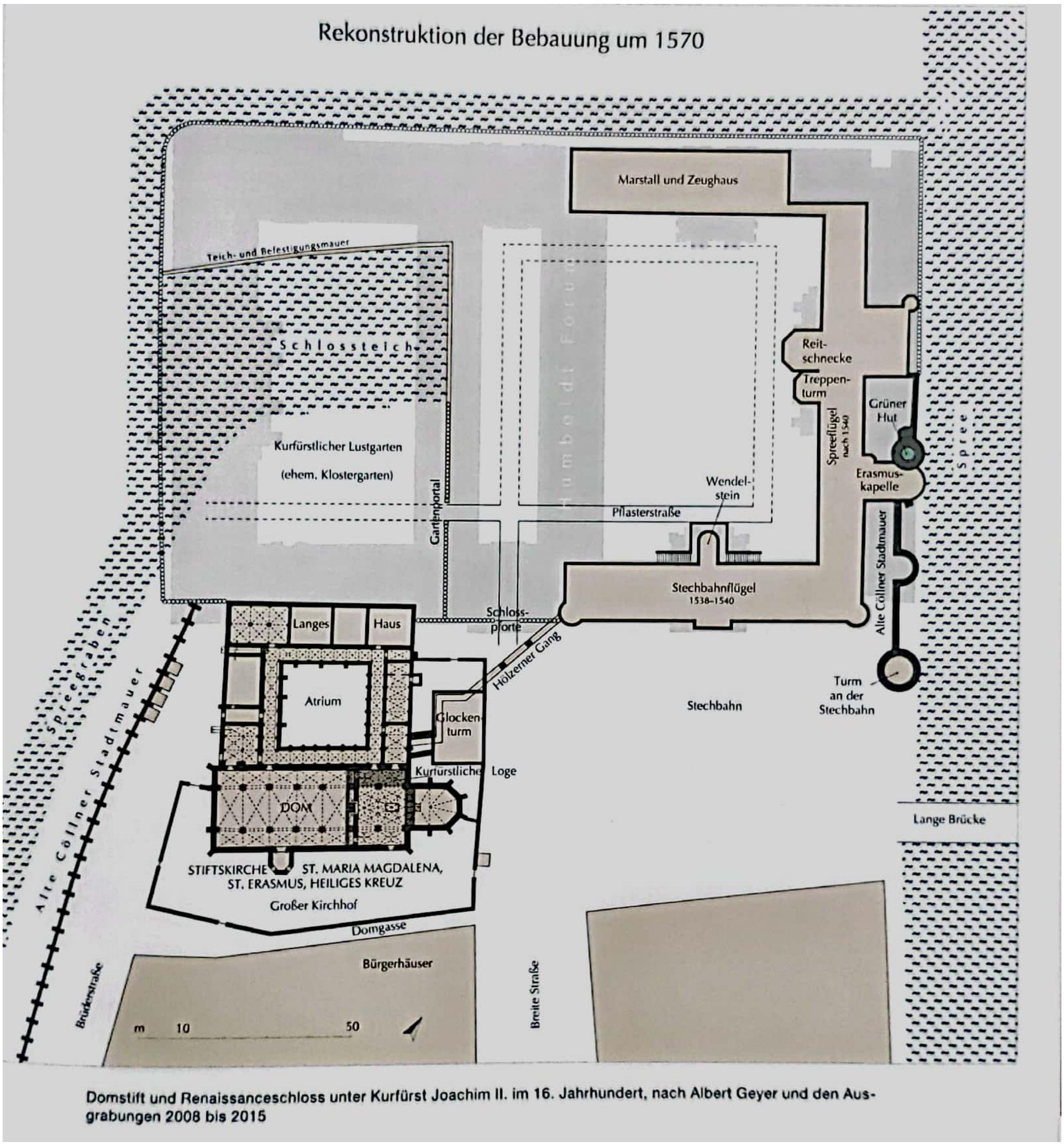
Appendix

Appendix A Plans of the Berliner Schloss from 1451 – 1936

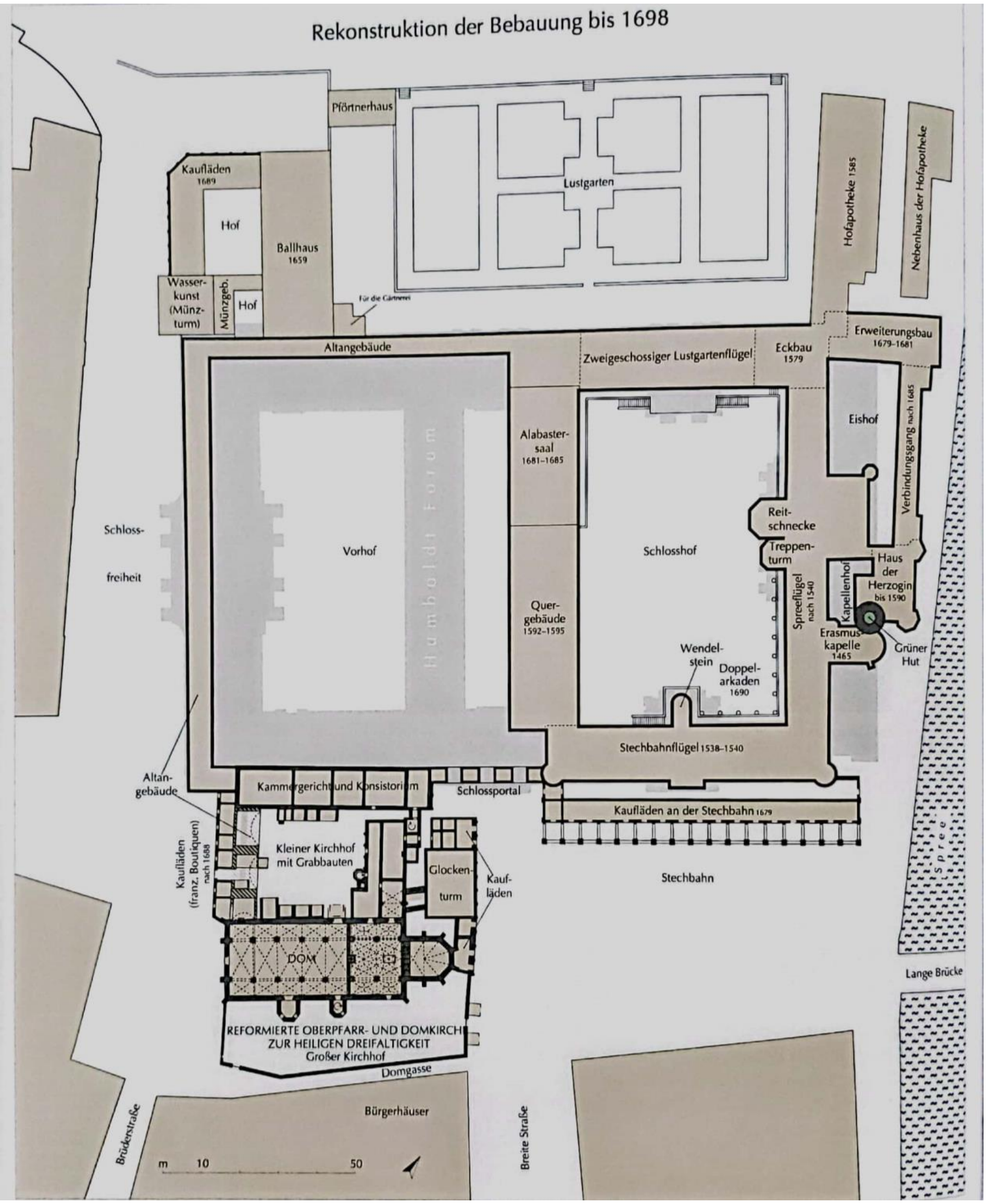


Erster Schlossbau und Dominikanerkloster im 15. Jahrhundert unter Kurfürst Friedrich II., nach Albert Geyer und den Ausgrabungen 2008 bis 2015

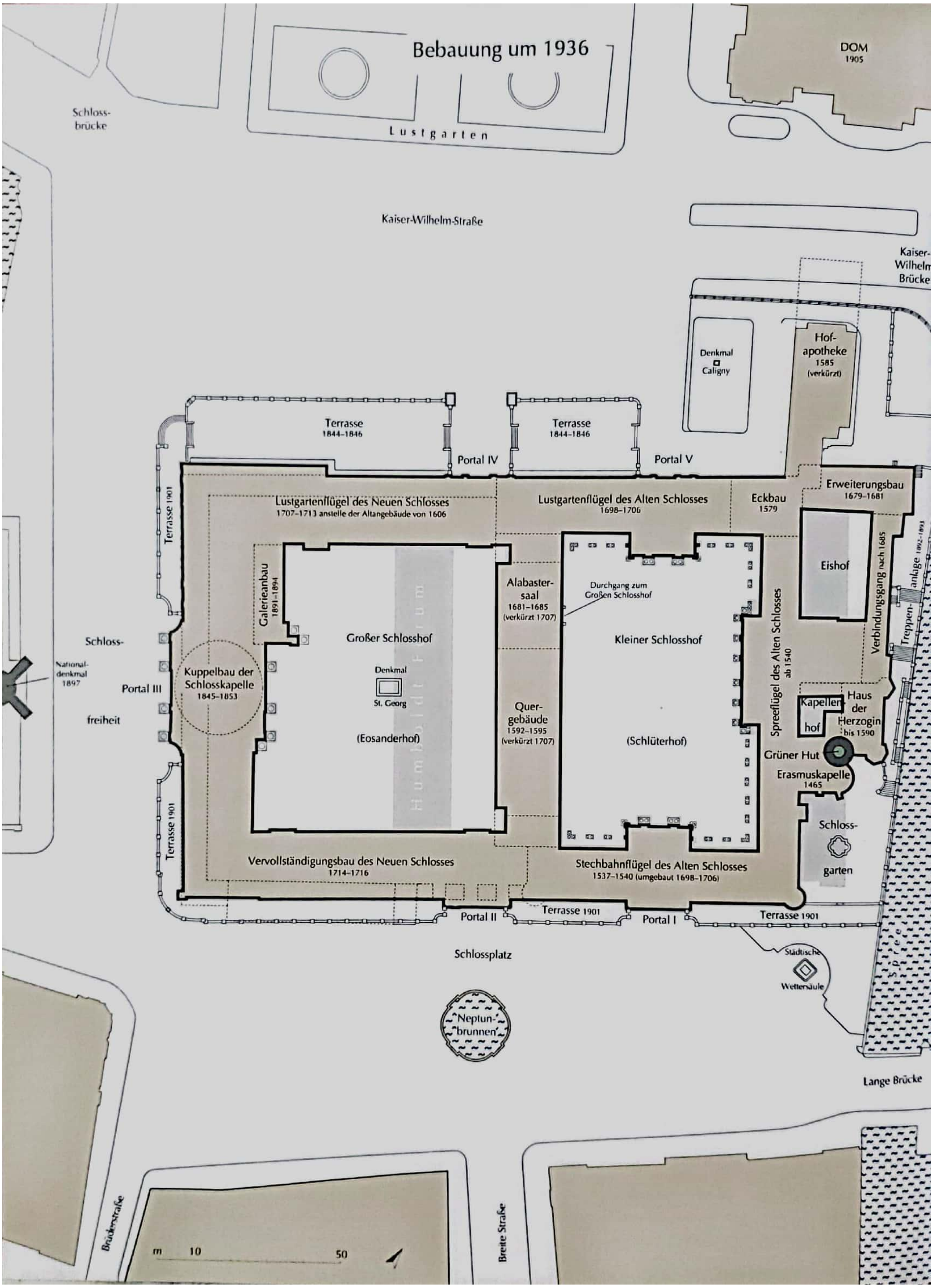
Appendix A1 Reconstruction of Berliner Schloss after 1451 (Malliaris & Wemhoff, 2016)



Appendix A2 Reconstruction of Berliner Schloss in 1570 (Malliaris & Wemhoff, 2016)



Appendix A3 Reconstruction of Berliner Schloss in 1698 (Malliaris & Wemhoff, 2016)



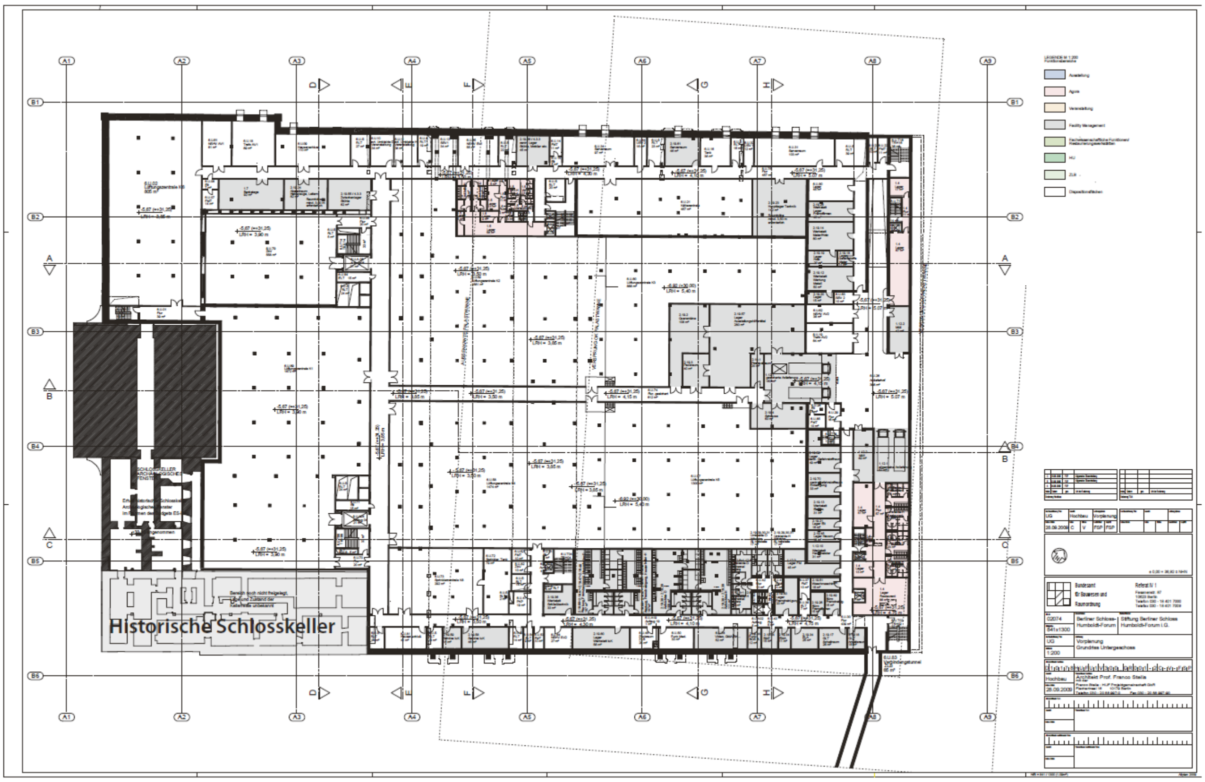
Appendix A4 Berliner Schloss in 1936 (Malliaris & Wemhoff, 2016)

Appendix B Photos of the model of the Berliner Schloss in 1900

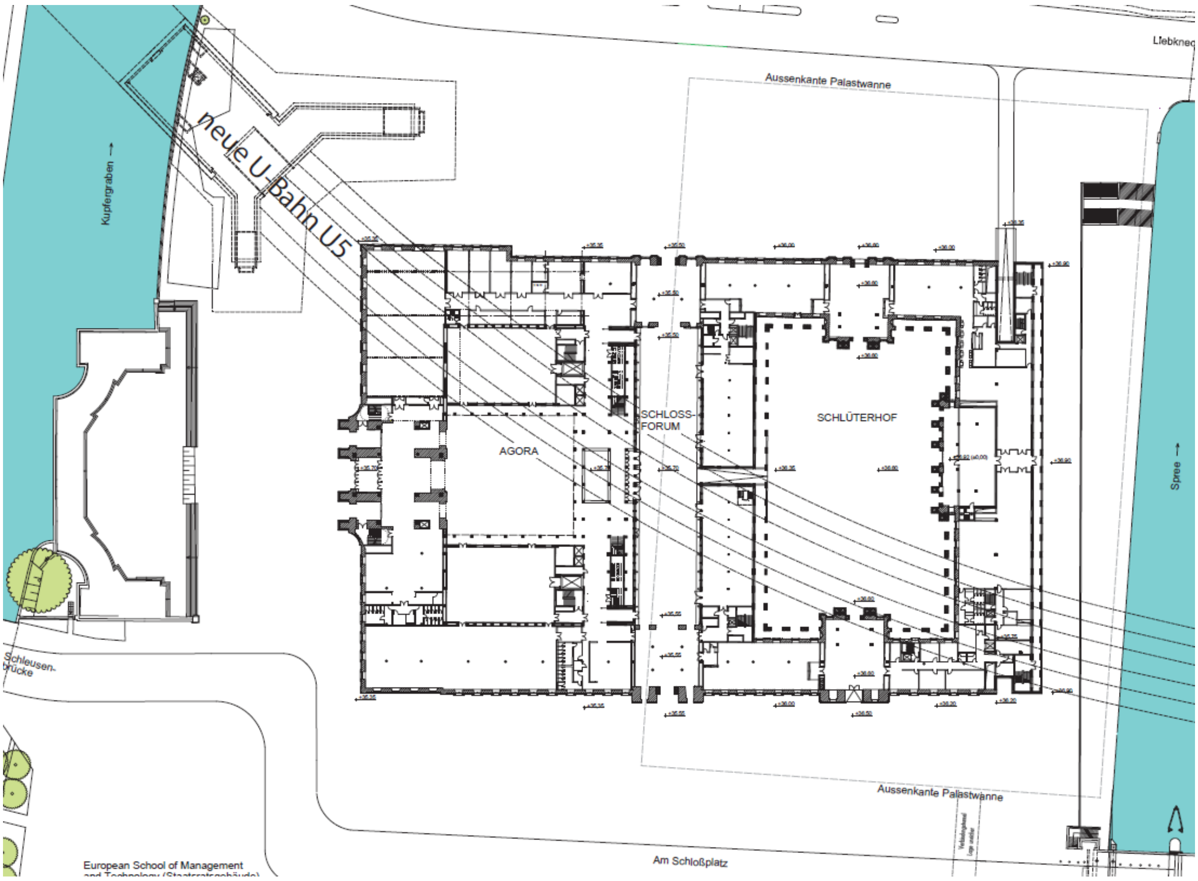
Appendix B1 Berliner Schloss in 1900 from above (Photo: Author, 2020)

Appendix B2 Berliner Schloss in 1900 (perspective view) (Photo: Author, 2020)

Appendix C Design Floor Plan of the Humboldt Forum



Appendix C1 Basement Plan of the Humbolt Forum (Berliner Schloss e.V., 2011)



Appendix C2 Location plan of the Humboldt Forum(Berliner Schloss e.V., 2011)

Appendix D Cost Calculation

Price Deflator(Fisher) Index of Multifamily Residential Units Under Construction
[2005 = 100.0. Index based on kinds of units built in 2005]

Year	First Quarter	Second Quarter	Third Quarter	Fourth Quarter
2005	100.0	100.6	102.9	105.8
2006	108.5	110.1	114.9	117.4
2007	115.4	115.4	118.0	119.0
2008	122.5	121.7	121.7	122.3
2009	123.6	123.8	123.6	126.5
2010	125.8	123.6	125.3	128.6
2011	127.8	124.8	122.8	120.5
2012	122.1	121.1	123.1	124.4
2013	128.5	128.4	129.0	127.8
2014	131.2	131.3	131.8	135.2
2015	144.1	146.5	147.6	151.1
2016	152.2	153.4	155.4	159.5
2017	160.4	163.0	168.0	170.9
2018	175.1	176.0	179.0	178.8
2019	179.9	179.4	179.7	181.7
2020	183.4	181.0	181.2	179.9 [r]
2021	180.7 [p]			

p Preliminary r Revised

Appendix D1 Construction Price Index (2005 Base)

Method	**Cost in** €/m2 floor	**Cost per home (x 1000€**)
Pile head lowering (from ground floor, A1)	600-900	approx. 40
Pile head lowering (from crawl space/basement, A2)	600-900	approx. 40
Table construction (from ground floor, B1)	1100-1600	approx. 70
Table construction (from crawl space/basement, B2)	900 -1600	approx. 60
Edge beams, prestressing beams (C1)	800-1400	approx. 50
Edge beams, beam grid (C2)	800-1600	approx. 60
Poles through the wall (from ground floor / inside, D1)	700-1200	approx. 50
Posts through wall (from crawl space or outside, D2)	700-1200	approx. 50

Appendix D2 Indication of costs for foundation repair according to TNO Report (van Etten et al., 2007)

Cost classification based on the Finnish Talo 2000 standard	Micropile type		
		Stage E1 or C1 RR140, impact driven	Stage E3 or C3 RD140, drilled micropile
1.1.2.1 Piles	€/pc	300	400
	€/m	150	200
1.1.2.2 Supports	€/m^2	20	20
1.1.2.3 Reinforcement	€/pc	1100	1600
2 HVAC	€/m^2	5	5
3 Project management	€/m^2	20	20
Totally	€/m^2	165	208
		cost increase	26 %

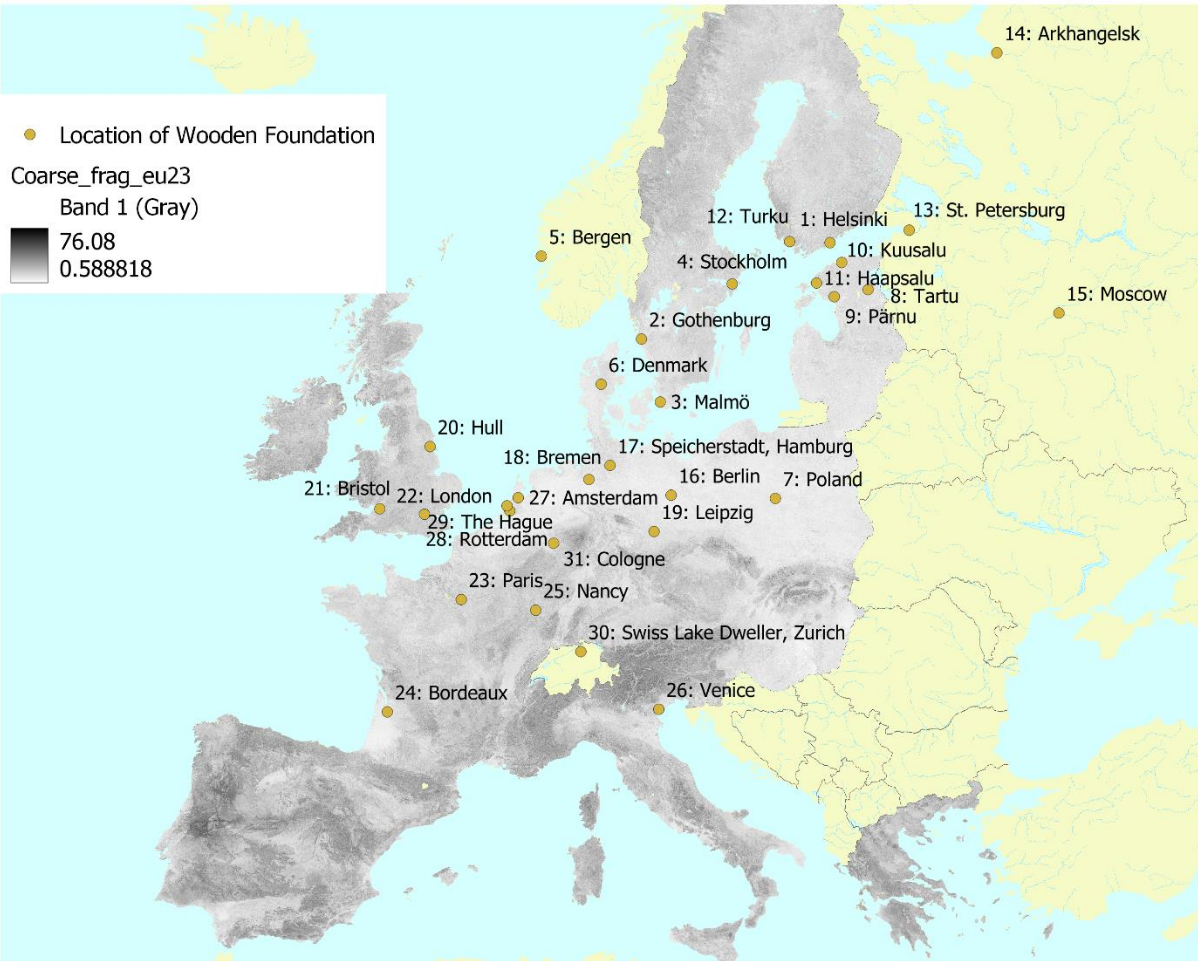
Appendix D3 Cost if underpinning according to (Lehtonen et al., 2010)

Total Area = 116 x 192 =			22272	m2	
	Year	Unit	Unit Price Reported year	Adjusted Unit Price to year	Construction cost
				2013	
		m2	Euro/m2	Euro/m2	
Pile head lowering	2007	22272	900	1002	€ 22,320,249.57
Table construction	2007	22272	1600	1782	€ 39,680,443.67
Edge beams, prestressing beams (C1)	2007	22272	1400	1559	€ 34,720,388.21
Edge beams, beam grid (C2)	2007	22272	1600	1782	€ 39,680,443.67
Poles through the wall	2007	22272	1200	1336	€ 29,760,332.76
Piles per Sq Meter	2010	22272	150	153	€ 3,412,502.38
Supports	2010	22272	20	20	€ 455,000.32
Project management	2010	22272	20	20	€ 455,000.32
1) Table construction of the whole area	2007	22272	1600	1782	€ 39,680,443.67
2) Project management costs	2010	22272	20	20	€ 455,000.32
Foundation Renovation Total					€ 40,135,443.99
Humboldt Forum Construction Cost					€ 650,000,000.00
Cost of renovating foundation					6%

Appendix D4 Cost Calculation of Humboldt Forum Foundation (Alternative Design)

Appendix E Mapping of Known Wooden Pile Foundations against Coarse Fragment Topsoil in Europe

Known wooden pile foundations are mapped against the map of the distribution of coarse fragments in the topsoil to compare the effect of topsoil type on the choice of wooden foundation. It confirms that in the south of Europe choice of wooden foundation is less common because the topsoil is more solid, and this renders the wooden foundations unnecessary. The soil data is taken from reference (European Soil Data Centre (ESDAC), n.d.; Panagos et al., 2012)



Appendix E1 Wooden foundation on rocky coarse fragment

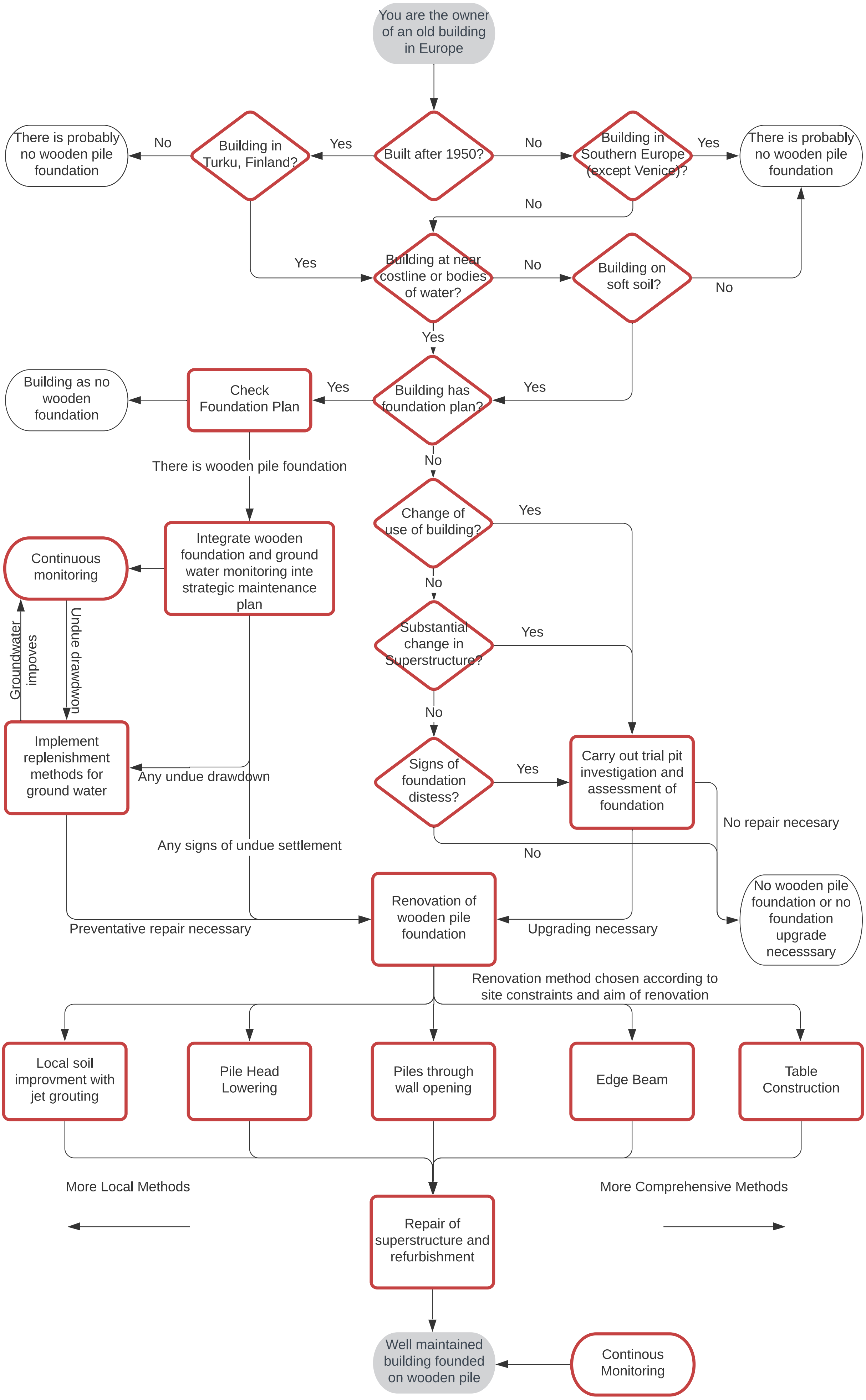
Appendix F Flow Chart of Wooden Building Foundation Maintenance

A flow chart is developed to help the owner of the FM to maintain an old building that may be supported by a wooden foundation.

[The flow chart is on the next page]

Flow chart for wooden pile foundation maintenance

Siukong Lau Appendix F, ConREM Master's Thesis



List of Literature

Algemeen Dagblad. (2020). Houses receive foundation label: 250,000 “high-risk” properties (in Dutch: Huizen krijgen funderingslabel: 250.000 panden met ’hoog risico’). *Algemeen Dagblad*. https://www.ad.nl/wonen/huizen-krijgen-funderingslabel-250-000-panden-met-hoog-risico~a7a1af20/?referrer=https%3A%2F%2Fwww.google.com%2F

BAKA Bundesverband Altbauerneuerung e.V. (2020). *Old Buildings - Foundation and Excavation*. https://www.bakaberlin.de/index.php?target=indexsuche&tree=65

Berliner Schloss e.V. (2011, September). BERLINER EXTRABLATT 74 Auflage. *Mitteilungsblatt Des Fördervereins Berliner Schloss e.V.* www.berliner-schloss.de

Berliner Schloss e.V. (2013). BERLINER EXTRABLATT 79 Auflage. In *Mitteilungsblatt des Fördervereins Berliner Schloss e.V.* www.berliner-schloss.de

Berliner Schlossdielen. (n.d.). *BERLINER SCHLOSSDIELE-DER FUSSBODEN MIT GESCHICHTE*. Retrieved July 29, 2021, from www.berliner-schlossdielen.de

berliner-schloss.de. (n.d.). *Short Architectural History*. Retrieved July 29, 2021, from https://berliner-schloss.de/en/palace-history/short-architectural-history/

Boston Groundwater Trust. (2018). *Wood Piles: Preserving Boston’s First Deep Foundations Part 1 of 3*. https://www.youtube.com/watch?v=2BGq2ikqdlc

Bowles, Joseph E. (1996). *Foundation analysis and design* (Fifth Edition). McGraw-Hill.

Ceccato, F. (2011). *Comportamento meccanico delle palificate lignee di Venezia (Master Thesis)*.

COLMENARES, KATJA. (2015, October 25). The old palace pile are now also available as floorboards (in German: Die alten Schloss-Pfähle gibt es jetzt auch als Dielen). *B.Z. Berlin*. https://www.bz-berlin.de/berlin/mitte/die-alten-schloss-pfaehle-gibt-es-jetzt-auch-als-dielen

Colombo, P., & Colleselli, F. (1997). Preservation problems in historical and artistic monuments. In C. Viggiani (Ed.), *Geotechnical engineering for the preservation in historic sites*.

de Kee, Daniel, Gopu, Vijaya, & Hetzer, Max. (2008). *Innovative Repair of Deteriorated Timber Piles Utilizing Nano-Polymer Composites*.

Döhner, Gregor, & Antkowiak, Matthias. (2013). *Ausgrabungen am Berliner Stadtschloss*. https://www.berlin.de/landesdenkmalamt/veranstaltungen/berliner-archaeologentag/2013-615658.php

EN 1991-1-1. (2002). *Eurocode 1: Actions on structures - Part 1-1: General actions - Densities, self-weight, imposed loads for buildings*.

EN 1997-1. (2004). *Eurocode 7: Geotechnical design - Part 1: General rules*. European Standard.

EN 1997-2. (2007). *Eurocode 7-Geotechnical design - Part 2: Ground investigation and testing*. European Standard.

EUROPEAN COMMISSION. (2019). *The European Green Deal*.

European Commission. (2021). *NextGenerationEU*. https://ec.europa.eu/info/strategy/recovery-plan-europe_en#nextgenerationeu

European Soil Data Centre (ESDAC). (n.d.). *esdac.jrc.ec.europa.eu*. European Commission, Joint Research Centre.

Famiglietti, J. S. (2014). The global groundwater crisis. In *Nature Climate Change* (Vol. 4, Issue 11, pp. 945–948). Nature Publishing Group. https://doi.org/10.1038/nclimate2425

Grundgesetz für die Bundesrepublik Deutschland, (1949). https://www.gesetze-im-internet.de/gg/art_14.html

Google Maps. (2021). *Google Maps: Location of Reichtag Building*. https://www.google.com/maps/@52.518215,13.3755788,17.25z/data=!5m1!1e2

GUDIĆ, DRAŽEN. (2019). Jeroslav Šegedin: The Pelješac Bridge will be completed by July 2021, but that does not mean that traffic will start immediately. *Slobodna Dalmacija*. https://slobodnadalmacija.hr/vijesti/hrvatska/jeroslav-segedin-peljeski-most-bit-ce-dovrsen-do-srpnja-2021-godine-ali-to-ne-znaci-da-ce-promet-odmah-krenuti-584135

Hämäläinen, Susanna. (2006). *The builder 's experience in strengthening the foundations (in Finnish: Rakennuttajan kokemukset perustusten vahvistamisesta)*.

Hansen, J. B. (1970). *A Revised and Extended Formula for Bearing Capacity*.

Hesso, Laura. (2005). *Preservation of Foundations in the underpinning of cultural historic buildings: needs and possibilities (in Finnish: Perustusten säilyttäminen kulttuurihistoriallisesti arvokkaissa perustustenvahvistuskohteissa: tarpeet ja mahdollisuudet)*.

Humboldt Forum. (2021). *Humboldt Forum*. https://www.humboldtforum.org/en/

JAUER, MARCUS. (2013, March 19). BERLIN IS AUCTIONING ITS HISTORY (In German: BERLIN IS AUCTIONING ITS HISTORY). *Frankfurter Allgemeine*. https://www.faz.net/aktuell/feuilleton/berlin-versteigert-seine-historie-vollholzpfosten-12120629.html

Joostdevree.nl. (n.d.). *Foundation Repair (in Dutch: funderingsherstel)*. Retrieved June 27, 2021, from https://www.joostdevree.nl/shtmls/funderingsherstel.shtml

Jovanovic, Mirjana. (2002). *Historische Holzgründungen - Tragverhalten in weichem Baugrund.* [s.n.].

Keller, Ferdinand, & Lee, John Edward. (1866). *The Lake Dwellings of Switzerland and Other Parts of Europe*. Longmans, Green, and Co.

Klaassen, René K. W. M., & Creemers, Jos G. M. (2012). Wooden foundation piles and its underestimated relevance for cultural heritage. *Journal of Cultural Heritage*, *13*(3 SUPPL.). https://doi.org/10.1016/j.culher.2012.02.014

KÖPPL, CHRISTIANA. (2012). *NUMERICAL STUDY ON THE LONG-TERM BEHAVIOUR OF WOODEN PILE FOUNDATIONS IN VENICE*.

Lambrechts, James. (2008). *AC 2008-1977: THE PROBLEM OF GROUNDWATER AND WOOD PILES IN BOSTON, AN UNENDING NEED FOR VIGILANT SURVEILLANCE The Problem of Groundwater and Wood Piles in Boston "An Unending Need for Vigilant Surveillance."* http://www.bostongroundwater.org/uploads/2/0/5/1/20517842/ac2008full1977_1.pdf

LeFrançois, Suzanne O'Neil. (2003). *Ground Penetrating Radar Characterization of Wood Piles and the Water Table in Back Bay, Boston*.

Lehtonen, Jouko, Perälä, Antti, & Hattara, Jussi. (2010). *New tool for choosing micropile type. Decay modeling of wood pile foundations in Turku, Finland*. https://www.researchgate.net/publication/319649828

Loy, Thomas. (2012, November 8). Root canal treatment at the Palace (In German: Wurzelbehandlung am Schloss). *Der Tagespiegel*. https://www.tagesspiegel.de/berlin/baubeginn-humboldtforum-wurzelbehandlung-am-schloss/7359678.html

Malliaris, Michael, & Wemhoff, Mattias. (2016). *Das Berliner Schloss: Geschichte und Archäologie*. Elsengold.

Mandala, A. (2002). STRENGTHENING TECHNIQUES FOR BUILDINGS. In F. M. Mazzolani & M. Ivanyi (Eds.), *Refurbishment of Buildings and Bridges* (pp. 197–264). Springer-Verlag Wien GmbH.

Meyerhof, G. G. (1951). The Ultimate Bearing Capacity of Foundations. *Geotechnique*, *2*(4), 301–331.

Panagos, P., van Liedekerke, M., Jones, A., & Montanarella, L. (2012). European Soil Data Centre: Response to European policy support and public data requirements. In *Land Use Policy* (pp. 329–338). https://doi.org/10.1016/j.landusepol.2011.07.003

Paz, Catarina, Alcalá, Francisco J., Carvalho, Jorge M., & Ribeiro, Luís. (2017). Current uses of ground penetrating radar in groundwater-dependent ecosystems research. In *Science of the Total Environment* (Vol. 595, pp. 868–885). Elsevier B.V. https://doi.org/10.1016/j.scitotenv.2017.03.210

Petrescu, Tudor-Cristian, Mihai, Petru, & Toma, Ionut-Ovidiu. (2021). Tensile Testing of a Biocomposite Material – "Liquid Wood." *Critical Thinking in the Sustainable Rehabilitation and Risk Management of the Built Environment CRIT-RE-BUILT. Proceedings of the International Conference, Iași, Romania, November 7–9, 2019*, 249–253.

Ramm, Hendrik. (2019). *Experimentelle und numerische Untersuchungen zur Wiedernutzung von Bestandsgründungen*. Technische Universität Darmstadt.

Römisch-Germanisches Museum. (2014). *THE “UBIER MONUMENT.”* https://roemisch-germanisches-museum.de/THE-UBIER-MONUMENT

Rossi, Cesare, & Russo, Flavio. (2016). *History of Mechanism and Machine Science 33 Ancient Engineers’ Inventions Precursors of the Present Second Edition*. https://doi.org/10.1007/978-3-319-44476-5

SCHÖNBALL RALF. (2021, February 25). Construction costs for Berlin Palace breaks 680 million mark (in German: Baukosten für Berliner Schloss knacken 680-Millionen-Grenze). *Der Tagesspiegel*. https://www.tagesspiegel.de/berlin/humboldt-forum-wird-immer-teurer-baukosten-fuer-berliner-schloss-knacken-680-millionen-grenze/26951796.html

Schultze, Joachim. (1928). *Der Grundbau I Der Baugrund und die Baugrube*. Walter de Gruyter & Co.

Gesetz zum Schutz von Denkmalen in Berlin, (1995).

Snow, Janice S. (2003). *Boston’s Groundwater Crisis: Seeking Sound Water Policies in an Unnatural Watershed*.

SSAB. (2017, October 2). *Underpinning in Turku City Centre*. https://www.ssab.com/News/2017/10/Underpinning-in-Turku-City-Centre

SSAB. (2020, May 18). *SSAB High strength steel piles to foundations of new hotel in Turku, Finland*. https://www.ssab.com/News/2020/05/High-strength-steel-piles-to-foundations-of-new-hotel-in-Turku

Stichting Platform Fundering. (2006). *The foundation under your home (in Dutch: De fundering onder uw woning)*.

STOLLOWSKY, CHRISTOPH. (2013, April 22). Piles of the Berlin City Palace auctioned (in Germany: Pfähle des Berliner Stadtschlosses versteigert). *Der Tagesspiegel*. https://www.tagesspiegel.de/berlin/die-neuen-stammhalter-pfaehle-des-berliner-stadtschlosses-versteigert/8099994.html

Taylor, Heather. (2015). *Cost of Constructing a Home*. https://www.nahbclassic.org/generic.aspx?genericContentID=248306

Terzaghi, K. (1943). *Theoretical Soil Mechanic*. John Wiley & Sons.

Turku AMK. (2007). *Database on Turku Underpinning Projects*. https://web.archive.org/web/20070313080140/http://www.datu.info/

Ulitskii, V. M. (1995). History of pile foundation engineering. *Soil Mechanics and Foundation Engineering*, *32*(3), 110–114. https://doi.org/10.1007/BF02336510

United Nations Department of Economic and Social Affairs. (2021). *THE 17 GOALS*. https://sdgs.un.org/goals

van de Kuilen, J. W. G. (2007). Service life modelling of timber structures. *Materials and Structures*, *40*(1). https://doi.org/10.1617/s11527-006-9158-0

van Etten, Bas D., de Jong, Jan D., & de Richemont, Sabine A. J. (2007). *TNO report - Inventory of repair techniques for problems with wooden foundations (In Dutch: TNO-rapport - Inventarisatie van hersteltechieken bij problemen met houten funderingen)*. https://zoek.officielebekendmakingen.nl/kst-30800-XI-114-b1.pdf

VROM. (n.d.). Recognizing and tackling potential foundation problems when buying or selling a home (in Dutch: Het herkennen en aanpakken van eventuele funderingsproblemen bij koop of verkoop van een woning). *Ministerie van Volkshuisvesting, Ruimtelijke Ordening En Milieubeheer*.

Wigger, Heinrich 1961-. (2000). *Crack formation as a result of forced settlement in historical natural stone masonry Observations, experiments and calculation model (In German: Rissbildung infolge Setzungszwang in historischem Natursteinmauerwerk Beobachtungen, Versuche und Berechnungsmodell)*.