Eveliina Suni

Classification and Methods for Splitting and Cutting Steel Piles

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This thesis is about steel piles, focusing on their classification and on the methods for splitting and cutting them. These methods are used to reach the designed cutting level. In general, a grinder or a flame cutter is used in splitting and cutting work, and if work is carried out underwater, a diver is needed to cut the pile. The goal of this work was to find methods to split and cut steel piles above and below water level. The thesis was commissioned by Sito and SSAB.

Piles can be classified based on material, function, method of installation or displacement. Mostly, it is important for a person to understand different ways to categorize piles to understand terms that are used in the field. This thesis studies the general classification of piles, the classification of steel piles, the design and installation of steel piles, the piling equipment and, lastly, the methods for splitting and cutting steel piles. The main interest focuses on the classification of steel piles and methods for splitting and cutting them.

This thesis compiled information about methods for cutting and splitting steel piles so that it would be easily accessible. The information provided by the thesis is based on available literature, Internet and information received from companies in this sector.

Keywords	steel piles, pile classification, pile cutting, pile splitting, cutting methods

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Opinnäytetyö käsitteli teräspaaluja; niiden luokittelua sekä halkaisu- ja katkaisumenetelmiä, joita tarvitaan saavuttamaan suunniteltu katkaisukorkeus. Yleisesti paalun halkaisu- ja katkaisutyössä on käytetty kulmahiomakonetta tai polttoleikkausta, ja vedenalaisessa työssä paalun halkaisun tai katkaisun suorittaa sukeltaja. Työn tavoitteena oli löytää erilaiset halkaisu- ja katkaisumenetelmät teräspaaluille. Työn tilaajana toimi Sito ja SSAB.

Työssä käsiteltiin yleistä paalujen luokittelua, teräspaalujen luokittelua, teräspaalujen suunnittelua ja asentamista, paalutuskalustoa sekä teräspaalujen halkaisu- ja katkaisumenetelmiä. Työn pääpaino oli teräspaalujen luokittelussa sekä niiden halkaisu- ja katkaisumenetelmiä koskevissa kappaleissa.

Opinnäytetyö keräsi saatavilla olevan tiedon yhteen, jotta menetelmien arviointi ja kohdekohtainen menetelmän valinta helpottuisivat. Työ pohjautui saatavilla olevaan kirjallisuuteen, Internet-lähteisiin sekä alan yrityksiltä saatuun tietoon.

Avainsanat	teräspaalut, paaluluokittelu, katkaisumenetelmät, halkaisumenetelmät

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Abbreviations

CC1…CC3	Consequences Classes
CED	Closed-end diesel hammer
CEP	Closed-end pile
Combi-wall	Continuous structure that comprises of sheet piles and pipe piles or H-piles
Concentric method	Drilling method where sand shoe is attached to the end of a drilling rod.
d	Diameter of the pile
DTH	Down-The-Hole hammer. It is used in installation of drilled piles.
e	Horizontal deviation measured from working level
e_{max}	Maximum horizontal deviation measured from working level
Eccentric method	Drilling method where eccentric reamer widens the drilled hole when drill bit pushes the casing into the ground. After desired level is reached, drill rods start to rotate to the opposite direction which causes the reamer to close. The casing is left to the ground and drilling equipment is lifted from the hole.
Franki-method	Concrete is put to the bottom of the pile and installation is done inside the pile. Close-end pipe pile with pile shoe is installed to the bedrock can be installed with Franki-method.
GC1…GC3	Geotechnical Categories
Hammer	Piling rig used to install large diameter piles.

i	Tangent of the angle of deviation
i_{max}	Maximum tangent of the angle of deviation
L	Length of the pile
Large diameter pile	Pile that has a diameter > 300 mm
MAPP gas	Mixture of hydrocarbons, mainly methylacetylene and propadiene. The gas is used in flame cutting.
Micropile	Small diameter pile that has a diameter ≤ 300 mm
OD method	Concentric method to install drilled piles
OED	Open-end diesel hammer
OEP	Open-end pile
PDA-measurement	Pile Driving Analysis. Dynamic test load –method which is used to evaluate bearing capacity of piles.
PTL1…PTL3	Piling Categories
Ram	Hammer used to install micropiles.
ROV	Remotely operated vehicle
SGS	Subsea Guillotine Saw
Θ	Angle between designed central line and horizontal line

1 Introduction

1.1 Background of the Work

It has been observed that some information about methods for splitting and cutting steel piles can be found, but the information is not easily available and centralized in one source. Piles need to be cut to reach the designed level in case there is a structure which is supported by piles or pile structure has to be removed. Cutting can be executed to reach the designed level because of the upper structure or pile structure has to be removed. Since new and more difficult areas are brought into use, working methods need to be updated. That means areas where cutting would be performed underwater, in cramped places or on piles forming a continuous structure with interlocking systems. In every situation where cutting or splitting needs to be executed, options need to be weighed, and there should be enough information about the procedure as well as about other factors that may influence the work.

This thesis is divided into five topic areas: general classification of piles, classification of steel piles, design and installation of steel piles, piling equipment and methods for splitting and cutting steel piles. The main interest focuses on the last topic area. In general, piles can be classified based on material, function, method of installation or displacement. It is important for a person to realize different ways to categorize piles to understand terms that are used in the field.

The thesis classifies steel piles in terms of pile diameter to micropiles and large diameter piles and introduces them on a general level. Design and installation of steel piles follow the guidelines from RIL 245-2016 Paalutusohje 2016, which is used in piling works in Finland. Equipment needed in the pile installation is divided into two categories based on the method of installation: driving and drilling.

Methods for splitting and cutting steel piles are divided into four categories based on the factor of cutting force: chapter is divided into mechanical, thermal, explosive and abrasive methods. Even though abrasive methods are categorized as mechanical methods in general, they are discussed in their own section in this thesis. Most of the methods are discussed on general level since there are many companies offering services in the field. There are a few exceptions in which companies are mentioned, mainly in abrasive methods.

1.2 Goals

Traditional methods for splitting and cutting piles are flame cutter and grinder. The focus of this work was to find information about splitting and cutting methods both for single piles and pile walls above and below water level. The goal was to compile information into one place so that it is easily accessible for use.

1.3 Research Methods

The thesis is based on literature, Internet and information received from companies operating in this sector. More specified information about methods has been gathered from different countries, for example, Sweden and England. Since the information is limited in Finnish, the thesis is basically based on English material. Some information has been gathered from the companies who are operating in the field.

2 Classification of Pile Foundations

2.1 Material

On the basis of the material, piles are classified into timber, concrete, steel and composite. Timber is used mostly for temporary piles and concrete in pre-cast concrete piles, cast-in-place and pre-stressed piles. Steel piles are utilized mainly in permanent constructions. The classification can be seen in Figure 1. (Taha et al. 2015)

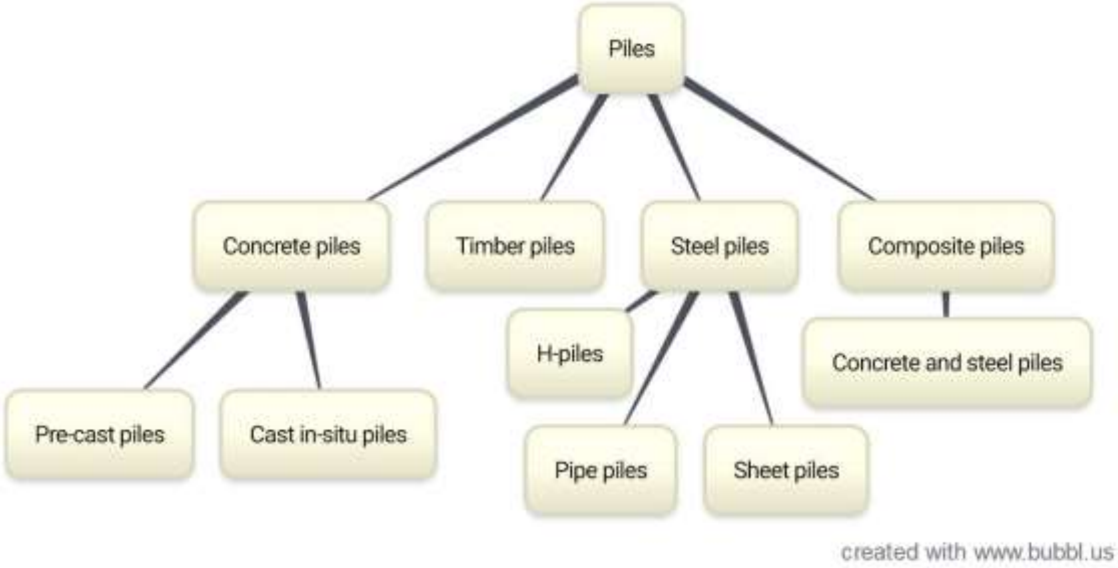

Figure 1. Pile classification based on their material. (Technical Instructions: Design of Deep Foundations, 1998)

Concrete piles are divided into pre-cast and cast-in-situ piles (Technical Instructions: Design of Deep Foundations, 1998). Pre-cast piles are cast and cured and then transported to the construction site. Cast-in-situ piles can be reinforced with reinforcing bars and piles are used for various lengths (Khan, 2015). The process of cast-in-situ pile installation includes drilling, placing reinforcement and then filling the hole with concrete.

Timber piles can also be used in permanent works, such as pipeline trenches and slopes, when there is enough material available. Timber is an option for long cohesion piling and piling beneath embankments. The quality of timber plays an important role. The length of timber piles is <14 m and pile’s end diameter is >150 mm (Types of piles, 2015). It is important that timber is driven into the ground in the right direction and because timber is easily damaged, not into the firm ground (Fang, 1991). Timber piles should be permanently below water level to avoid decay. Timber piles are easy to handle, relatively inexpensive and can be joined and cut easily, but the piles rot above water table, have low bearing capacity and can be easily damaged (Hansbo, 1994).

Steel piles are generally classified into pipe piles, sheet piles and H-piles, and they are suitable for various lengths. Steel piles have high strength in relation to their cross section, which enables penetration to firm soil. It is also possible to cut and join piles together. There is a risk of corrosion when it comes to steel with soil with low pH, but protection against it can be added with a tar coating or cathodic protection (Technical Instructions: Design of Deep Foundations, 1998). Corrosive treatment can be included in the design, meaning that the cross-sectional area is larger than needed and the surface is corroded. Corrosive treatment can prolong the pile's operating life by an extra 50 years. (Types of piles, 2015). Other disadvantages besides corrosion are high price and relatively high noise in installing the pile into the ground (Khan, 2015). More information about steel piles can be found in Chapter 3. Composite piles are a combination of different materials in the same pile. For example, timber or steel can be adjoined with concrete.

2.2 Function

There are five different types of piles when they are classified on the basis of their function. Most commonly types used in Finland are end-bearing piles, friction piles and cohesion piles, and the principles are shown in Figure 2. Classification based on their function is in Figure 3.

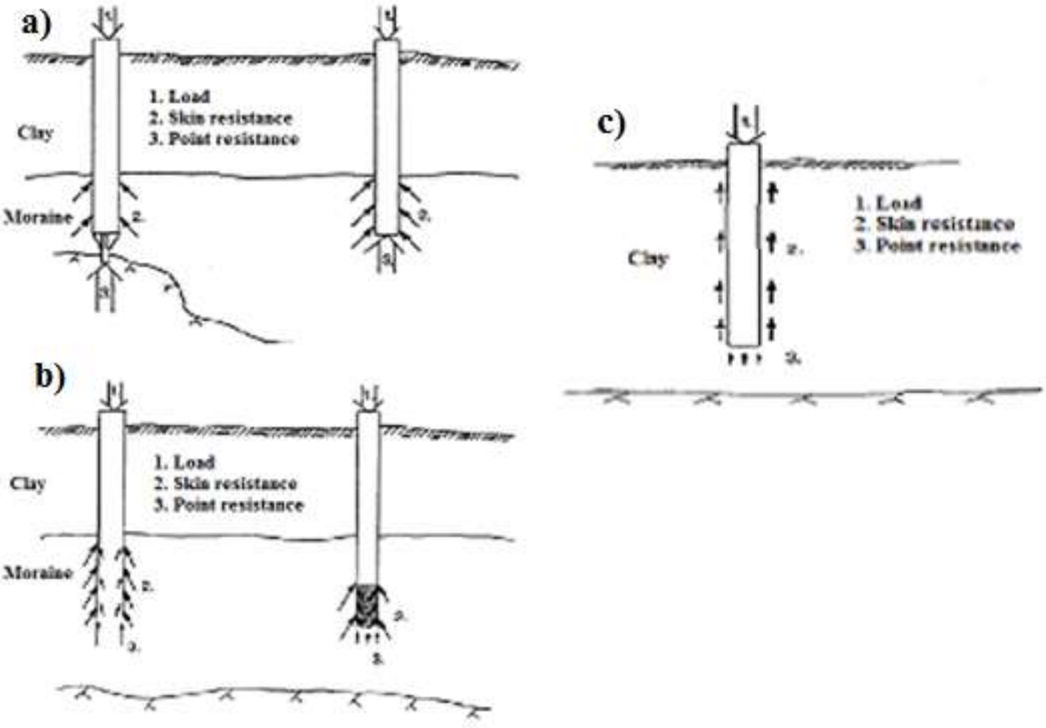

Figure 2. Principles of a) end-bearing pile, b) friction pile and c) cohesion pile. (TIEL 2173448E-99, 2000)

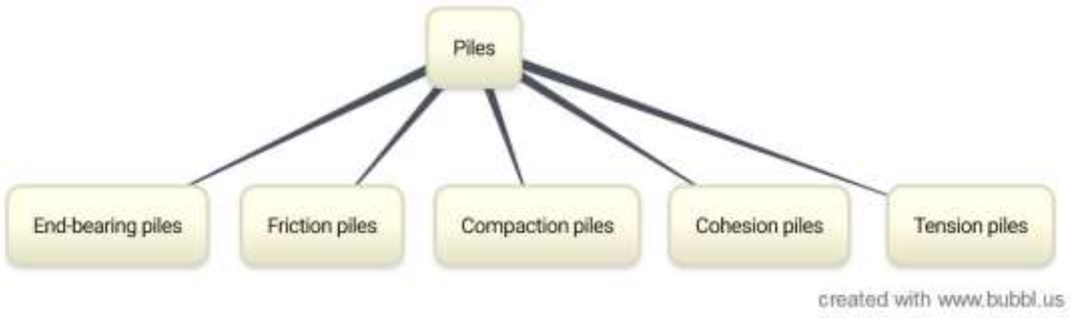

Figure 3. Pile classification based on their function. (Technical Instructions: Design of Deep Foundations, 1998)

End-bearing piles have the end of the pile resting on a strong soil or bedrock. The load is transmitted through the pile to the strong layer of soil. The main point is that the end of the pile rests in the intersection point of weak and strong layer even though some settlement may appear. (Pile Foundations, 2016)

Friction piles, also known as floating piles, transfer load by friction across the length of piles, and they are used in granular soil. Friction piles' surfaces transfer forces to the surrounding soil. The amount of compaction in the soil varies. It is important to understand that the magnitude of support is directly related to the pile's length (Pile Foundations, 2016).

Compaction piles are driven into granular soils. The aim is to increase bearing capacity of the soil. These types of piles transmit most of their load through skin friction, but they are driven to the soil very close to each other in groups to reduce the porosity and compressibility. Sometimes the soil becomes molded in the driving process and loses its strength. It is possible that the soil regains some of its strength back in three to five months after the driving process. (Types of piles, 2015)

Cohesion piles transfer load with adhesion from upper layers to cohesive layers (clay and silt) surrounding the pile. The carrying capacity is based on the grip between cohesive soil and pile. Cohesion piles are not used in permanent structures because piles load compressible soil layers which cause settlements of the soil (Jääskeläinen, 2009). Tension piles, also known as uplift piles, are used to hold down the structures that are easily subjected to uplift caused by hydrostatic pressure (Khan, 2015).

2.3 Method of Installation

There are three types of pile foundations when it comes to the installation method. Installation is done either by drilling or driving and the classification divides piles to drilled piles, driven piles, and driven and cast-in-situ piles (Figure 4).

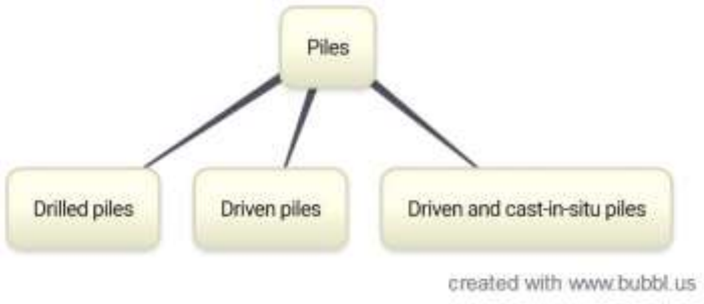

Figure 4. Pile classification based on the method of installation. (Khan, 2015)

In bored piles, the installation process requires casing or slurry as a stabilizer. After pile is put to the place, the drill hole can be filled with concrete. Drilled piles do not get damaged in handling or installation process. There are three types of drilled piles: small diameter piles ≤ 300 mm, large diameter piles > 300 mm and under-reamed piles (TIEH 2000002E-03, 2003).

Driven piles are fabricated of steel or timber. Piles are driven to the soil with a ram or a hammer instead of drilling. Driven piles increase the strength of granular soils, but reduce the strength of saturated clay because gets remolded. Driven and cast-in-situ piles are driven into the soil with steel casing. After pile is in place, reinforcement can be added, and the hole can be filled with concrete and the casing is gradually lifted from the soil. (Hansbo, 1994)

2.4 Displacement

Piles can also be categorized into three groups based on the magnitude of displacement in the soil (Figure 5). Displacement pile is a pile which causes a displacement of equivalent soil volume by lateral or vertical displacement or by compaction. Majority of displacement piles are pre-cast concrete piles, timber piles or steel piles that are driven into the soil. Displacement piles are usually driven into the soil by gravity hammers.

There are different problems in the driving process depending on the type of soil. In loose granular soils driving can cause large and destructive settlements of adjacent buildings. In fine grained loose soils, driving may induce higher residual excess pore water pressure which may lead to liquefaction. In dense saturated granular soil, driving may be very time consuming and may cause concrete piles to crack. (Hansbo, 1994; Fang, 1991)

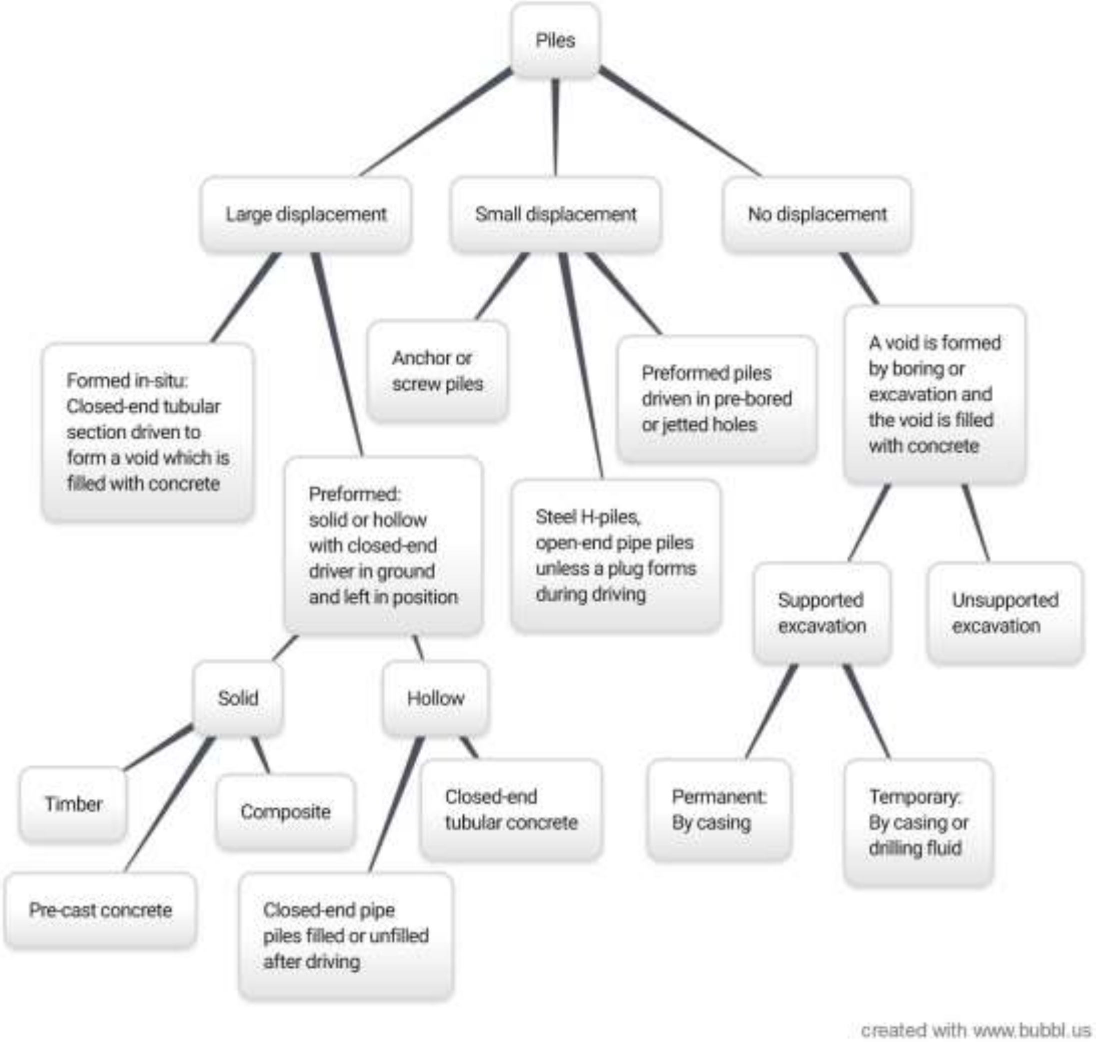

Figure 5. Chart for selecting pile type based on magnitude of displacement. (Technical Instructions: Design of Deep Foundations, 1998)

Non-displacement piles are installed by drilling or other ways of excavations. Bored piles can be installed using sludge pumps, hammer grabs, augers, rotary buckets, continuous augers, coring buckets etc. Problems with installation may cause excess pore water pressures, and in sandy and silty soils a risk of bottom erosion, which is also called piping. (Hansbo, 1994)

3 Classification of Steel Piles

Steel piles can be classified in many ways like piles in general. This chapter divides steel piles based on their diameter. Steel piles are distributed into micropiles and large diameter piles which are divided into subcategories.

Steel piles can also be classified based on method of installation. Piles are either driven or drilled into the ground. Driven piles cause displacement of soil in installation and it is not as precise method as drilling. Driven piles are prefabricated, and they are equipped with sand shoe or in some cases with bottom plate. In case the rock is inclined, the pile can be equipped with a rock shoe which prevents creeping of piles. Driving causes additional vibration to the soil; thus, the installation method cannot be used in areas where it might cause failure of adjacent structures.

Drilled piles are commonly used in areas where there are layers which are hard to penetrate, like layers with blocks, stones or old foundation structures. Drilled piles are also suitable to areas in which surrounding structures are predisposed to vibration, soil deflections and displacements. Drilled pile is an obvious choice in locations where piles need to reach a certain penetration depth or they require positional or inclination accuracy. (SSAB:n teräspaalut. Suunnittelu- ja asennusohjeet, 2015)

Drilled piles are suitable for foundation structures where they need to bear large-scale loads. Drilled piles which are supported by soil are used to withstand tensile stress. In Nordic countries drilled piles are almost exclusively end-bearing piles supported by bedrock (SSAB:n teräspaalut. Suunnittelu- ja asennusohjeet, 2015). Horizontally loaded drilled piles supported by surrounding soil can be considered when there is a coarse-grained layer on top of the bedrock or a thick layer of moraine. Vertically loaded end-bearing piles are usually supported by surrounding soil (TIEH 2000002E-03, 2003).

The competence of a pile is shown with CE-marking. The minimum requirements for steel material are listed in RIL 254-2016, 2016. Manufacturer needs to provide material certifications to the buyer according to SFS-EN 10204 before piling work can start.

3.1 Micropiles

Steel pipe piles that have a diameter ≤ 300 mm are called micropiles or small diameter piles. The Finnish Association of Civil Engineers (RIL) has published instructions and norms for micropiles (RIL 254-2016, 2016). This chapter divides micropiles into driven piles and drilled piles based on method of installation.

3.1.1 Driven Piles

Small driven piles are typically steel pipe piles that are supported by the bedrock or dense soil. Piles are driven into the soil with hydraulic rams, pneumatic rams or vibration rams. More information about pile equipment can be found in Chapter 5. The pile consists of pile pipe, pile splices, sand or rock shoe and pile cap. Bearing resistance varies between 100 and 2000 kN. (RIL 254-2016, 2016)

3.1.2 Drilled Piles

Drilled piles are divided into drilled steel pipe piles and steel core piles. Drilled steel pipe piles are designed as end-bearing piles supported by bedrock. Pipe piles have a thickness of up to 23 mm; thus, they can operate as a casing during the installation and after installation as a load bearing structure (Figure 6). Installation is executed with top hammer or down-the-hole hammer, and the drilling is carried out with eccentric or concentric drilling method. Pipe piles can be lengthened if needed with welding or mechanical splices. If the pile is filled with concrete after the drilling, the pile has to be rinsed. Drilled piles can have reinforcements, and their bearing capacity varies between 200 and 2500 kN. (RIL 254-2016, 2016; SSAB, 2017)

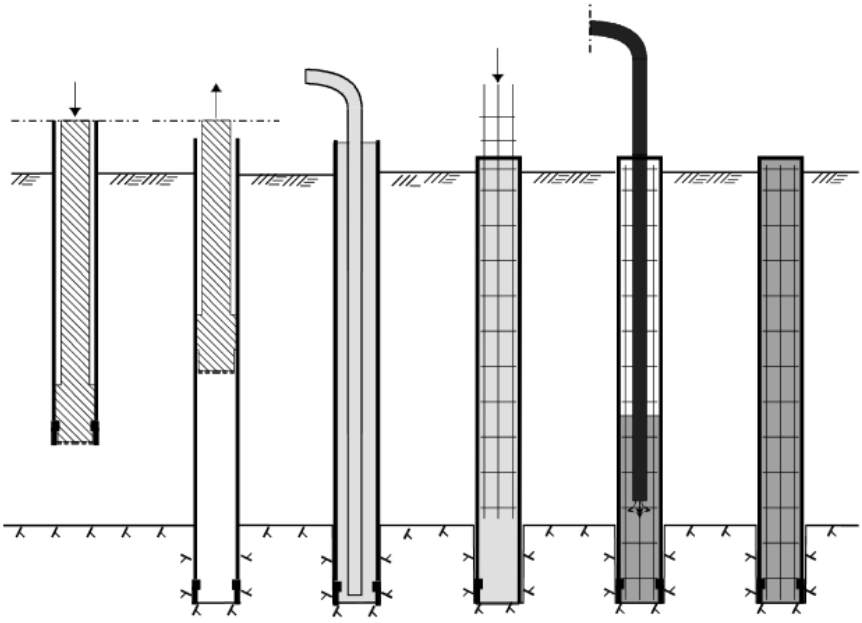

Figure 6. Drilled pipe pile with reinforcement. (TIEH 2000002E-03, 2003)

Steel core piles are made of solid steel. First, the casing is drilled to bearable soil. After drilling, the casing is filled with mortar, and then, steel core pile is installed. Steel core piles are normally used when there is restricted space for piling or when there are blocks and infill material. They are also used when there is need for tension capacity or when side support above the rock is insufficient. Typical load bearing capacity is between 400 and 3000 kN. The installation is done with same equipment as drilled steel pipe piles. The pipe operates as casing and the steel inside as supporting structure. (Steel Core Piles, 2016; RIL 254-2016, 2016)

3.2 Large Diameter Piles

Large diameter piles are used in bridge construction, harbor structures, industrial buildings, support walls in excavations and other heavy structures. It can be said that large diameter piles have advantages that other driven piles do not offer. Large diameter piles include the piles that have load bearing capacity ≥ 1500 kN and diameter > 300 mm. Large diameter piles typically have great load bearing capacity and bending resistance. They can be used in areas with boulders and rocky layers, filling areas, soft soil areas and areas with water. (Jääskeläinen, 2009)

In Finland the most used type is closed-end steel pipe pile with rock shoe. Large diameter piles can be installed with Franki-method (in case of open-end pile) so that the pile is not subjected to great stress. If the pile is open-end, steel plate in the end of the pile can be used. Closed-end piles can be reinforced with concrete and steel even when the pile is in water. (Jääskeläinen, 2009)

Steel piles have high strength, relatively lightweight and can transfer heavy loads into bearing stratum. Steel piles can be cut and extended easily, which is an advantage in general, but also in areas where the depth of bearing stratum varies.

Steel piles are most commonly divided into pipe piles and H-piles. Sheet piles are a pile type that is used as retaining structure and it is sometimes accompanied with pipe piles and H-piles. There are also pile walls, I-piles, disc piles and screw piles available.

3.2.1 Steel Pipe Piles

Steel pipe piles (Figure 7) can be categorized based on their performance. Pipe piles can operate as end-bearing or friction piles (TIEL 2173448E-99, 2000). Steel pipe piles can be open-end (OEP) or closed-end piles (CEP). Closed-end piles are normally end-bearing piles and open-end friction piles. Open-end piles are only used in pier structures and combi-walls where vertical loads are small. Steel pipe piles can be driven into the ground with drop hammer, hydraulic hammer, diesel hammer or vibratory hammer. (Jääskeläinen, 2009)

Figure 7. Steel pipe piles. (Teemu Kallio, 2006)

Large-diameter steel pipe piles are mostly used in port construction, but also in foundations of bridges. Steel pipe piles come in different sizes, and piles can be inspected internally after installation (Jääskeläinen, 2009). Their diameter is 75-1220 mm and all thickness 6.3-23 mm (SSAB, 2017). Advantages and disadvantages are listed in Table 1.

Table 1. Advantages and disadvantages of steel pipe piles. (Advantages of steel pipe piles; Warrington 2007)

Advantages	**Disadvantages**
Can be used in great depths	Open-end pipe piles are not as well suitable as H-piles for non-displacement applications
High strength and durability, and can be inspected for material damage after installation.	Closed-end pipe piles have problems with displacement
Fast installation	High cost of material
Small replacement	
Less number of piles and small foundation area	
Available in many sizes and thicknesses. Long service life	

Pipe piles can be driven or drilled into the ground. If driving is done with open-end pile, soil can enter the pile from the bottom of the pile. Soil can be removed if needed. Closed-end pipe pile has a steel plate or a rock shoe in the bottom preventing soil from entering the pile while driving (Pipe piles, 2016). There are three types of closed-end piles; piles equipped with a rock shoe, piles equipped with a bottom plate and Franki pipe piles. There are two types of open-end piles; plugging pile and unplugged pile. Open-end piles have smaller resistance when they are driven into the ground, and that is why they can be driven into the ground with boulders and bedrock (Prakash and Sharma, 1990).

Since steel pipe piles are normally driven to bedrock or moraine, they are equipped with a rock shoe. Sand shoes can also be used if the pile is not supported by bedrock. A pile cap can be installed to the top of the pile to transfer the load to the pile. Load-carrying capacity of the pile can be improved if the pile is filled with concrete and steel. (RR®- ja RD® -paalut. Suunnittelu- ja asennusohjeet, 2017)

Steel pipes used in piles are produced to SFS-EN 10219-1 (cold roll-formed) and SFS-EN 10210-1 (hot roll-formed) (RIL 254-2016, 2016). Commonly used manufacturing processes are electric resistance welding, fusion welding and flash welding. Pipe piles are either seamless, spiral welded or longitudinally welded steel pipes. Their normal thickness varies from 2.8 to 63.5 mm. The diameter is from 203.2 to 1500 mm. Load-carrying capacity varies depending on the properties of the pile. Piles are used as combination end-bearing/friction piles where the pile is driven closed-end and filled with concrete. (Warrington, 2007)

Two advantages of the circular shape of pipe piles are that the soil within the pile can easily be extracted and the shape also minimizes drag from waves and current forces if the piles are installed in deep water. Pipe piles can be inspected easily for damage and deviation with light inspection done in the hollow part. End caps can be used in pipe piles in case the soil is very dense. In case the soil is inclined or sloping, conical points should be used to avoid stress concentration and crippling of the pile (Prakash and Sharma, 1990).

3.2.2 H-Piles

The basic idea of H-pile is the same as in other piles; thus, it is designed to transfer structural loads to bearing layers below. H-piles transfer load through the pile to the tip. H-piles are mostly used in dense soil, when the pile is founded on rock and where other piling systems do not offer better pile resistance at the tip for point-bearing capacity. In other words H-pile is most effective in sites where the load is concentrated and bearing capacity is needed at the tip of the pile. The profile of H-pile is shown in Figure 8. (H-piles, 2016)

Figure 8. Profile of H-piles. (Steel for sale, 2014)

H-piles can be used in diverse situations. H-piles are mainly used in highway bridge piers and abutments, multi-storey buildings with high unit loads and earth retention. These piles can be used as friction or end-bearing piles; yet, they work most efficiently in end-bearing applications. Piles can be driven into the ground using standard equipment. The cross-sectional shape of the pile together with the entrapment of soil provides effective resistance to pullout. H-piles are good in situations where the structure is tensed. (Warrington, 2007)

H-piling refers to elements used in the design of deep foundations. H-piles are commonly used with sheet piles, where H-piles add lateral stiffness and bending resistance to the structure. Their robust cross section and strength of material provide excellent driving characteristics in difficult soils. The advantages and disadvantages of H-piles are listed in Table 2. The combination of point bearing and skin friction allows pile designers to maximize design loads. (H piles, 2016)

Table 2. Advantages and disadvantages of H-piles. (Warrington 2007)

Advantages	**Disadvantages**
High load capacity when driven in dense material	Relatively high price
Good availability: Only standard driving equipment is needed	The physical conditions of the pile are unknown after driving
Lengths can be easily adjusted	Corrosion problems
Small displacement and disturbance to adjacent piles and structures. Can be used in restricted areas	
High bending strength. Can be used in applications with lateral loads	
Good tension piles for uplift	

H-piles are hot roll-formed from ingots. Steel H-piles have many variations when it comes to shape and thickness, and they are used for design load varying from 365 kN to 2224 kN. (Warrington, 2007)

3.2.3 X-Piles

X-piles get their name from their cross section, which is the shape of an X. X-piles are manufactured from form-rolled steel, and they are suitable for sites where only small displacements are allowed. X-piles penetrate easier to the layers of cobblers than pipe pile does. (Kemppainen, 2016)

3.2.4 Sheet Piles

Sheet piles are steel sheet sections interlocked to each other forming a continuous wall. Sheet pile walls are used for temporary and permanent lateral earth support, and they can be anchored if needed. The performance of a sheet pile depends on its geometry and properties of the soil. Sheet piling is most commonly used in earth or water retention and excavation support. Yet it must be taken into consideration that sheet pile structure is not necessarily waterproof. Sheet piles have been used below grade parking structures, basements, foundations and to construction of seawalls and bulkheads. The advantages and disadvantages of sheet piles are listed in Table 3. (Sheet piles, 2015; Steel Sheet Piling, 2016)

Table 3. Advantages and disadvantages of sheet piles. (Sheet pile walls, 2003-2016)

Advantages	**Disadvantages**
High resistance to driving stresses	Can be rarely used as a part of permanent structure
Light weight	Not well suitable in soil with boulders or cobbles
Reusable	Sheet piles dictate the shape of the excavation
Long service life	Installation can disturb neighboring structures
Can be used above and below water level	
Easy to elongate and shorten	

Sheet piles are installed with vibratory hammers. Installation can be assisted with an impact hammer in case the soil is very dense. The material of sheet piles is sustainable, and the piles are often reused. Sheet piles in use are seen in Figure 9. (Sheet piles, 2015)

Figure 9. Sheet piles.

There are two primary ways to manufacture sheet piles: hot roll-formed and cold roll-formed method. Hot roll-formed sheet piles are interlocked tighter, they are generally larger, and they have larger scale of strengths. (Steel Sheet Piles, 2016)

3.2.5 Pile Walls

RD® pile wall is a structure of steel pipe piles and interlocking profiles attached by welding and drilled to bedrock (Figure 10). It is normally a part of permanent structure and can be waterproof with sealant. The pile wall is installed by drilling in a concentric method. The pile wall is best suitable for structures where great resistance for horizontal and vertical loads is needed. Pile walls can be constructed to save total costs in construction when temporary walls are not needed although wall structure is suitable for temporary use as well. Steel grades available for pile walls are S440J2H, S550J2H, RD400, S355J2H, X60 and X70. Conditions in the construction site as well as demands for the structure determine the steel grade that is selected. (SSAB RD® pile wall, 2015)

Figure 10. RD® pile wall.

RD® pile walls are suitable for various purposes. Pile walls can be used in buildings with a basement or column frame, as a temporary retaining wall during construction, in excavations and structures extending into bedrock, in bridge abutments, in intermediate bridge supports as well as in harbor wharves, wind turbine foundations and trough structures. (RD ® pile wall – Design and Installation Manual, 2016)

Another pile wall type is Combi-wall (Figure 11). Combi-wall is a continuous structure that comprises of sheet piles and pipe piles or H-piles. Piles are attached to each other by welding or interlocking systems. Pipe piles operate as a bearing structure and sheet piles create a continuous wall structure. Combi-walls can be used as retaining walls, in foundations, in pier construction as well as in road and rail structures and bridges (Combi-seinä, 2017).

Figure 11. Combi-wall. (SSAB, 2017)

4 Design and Installation of Steel Piles

4.1 Guidelines in Finland

Finnish Association of Civil Engineers (RIL) has published instructions and norms for piling works (RIL 254-2016, 2016). The publication consists of two parts: the design criteria and instructional part for piling. The guide is used alongside with Eurocode-system and the guide can be used for piles that are manufactured of steel, ductile iron, concrete, timber or composite materials. The guide divides piles based on displacement. As mentioned before, displacement piles can be installed to the ground by driving, vibration, compression, screwing or combination of these methods. Non-displacement piles are installed to the ground either with excavation or drilling.

There are three geotechnical categories based on the conditions of the construction site. Geotechnical category 1 (GL1) consists of relatively simple and small structures where former experience and qualitative geotechnical investigations are enough to ensure the fundamental requirements. Geotechnical category 2 (GL2) includes structures which require quantitative geotechnical data and analysis to ensure the requirements of the structure. The category also includes structures which do not have exceptional risks or unconventional loading or soil conditions. Geotechnical category 3 (GL3) is for big and unconventional structures, structures which have unconventional risks or difficult loading or soil conditions. Geotechnical category 3 also includes structures in highly seismic areas and areas which are unstable or have persistent ground movements. (RIL 254-2016, 2016)

Chapters 4.2 and 4.3 explain the design and execution of piling according to Finnish Association of Civil Engineers (RIL) instructions and norms for piling works RIL 254-2016 (2016).

4.2 Design of Piling

Design standards for piles are listed below:

- SFS-EN 1990 Basis of structural design
- SFS-EN 1991-1 Actions on structures
- SFS-EN 1992-1-1 Cast in place concrete piles
- SFS-EN 1992-1-1 Pre-cast concrete piles
- SFS-EN 1993-5 Design of steel piles
- SFS-EN 1994-1-1 Design of composite steel and concrete structures
- SFS-EN 1995-1-1 Design of timber structures
- SFS-EN 1997-1 Geotechnical design

In the design process the pile type, size and method of installation must be determined, and they must be suitable for the conditions in the area. Test piles must be performed before actual piling work when there is no previous piling experience. Test piles are beneficial because they offer a possibility to research working methods and devices, and also to evaluate the impact of pile installation to the soil and environment. Test piles can also be used to evaluate criteria of installation, and give reference values for the pile’s length and geotechnical strength.

All the material about piling must be available in the construction site. The minimum information, that must be available, are soil investigation report or reports, the instructions for design and execution of piling, quality requirements, requirements for supervision and testing, and conditions and limitations in the construction site that might effect on the execution of piling. Examples of these conditions are the size of construction site, topography of the area, cables and power lines, possible unstable slopes and logistics of construction site. Other information that must be available is environmental conditions, such as limitations for noise and vibration, and location of existing weak structures.

4.2.1 Placement of the Piles

In the design of piling, cutting and center distance need to be taken into account. Other aspects that need to be considered are distance of the pile footing’s edge from the pile, pile distance to other structures and inclination of piles.

The minimum cutting level is that the pile must be at least 50 mm in the pile footing. In small diameter piles the pile cap must be considered in the cutting level. In case reinforced concrete or excavated pile needs to be attached to pile footing firmly, the cutting level is pile’s effective length plus the grip length of reinforcement. After cutting, the steel of the pile is exposed until the effective length. Steel pipe piles are recommended to be closed after cutting so that they will not fill with foreign material.

The distance between piles must be determined in design documents. Piles cannot reduce the carrying capacity of adjoining piles or damage them while installing, and center distance should never be under 0.8 m. In pile walls, center distance is determined by supported material and properties of piles.

4.2.2 Approved Location Deviations

The tolerances for deviations depend on the pile type. Figure 12 illustrates abbreviations used to describe location deviations.

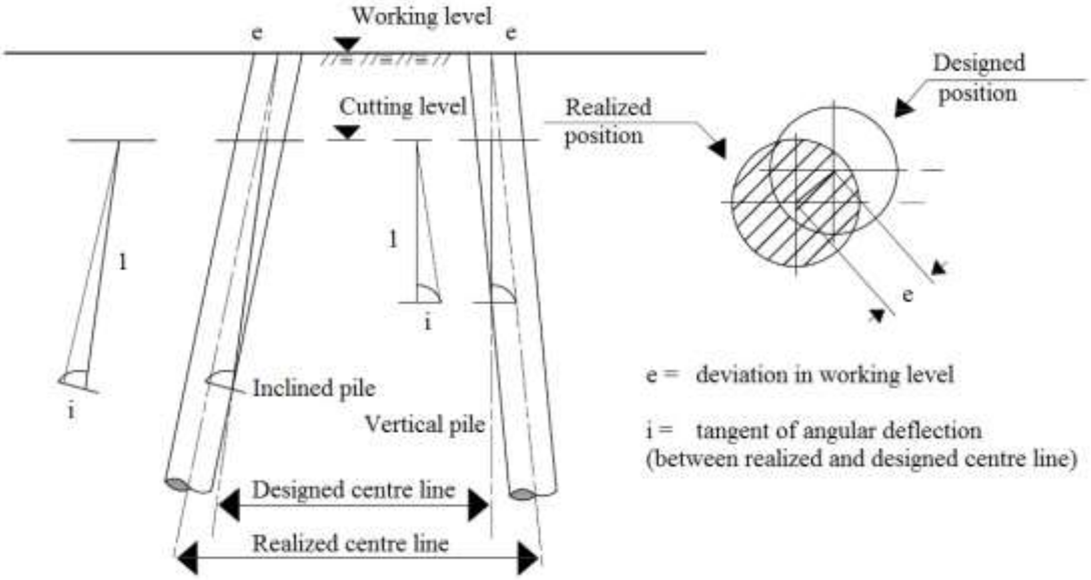

Figure 12. Abbreviations used in location deviations. (RIL 254-2016, 2016)

Driven large-diameter steel pipe piles and excavated piles have the following tolerances:

- Vertical and inclined piles horizontally located pile measured from working level:
  $e \leq e_{max} = 0.10\ m$ for piles in which $d \leq 1.0\ m$
  $e \leq e_{max} = 0.1 \times d$ for the piles in which $1.0\ m < d \leq 1.5\ m$
  $e \leq e_{max} = 0.15\ m$ for the piles in which $d > 1.5\ m$

- Vertical or inclined piles in which the inclination $\theta \geq 86°$: tolerance of inclination $i \leq i_{max} = 0.02\ (0.02\ m/m)$

- Inclined piles in which the inclination $76° \leq \theta < 86°$: tolerance of inclination $i \leq i_{max} = 0.04\ (0.04\ m/m)$

Driven micropiles must be installed in accordance with the following guidelines:

- Individual vertical ja inclined pile, pile slab or pile cap structure:
  $e \leq e_{max} = 0.10\ m$
- Individual pile of small pile group (2-8 piles):
  $e \leq e_{max} = 0.15\ m$
  Individual pile of pile group:
  $e \leq e_{max} = 0.2\ m$
  Yet pile group's center of gravity:
  $e \leq e_{max} = 0.05\ m$
- Individual vertical piles and inclined piles:
  $i \leq i_{max} = 0.04\ (0.04\ m/m)$
  In parallel pile groups:
  $i \leq i_{max} = 0.02\ (0.02\ m/m)$
- Horizontal direction of inclined piles can deviate 2° ($i = 0.035\ m/m$) from presented direction

Drilled piles must be installed within tolerances mentioned in the last two paragraphs. Yet tolerances can be smaller because the installation method is more precise. The recommended deviation tolerances are the following:

- Vertical and inclined piles horizontally located pile measured from working level:
  $e \leq e_{max} = 0.025\ m$
- Vertical and inclined piles in which the inclination $\theta \geq 86°$: tolerance of inclination: $i \leq i_{max} = 0.015\ (0.015\ m/m)$
- Inclined piles in which the inclination $76° \leq \theta < 86°$: tolerance of inclination: $i \leq i_{max} = 0.025\ (0.025\ m/m)$
- Horizontal direction of inclined piles can deviate 1° ($i = 0.0175\ m/m$) from presented direction

4.2.3 Design of Installation

There are quality requirements for every project. Requirements have to present acceptable limit values for adjacent structures. If piles are installed to bearing stratum or bedrock, the minimum depth and diameter must be presented in quality requirements. In case the conditions of the soil differ from design conditions or pile hits to impermeable barrier before reaching the designed depth, the plan must be changed so geotechnical strength is reached. When steel piles are installed, the maximum energy obtained from the pile driver cannot cause steel pile stress reach higher values than 0.9 x steel’s yield strength.

When piling work is planned, there are things that need to be considered, like requirements that come from the environment. For example, in excavation work, backfilling and piling work the design and execution cannot reduce the strength of existing piles and harm the structures in immediate surroundings. Other factors that need to be considered are soil transfer and displacement, disturbance of the soil, rise of piezometric level and artesian water, compaction and bulking of soil, and also vibration and noise.

Pile walls can be designed for vertical and/or horizontal loads. Tolerances can be more accurate than the values mentioned before, especially when compactness against soil or water is in demand. Inclination, distance between center points, geometric tolerances, lapping and demand for water tightness must also be determined.

4.3 Execution of Piling

The executor of piling work drafts a site planning scheme. If the piling category is PTL2 or PTL3, a separate document of quality assurance must be executed. The piling category depends on the consequences class (CC1…CC3) and the geotechnical category (GL1…GL3). The categories are classified in Table 4. The site planning scheme describes the chosen foundation structures in detail, and the scheme is verified by the party implementing the construction project. Site planning scheme presents working procedures and machinery, and it also has to consider the conditions on the site.

Table 4. Piling categories PTL1, PTL2 and PTL3 in construction. (RIL 254-2016, 2016)

Geotechnical category	Consequences Class (SFS-EN 1990)		
	CC1	CC2	CC3
GL1	PTL1…(PTL3)	PTL2…(PTL3)	PTL2…(PTL3)
GL2	PTL1…(PTL3)	PTL2…(PTL3)	PTL3
GL3	PTL2…(PTL3)	PTL2…(PTL3)	PTL3

There are requirements for the supervisor of piling, and also for the person using the piling rig. The supervisor normally needs to have years of practical experience in piling works and adequate theoretical knowledge, and the person using the pile-driver needs to know the process of piling. The person needs to know the reason for piling at the construction site, the basics for using a specific working method and the influences of work quality for the next phases of construction and also for the final structure. There are also other demands depending on the piling category. For example, in PTL3, a test loading must be executed. Test loadings are performed to ensure geotechnical resistance and to observe a possible damage of the pile. There are static and dynamic test load methods available, and the most commonly used method is a dynamic PDA measurement.

During piling, all prevented measures need to be performed to ensure the safety of the construction site and surroundings, and to minimize the harm caused by noise and vibration and also the risks to nearby structures. Piling is implemented with the approved site planning scheme. If possible, the installation of the test pile or the first pile should be performed close to the areas where, soil tests have been carried out. All significant deviations in the soil must be reported and considered in the pile planning scheme.

There are a few specifications for driven steel piles. Driving is executed along the longitudinal axis and centralized to the pile head. If the piles are not well supported horizontally, buckling is considered in driving equipment or in the length of the piles.

The manufacturers of piles define acceptable maximum values for the drop height. The contractor chooses suitable piling equipment, which ensures that the designed driving energy is reached. The energy transferred to the pile can be ensured with dynamic loading tests.

5 Piling Equipment

When it comes to the structure of piling equipment, it has to be possible to observe the penetration of the pile to the soil, and to stop the installation if needed. In addition, the equipment needs to fulfill the work safety requirements. More information can be found in SFS-EN 791 and SFS-EN 996.

5.1 Equipment for Driven Piles

Piling rigs need to have the qualities that ensure their reliability and safety, and that they fulfill possible size and weight demands for the specific construction site. Hammers need to have the qualities, which enable the pile to be driven into the ground to the designed depth, and that the pile remains intact. Impact velocity and weight of the hammer depend on the pile type and the conditions of the soil. If the piling category is PTL2 or PTL3, the factors influencing piling have to be determined by the manufacturer, importer or user. If the cutting level of the pile is below ground or water level, a standby pile can be used. (RIL 254-2016, 2016)

5.1.1 Drop Weight Hammers

Drop weight hammers (Figure 13) are normally wire suspended, in which the hammer is lifted with a hoist to the desired drop height. Next, the wire will be released, and the hammer with the wire will fall against the pile cap, which is placed on top of the pile. The weight of the hammer depends on pile size and conditions of the foundation. (RIL 254-2016, 2016)

Figure 13. Drop hammer. (Heavy Civil Construction, 2016)

Drop weight hammers can be used for concrete piles and other piles, which have an ultimate pile capacity < 60 t. The weight of the ram has a weight > 1.0 t, and the drop height is < 3.7 m. The weight of the ram has to be greater than combined weight of the helmet and the pile. If a drop hammer is used, hammer guides and a helmet are recommended to ensure a centered impact to the pile. (Installation Specification for Driven Piles, 2007)

A required blow count can be calculated with a dynamic formula or a wave equation. If dynamic formula is used, the weight of the striking parts has to be > $\frac{1}{3}$ of the combined weight of pile and drive cap. If wave equation is used to calculate the blow count, the limitation of the ram weight is not essential. The performance of the hammer is evaluated after driving by blows per minute. The results are compared to the recommendations of the manufacturer. (Installation Specification for Driven Piles, 2007)

5.1.2 Diesel Hammers

Diesel hammers (Figure 14) are mainly used in installation of piles with a large diameter. The hammer type causes highest noise and air pollution of all hammer types. The diesel hammers can be open-end (OED) or closed-end (CED). OED hammers are single acting hammers, and they usually have a device to measure the impact velocity during pile driving. The impact velocity can be obtained by measuring the speed manually or automatically. CED hammers are double acting. They normally have a bounce chamber pressure gauge. The correlation chart of the chamber pressure and the potential energy should be provided by the contractor. (Installation Specification for Driven Piles, 2007)

Figure 14. Diesel hammer. (DELMAG Diesel Pile Hammers, 2017)

5.1.3 Pneumatic Hammers

Pneumatic hammers, also known as air hammers (Figure 15), are used in piles with a small diameter. A percussion piston is lifted with compressed air. When the piston has reached the maximum height, the lower cylinder empties and the piston falls. (Installation Specification for Driven Piles, 2007)

Figure 15. Pneumatic hammer. (Vulcan: The First Hundred Years, 1997-2017)

5.1.4 Hydraulic Rams

Originally hydraulic rams (Figure 16) were used to break rocks, but currently they are used to install micropiles. A percussion piston is lifted hydraulically, and gas pressure induces the speed of the falling piston. The percussion force can be adjusted with a change of the pressure. The number of percussions is adjusted with increasing or decreasing hydraulic flow. Hydraulic rams should be equipped with a device that measures the energy of the ram (Installation Specification for Driven Piles, 2007).

Figure 16. Hydraulic ram. (Hydraulijärkäleet, 2017)

5.1.5 Vibratory Hammers

A vibratory hammer (Figure 17) can be used independently or with another pile driver. The vibratory hammer is used to drive a pile through soft layers of soil, and the other device, for example pneumatic hammer, is used for the impact resistance and to reach a designed depth. If vibratory hammer is used for the installation of the pile into the ground, the hammer should be placed centralized to the pile head. The centrifugal force, vibration frequency and vibration amplitude of the hammer can be chosen to be suitable for the conditions of the soil and the pile. Since the principle of the hammer differs a lot from other hammers, the criteria for piling should always be ensured with another hammer afterwards. (Installation Specification for Driven Piles, 2007; RIL 254-2016, 2016)

Figure 17. Vibratory hammer. (DAEDONG Engineering, 1996)

5.1.6 Appurtenances

Hammer cushions, helmets, pile cushions as well as sand and rock shoes (Figure 18) are used in pile driving. Hammer cushions are used to protect the hammer, whereas pile cushions and helmets protect the pile. Helmets are used, when piles are installed with an impact hammer, to divide the hammer blow concentrically and uniformly. Driven pipe piles are normally equipped with either sand or rock shoe. The shoe is connected to the pile with friction or welding. (Installation Specification for Driven Piles, 2007)

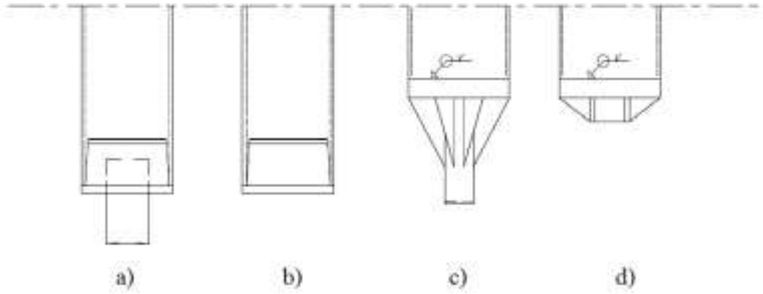

Figure 18. Pile shoes. a) Rock shoe attached to the micropile by friction, b) Sand shoe attached to micropile by friction, c) Rock shoe attached by welding to large diameter pile d) Sand shoe attached by welding to large diameter pile. (RIL 254-2016, 2016)

5.2 Equipment for Drilled Piles

Pile drilling machines have to be able to move around in the construction site, and have the qualities needed in terms of size, weight and length of the pile element. Piling equipment used for drilling is a top hammer and a Down-the-Hole hammer (DTH), and both can be used in concentric or eccentric method. The idea of the top hammer and the DTH hammer are shown in Figure 19.

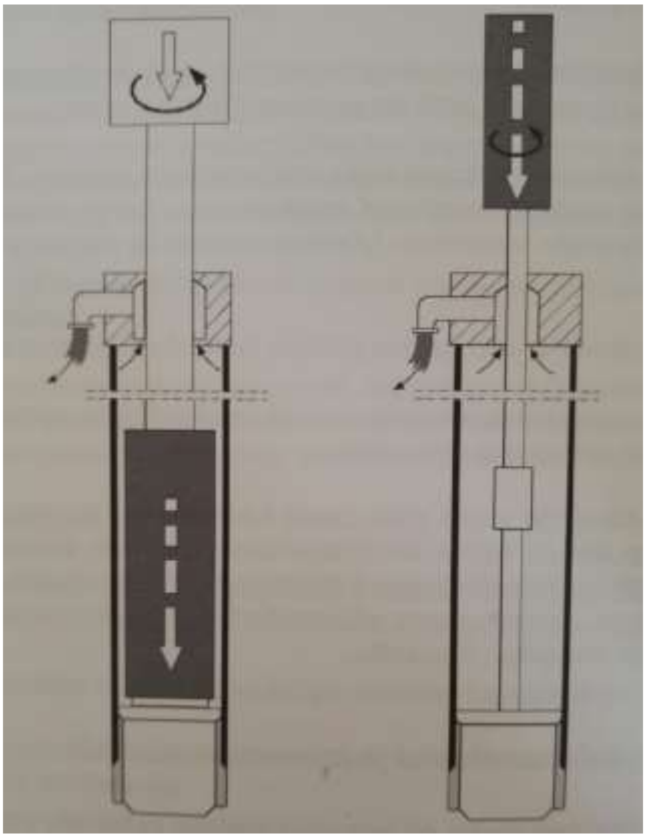

Figure 19. Generalization of a) DTH hammer and b) top hammer. (RIL 254-2016, 2016)

In the eccentric method (Figure 20) there is a pilot bit and an eccentric reamer. During the drilling the eccentric reamer widens the drilled hole, while drill bit pushes the casing into the ground. There is a flusher that pushes the excess soil up. After the desired level is reached, the drill rods start to rotate to the opposite direction, which causes the reamer to close. The casing is left to the ground and the drilling equipment is lifted from the hole. (RIL 254-2016, 2016)

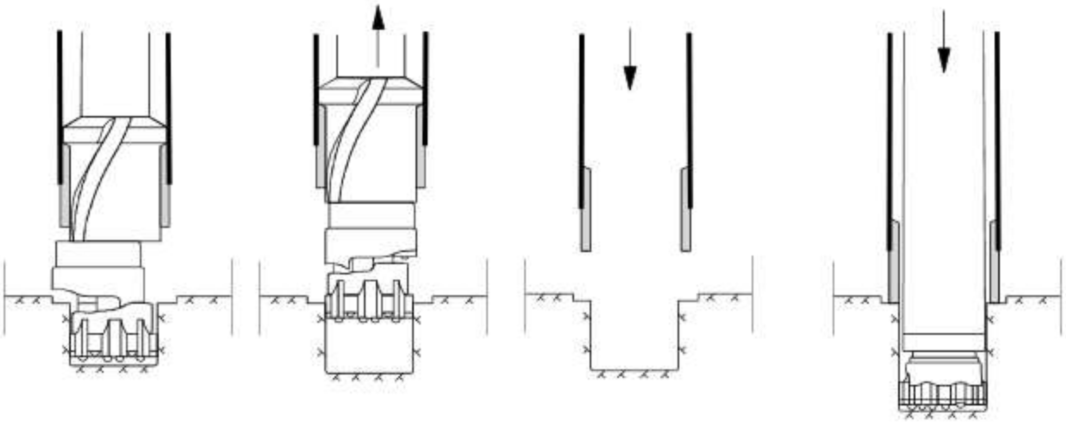

Figure 20. Eccentric method. (TIEH 2000002E-03, 2003)

In the concentric method (Figure 21) there is a pilot bit and a concentric reamer, which is also called a ring bit. There are two concentric methods available. In OD method the casing rotates and the head of the casing is attached with the reamer. The method is unsuitable for large diameter-piles. (RIL 254-2016, 2016)

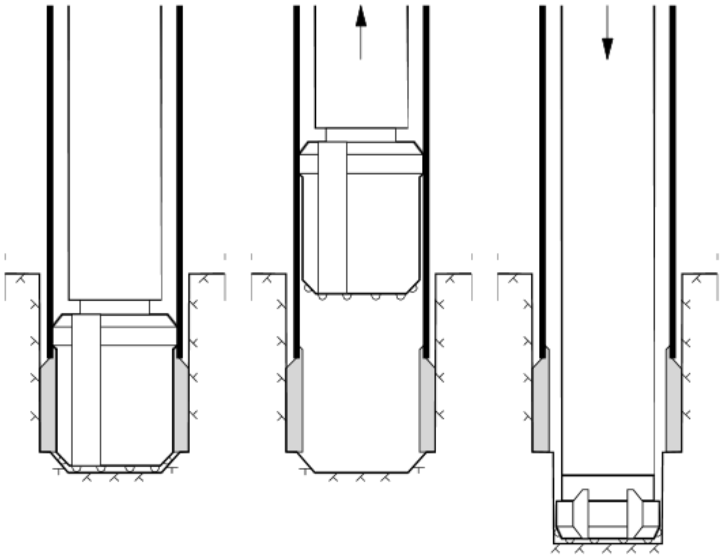

Figure 21. Concentric method. (TIEH 2000002E-03, 2003)

In the other concentric method the casing doesn’t rotate. The pilot pit and the reamer are locked to each other, and they rotate drilling a hole. Afterwards the pilot bit pulls the casing down. When desired depth is reached, the pilot bit is detached from the reamer and pulled up. The method is suitable for large-diameter piles, since it does not require high torque like OD method does. (RIL 254-2016, 2016)

5.2.1 Top Hammer

Top hammer is typically pneumatic or hydraulic (Figure 22). The drilling device is attached to a hydraulic rotating unit and drill rods. Pneumatic hammer’s percussion rate varies between 1600 to 3400 percussions per minute and hydraulic hammer’s 2000-4000 percussions per minute. Top hammer can install piles with diameter ≤ 200 mm. (RIL 254-2016, 2016)

Figure 22. Top hammer. (Top hammer drilling vs. Down-the-hole drilling)

Percussion of the pile is aligned with a drill rod inside the pile. The drill rod rotates simultaneously. Because of the previous, drilling power reduces when pile length is increased. The maximum length of the pile is around 30 meters, but in cohesive layers piles up to 50 meters can be installed. (RIL 254-2016, 2016)

5.2.2 DTH Hammer

DTH hammer (Figure 23) is typically pneumatic but water-driven hammers can also be used. The device is attached with a hydraulic rotating unit and drill rods. The installation speed and drilling power are not affected by the length of the pile. Drill rods are attached to the hammer, which is attached to the drill bit. Percussion is ultimately transferred into a sand shoe, while rotating unit spins drill rods. (RIL 254-2016, 2016)

Figure 23. DTH-hammer. (DTH Reverse Circulation Hammer Drilling)

6 Splitting and Cutting Steel Piles

6.1 Guidelines

Micropiles are cut perpendicularly against pile's longitudinal axis from designed cutting level. Cutting can be executed with a flame cutter or a cut-off wheel, also known as a grinder. The grinder can also be used to level uneven surfaces. The head of the pile is recommended to close after cutting. The allowed deviation of right angle of the pile is < 2 % compared to perpendicularity of the axis. The same deviation is allowed in large-diameter piles. Large diameter piles must be closed after cutting in terms of safety. (RIL 254-2016, 2016)

Drilled piles are cut at the cutting level, which is specified in the piling plan. Piles are cut perpendicular to the pile axis. Without plan stating otherwise, the deviation of the cutting angle must be 2 % as in driven piles. Pile heads are closed after cutting. (TIEH 2000002E-03, 2003)

6.2 Safety in Piling Works

Since there are no European standards available for the safety in piling works, national standards must be followed. There are also variation of legal requirements, laws, norms and instructions, which need to be considered in the piling works. All the information mentioned concerns about the safety of working area, safety of working procedures and methods, legality of work phases and inspections done by hand inside pile excavations, and also employment security of the equipment used in piling works. The equipment must follow SFS-EN 791 and SFS-EN 996 (manufactured before 2015) or SFS-EN 16228 (1-6) (manufactured after 2015), and inspections for machinery are performed every fifth year. Special attention must be paid to all work phases where a person is working close to heavy machinery or pile excavations. Attention must be paid also when piles are open, when inspections made by hand and when material is transferred and lifted. (RIL 254-2016, 2016)

An approach for the safety procedure varies depending on the company. For example, in Skanska a safety plan should be concluded before piling work can be executed, and the plan needs to be shown to the workers before the execution. The site manager ensures that everybody in the construction site is aware of the instructions and the risks of piling work. Before pile cutting, the soil surrounding the pile must be removed, and the pile must be exposed to ensure an easy access to the pile. The working area must be leveled and safe, and all excess water has to be pumped to avoid potential risks. The piling area is restricted from other people excluding the cutter. The safety zone is 2 x pile length to be cut, but always > 5 m. There is a risk of falling short under the pile or get hit by sparks. The steel piles are cut, when pile is still attached to the machinery, if possible. The cutting work causes noise and dust; thus, people working in surroundings should use eye and hearing protection. (Paalujen katkaisun turvallisuusohje, 2015)

6.3 Mechanical Methods

6.3.1 Grinder

Grinders are generally used for cutting and splitting micropiles. Grinders and grinding machines have a wheel, a belt or a disc, that has an abrasive material. Abrasive spinning of the wheel removes material and improves surface finish. The grinding machines normally operate pneumatically, or they are powered by combustion engine or electric motor. The grinders are available in variety of models with different wheel sizes, and there are also subsea models available. The properties of the wheel are chosen according to the thickness and material of the pile. The grinders can be automatic, have numerical control through computer or be controlled by a program or an interface. The grinders also come in several shapes. They can be bench mounted, floor mounted, handheld (Figure 24) or portable. (Grinders and Grinding Machines Information, 2017)

Figure 24. Handheld grinder. (New Milwaukee M18 Fuel Braking Grinder, 2015)

Grinder is a versatile machine that is used to cut many materials in the construction site. Grinders can also be used to clean or prepare a surface, sharpen tools and in different repair and maintenance works. The grinder type can be selected depending on the need. In piling work the grinder is instructed and commonly used to cut pile heads (RIL 254-2016, 2016).

6.3.2 Diamond Wire Saw

Diamond wire saws have a steel wire, which is embedded with diamond particles. The cutting force is based on the particles, which have mineral hardness (Mohs scale) of 9. Untreated steel is around 6, yet the diamond wire saw is more commonly used to cut softer materials, such as concrete that has hardness around 3. The length of the wire can be adjusted to suit the purpose. Diamond wire saws work the same way as chain saws so the wire rolls around the frame. Diamond wire saws are used to cut piles externally, and they are used to cut medium to small tubular structures and standard steel shapes. The machine is big and difficult to handle, and the development of the technique has been slow. Diamond wire saws are generally used to cut monopoles, and attention must be paid on the safe zone; thus, the device can operate around the pile. Due to the size of the machine, the diamond wire saw is not suitable for cramped areas. (The Pioneer of Diamond Wire Sawing, 2017)

There is a hydraulic motor that drives the main wheel. The main wheel and two smaller guide wheels control the wire. Diamond particles in the wire cut the surface by friction. The basic idea of the diamond wire saw is shown in Figure 25.

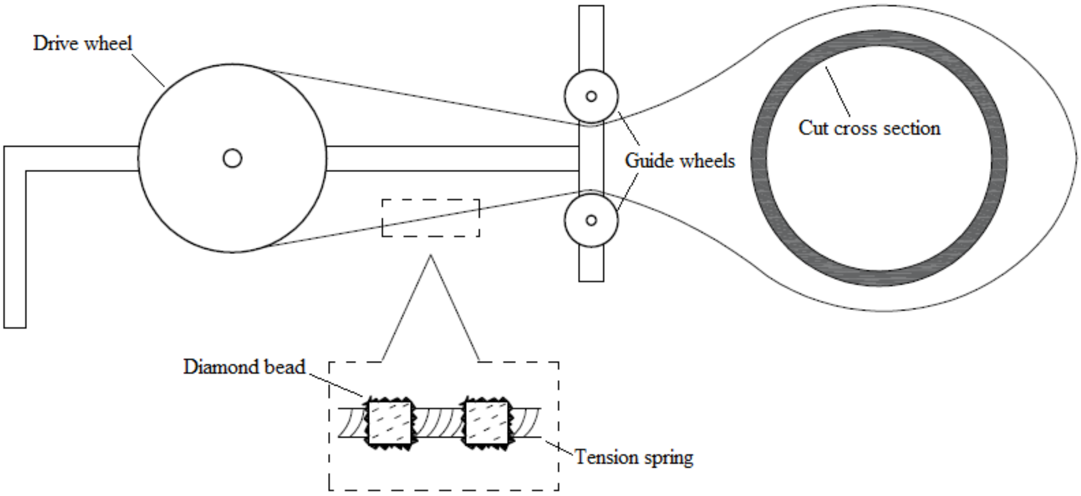

Figure 25. Basic idea of a diamond wire saw. (The Pioneer of Diamond Wire Sawing, 2017)

There are many types of diamond wire saws. The cutting speed depends on the thickness and the surface treatment of the steel. The maximum diameter of the pile for cutting depends on the manufacturer. For example, a company called Wachs has machinery in the market that cuts pipes with a diameter from 101.6 to 1320.8 mm. There are types, which can be used above and below water level, and devices, which are only suitable for certain conditions. Since diamond wire saws cut externally in a certain method, they need a lot of space around them.

6.3.3 Pile Cutting Machine

Aggregate Technologies has designed and patented a Pile Cutting Machine (PCM), which can cut steel and concrete piles. There is a Gradall track-mounted excavator modified for pile cutting. The device has compressible grippers and a cutting blade (Figure 26), and the machine is holding the pile in place while cutting, and then moves it aside. The blade can be changed to suit the purpose. PCM is used in external cutting, and it demands space to operate, yet it works in most conditions. (Cut pile with one man and one machine, 2014)

Figure 26. Pile Cutting Machine of Aggregate Technologies (Cutting Steel Piles)

6.3.4 Guillotine Saw

Guillotine saws are used to cut steel pipes. Guillotine saw (Figure 27) is operated hydraulically, pneumatically or manually. There are many companies that provide guillotine saws or cutting services with guillotine saws. There are different blades for different purposes, and also different devices for cutting above and below water level. Generally saws cut 0.8 mm - 610 mm pipes, but there are devices that are able to cut pipes with larger diameter. The cutting is carried out externally. (Guillotine Pipe Saw, 2009-2017)

Subsea Guillotine Saws, SGSs, (Figure 27) are patented devices, which are suitable for cutting pipelines, bracings and beams below water level. SGSs can cut pipes with outside diameter from 127 to 812.8 mm. The saw has a dual blade system, which is attached to a remotely operated vehicle (ROV) or a tool basket depending on the size of the saw. (Decommissioning and Cutting Services, 2016)

Figure 27. Guillotine pipe saw and SGS. (Guillotine Pipe Saw, 2009-2017; DTS Tooling, 2013)

6.4 Water Jet Based Abrasive Methods

Even though abrasive methods belong to mechanical methods, it is important to realize the development in abrasive methods, especially in water jet cutting which is a remotely operated vehicle (ROV). The water jet cutting method has thin water jets, which are used under a high pressure. The water jets are attached with abrasive slurry that cuts the material by erosion. The technique has been initiated in 1980’s. Before, the cutting was executed by high pressure water, and with time abrasive grains were added, which made it possible to cut harder materials. Abrasive grains are alluvial garnets, and properties of the grains should be chosen depending on the material that is cut. The proper term for the treatment is a hydro-abrasive technique. The general procedure is that water is fed by a pump under pressure, and water is mixed with abrasive material inside a water jet nozzle. The mixture is then transferred into a mixing nozzle, where it stabilizes. The stream of hydro-abrasive mixture is directed to the target material. High pressure water pumps are available with a pressure from 276 to 689 MPa. There are devices available for cutting above (Figure 28) and below water level. Generalized features of abrasive water jets are shown in Table 5. Examples can be found in the next chapters. (Krajcarz, 2014)

Figure 28. Water jet cutting above water level. (External Abrasive Waterjet Cutting, 2016)

Table 5. Features of abrasive water jet cutting. (Krajcarz, 2014)

Method of cutting	**Abrasive water jet**
Speed	Slow
Thickness of steel	Depends on the manufacturer
Size of the material	< 600 mm
Shape	Complicated shapes
Suitable materials	Most of solid
Suitability for rusty materials	Very good
Composites	Yes
Thermal deformation	No
Hazardous vapors	No
Multilayer cutting	Possible
Precision cutting	High

6.4.1 RGL’s Abrasive Water Jet

RGL’s Ultra High Pressure Abrasive Water Jet Cold Cutter is able to cut steel piles and also other materials without a spark or heat. The water jet can cut piles with variety of thicknesses, lining material or substrate material. The method is used in many different fields: civil engineering, petrochemical and oil refining, oil and gas exploration, marine structures etc.

Abrasive water jet system is controlled remotely. Fine ultrahigh pressure water jet nozzle with abrasive crushed rock is used in a diesel-powered device. It is possible to bespoke variety of nozzles to reach the desired objective, also in complex shapes and radiuses. The cold cutting system can be used to cut pile walls by fixing a track to the piles, where a water jet head can traverse along. The maximum cutting depth is 60-80 m. (Weeks, 2017)

The system can be used to cut piles above and below ground, but also below water level, and the cutting pressure can reach 3000 bar. The general process of cutting and two case studies can be found in Appendix 1. In general, the process of internal pile cutting has six phases. First, pile’s top section or any structure, that is covering the pile, is cut and removed. In the second phase, a hydraulic dredge grab is collecting foreign objects and large debris inside the pile. After large debris is removed, the dredge pump is lowered inside the pile to remove smaller debris. Fourth phase is to clean the rig 1-2 m below cutting level. After cleaning, a cutting rig is lowered into the designed depth, and in sixth phase, the actual cutting is executed and the cut section is lifted. (Weeks, 2017)

The cutting method does not remove a lot of material, create a heat-zone, alter metallurgical properties or create any risks of fire or explosion. Other advantages and disadvantages are shown in Table 6.

Table 6. Technical, safety and environmental advantages and general disadvantages of cold abrasive jet cutting method. (Abrasive water jet cold cutting, 1998-2013)

Technical advantages	**Safety and environmental advantages**	**Disadvantages**
Safe in means of cutting	Remote controlled, increases safety	Abrasive waste
Can cut metals <600 mm thick	Ultrahigh pressure water is mixed with inert rock. No environmental consequences.	Relatively slow
Precision and crap cuts can be made. Re-use of the cut section is possible	In case the water is contaminated → vacuum tanker for licensed disposal. Otherwise plan drainage system can be used to dispose waste water,	Debris control
Precise angle cuts can be made leaving surface for welding	Efficient and safer method underwater.	

6.4.2 Coldcut™ Pipe Cutter

The Coldcut™ Pipe Cutter has an abrasive water jet cutter and a water spray extinguisher combined into one. High water jet pressure cuts rapidly by abrasion, and method can be used in all kinds of materials. It can be used in variety of diameters, and the device is used externally (Figure 29). The pipe cutter's nozzle is carried along dual chains. The method is powered by hydraulic motor that runs by oil. Nozzle's slurry is controlled manually or by cobra's radio. There is also a separate hydraulic valve control unit. (Coldcut™ Pipe Cutter)

Figure 29. The Coldcut™ cobra. (Coldcut™ Pipe Cutter)

6.5 Thermal Methods

Thermal methods can be divided into flame cutting, plasma cutting and laser cutting. Flame cutting is widely used in the construction industry but plasma and laser cutting are continuously developing. The comparison of thermal methods is shown in **Virhe. Viitteen lähdettä ei löytynyt.**, and next chapters consider each method individually.

Table 7. Comparison of thermal methods. (Krajcarz, 2014; What is CNC Plasma Cutting? 2017)

Method of cutting	**Flame cutter**	**Plasma cutter**	**Laser cutter**
Speed	Fast	Slower	Fast
Thickness of material	152.4-304.8 mm	≤ 25.4 mm	Thin and medium
Size of the material	Medium and large	Large	Small and large
Shape	Simple	Simple	Complicated
Suitable materials	Metals and conductive materials	Metals and conductive materials	Homogenous with no reflective bodies
Suitability for rusty materials	Good	Average	Good
Thermal deformation	Yes, large area	Yes, wide area	Yes, small area
Multilayer cutting	-	Impossible	Impossible
Precision cutting	Poor	Good	Very good

6.5.1 Flame Cutting

Flame cutting is also known as oxyfuel cutting. First, steel is preheated with the mix of fuel and preheating oxygen. The result is a flame that heats steel to the temperature of ignition. After the ignition temperature is reached, the cutting oxygen is directed to the desired spot (Figure 30). When the steel starts to ignite at the surface, the cutting begins. The mixture of gases releases a lot of heat that melts the steel below the surface. The steel melts and the flame ignites it again, which heats the steel below. In other words, the process is progressive and continues until the steel is cut. (Warrington, 2007)

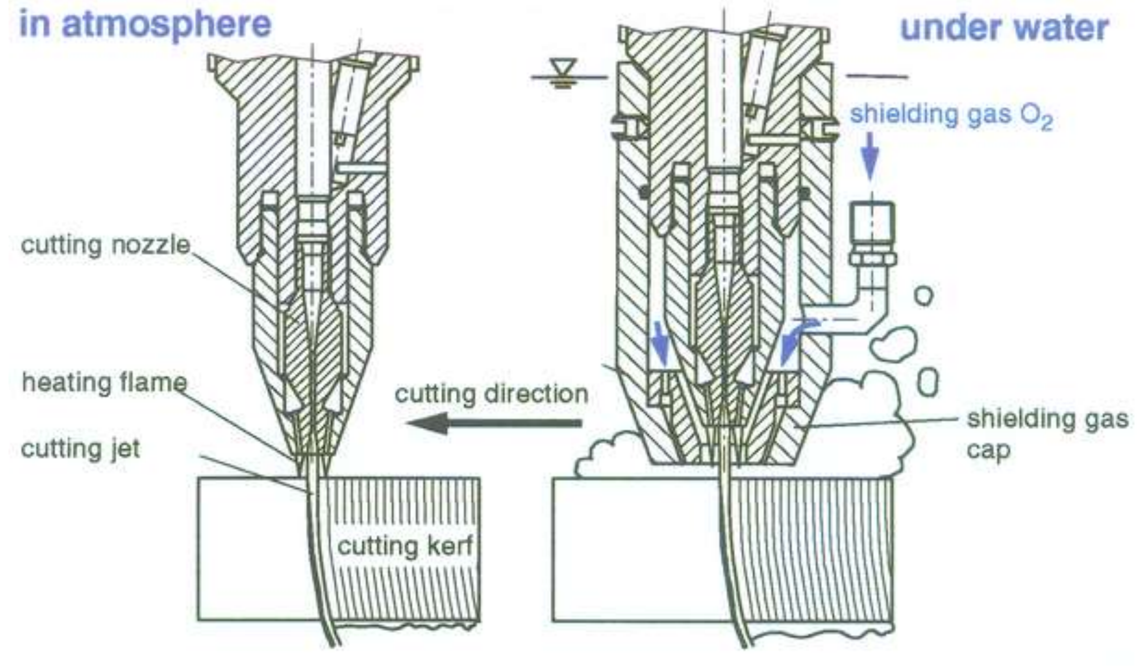

Figure 30. Process of flame cutting above and below water level. (Bach and Lindemaier, 1998)

In steel, the cut is normally started from the edge, but in case it is not desired, a hole needs to be done to the steel to start the cutting. It can be done by heating the area and burning a hole into the steel (Warrington, 2007). In general, a hand-held flame cutter is used to cut steel with thicknesses up to 304.8 mm (Choosing between Oxy-fuel and Plasma Cutting Systems).

There are different fuels, which can be used with oxygen. These gases are acetylene, propane, propylene, MAPP gas, natural gas, hydrogen and mixes of the gases mentioned. Acetylene is the most common gas used in cutting, but also in welding. Hydrogen is used in water submerged cutting, since acetylene becomes unstable in 10 m below water. The properties of the material, that needs to be cut, has an influence to the chosen fuel. (Oxyfuel cutting - process and fuel gases, 2017)

6.5.2 Plasma Cutting

Plasma cutters work through electrical reaction. In other words, they can only cut materials, which are conductive. When a gas stream is in a compressed form of an arc, and it is passed to the phenomenon, the result is ionization and high power density, which creates a stream of plasma. Heated plasma combined with a stream of gas can cut and melt metal. The most commonly used gas is air, but high-power devices use argon, nitrogen, hydrogen and carbon dioxide. The machine has a torch that has an ohmic censor in the tip. The censor is put to the surface that needs to be cut (Figure 31). As soon as the censor touches the surface, the torch is lifted to the pierce height. When the height is reached, the torch moves down to the cutting height and cutting begins. Pierce height, cutting height and feed rate depend on the properties of the material. Torch height is controlled automatically by reading the voltage from the plasma arc. Since the plasma arc is extremely hot, the beam has a destructive influence to the surrounding area. Plasma is normally used for thicknesses ≤ 25.4 mm. (What is CNC Plasma Cutting? 2017; Hanchette, 2003; Krajcarz, 2014; Choosing between Oxy-fuel and Plasma Cutting Systems)

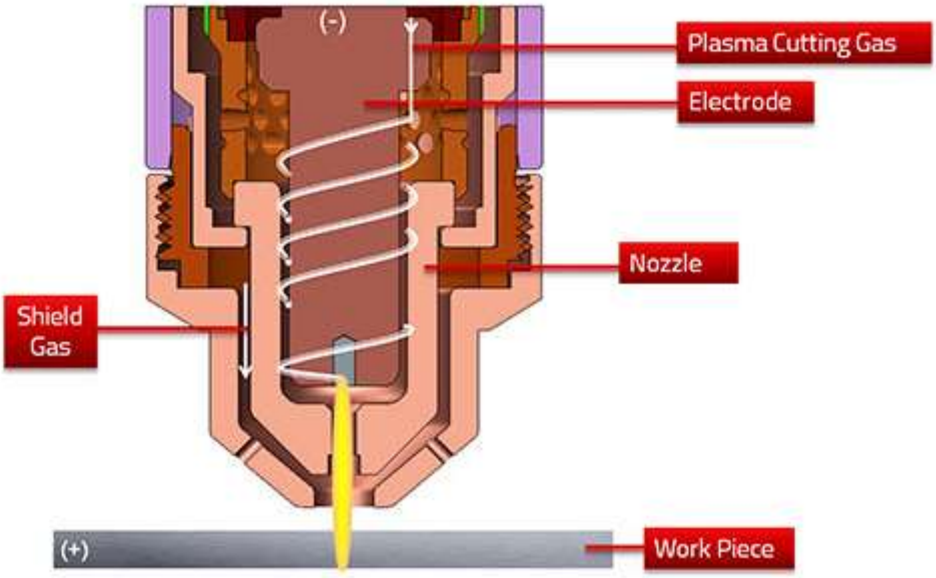

Figure 31. Process of plasma cutter. (How a Plasma Cutter Works, 1999-2017)

A Finnish company, MotoCut, has developed a portable plasma cutter. It can be used for steel pipe piles of 140-270 mm diameter with a maximum wall thickness of 20 mm. It is attached to an excavator, where it replaces the excavator bucket. It takes a hold of the pile, and the cutting will be executed below clamps. The clamps hold the excess part of the pile in place before lifting (Figure 32). Motocut’s plasma cutter is being tested and it will be launched in autumn 2017. It is designed for building construction sites, but it can be adjusted for other applications according to clients’ demands. If it would be used underwater, the electrical parts need to be covered. The goal in the future is to be able to use the cutter for bigger pile dimensions. (Plasma Cutter; Henttonen, 2017)

Figure 32. Plasma cutter of MotoCut. (Plasma Cutter)

6.5.3 Laser Cutting

In laser cutting the idea is similar to oxyfuel cutting, but instead of heat, a laser beam is pointed to the material (Figure 33). A laser beam is created with lasing material and electrical discharges or lamps in a closed container. The beam is reflected through a mirror until sufficient energy is achieved. After, the beam escapes from the space as monochromatic coherent light. The smallest diameter of a laser beam can be from 0.1 mm to 0.32 mm (Krajcarz, 2014). The radiation is absorbed by the material and energy is converted into heat. The laser can be used alone or it can be adjoined with oxygen. The mix of oxygen and radiation react with most metals.

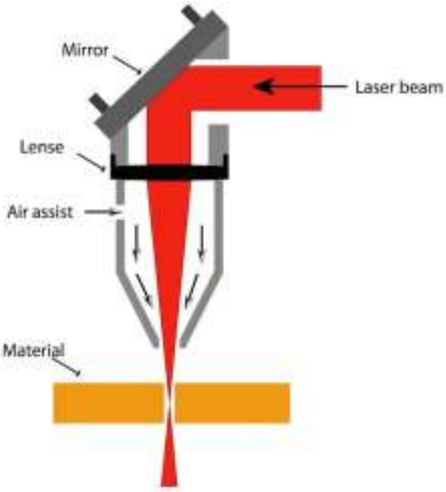

Figure 33. Process of laser cutter. (How does CO2 laser cutting work?, 2015)

The laser beam can cut steel with variety of thicknesses up to 304.8 mm (Krajcarz, 2014). The method is used diversely in industrial fields, and it is spreading into a wider use. It is used in dry conditions as a laser beam damp rapidly in fluid. Nonetheless, there are some devices that can operate under water, but the development is still in its early stages.

6.6 Explosive Methods

Explosives, which are chemical substances, are used to create high pressure shocks. Explosive methods can be used in offshore applications and generally in demolition. Explosive methods for pile cutting can be divided into bulk explosive charges, configured bulk charges and cutting charges.

6.6.1 Bulk Explosive Charges

Bulk explosives are the most commonly used technique of explosives used in pile cutting. Explosive materials in use are Comp B and C-4. Previously mentioned explosives are castable and moldable, and they have a high velocity of detonation and shattering power. Since explosives are moldable, they can be used in different shapes fitting the dimensions of piles in case they differ from drawings. (An Assessment of Techniques for Removing Offshore Structures, 1996)

Tubular sections are formed by welding piles together during platform installation. Cylindrical steel guides, also known as stabbing guides, are welded to the bottom of each pile, which will facilitate mating with preceding section. Therefore the diameter of the stabbing guide is smaller than the diameter of the pile. Bulk charges are lowered along stabbing guides to the bottom of the pile, and charges will be detonated almost simultaneously in groups of ≤ 8. The delay is approximately 0.9 seconds. Bulk charges are put to the pile from above so there is no need for divers. (An Assessment of Techniques for Removing Offshore Structures, 1996)

The downsides of using bulk charges are that piling generally drops a few centimeters, they can easily be damaged during the work and the cut may be uneven. There is also environmental aspect that needs to be considered when using explosives. Yet method can be used in various depths, and explosives are inexpensive. (An Assessment of Techniques for Removing Offshore Structures, 1996)

6.6.2 Configured Bulk Charges

Configured bulk charges can be divided into ring charges and “focusing” charges. The charges are prefabricated and pre-molded to fit each situation, although small miscalculations in pile diameter and dimensions are considered. Both charges are lowered into the pile from pile head. There can be problems to put the charge in if the diameter of the casing is very small. (An Assessment of Techniques for Removing Offshore Structures, 1996)

Ring charges are made of Comp B and C-4, which are molded into the shape of rings. The shape concentrates the explosive closer to the walls of the pile and also reduces the amount of explosive by 10 to 15 %. “Focusing” charges have explosive, which is accompanied with steel stamping plates above and below. Stamping plates induce the horizontal force of the explosion, which enables a smaller amount of explosive to reach the same effect if ring charges would have been used. (An Assessment of Techniques for Removing Offshore Structures, 1996)

6.6.3 Cutting Charges

High-velocity explosive energy is used to accelerate a v-shaped linear material into a high-velocity jet. The jet then cuts the steel. The material used in cutting is usually copper. The charge-material is in ring-shaped container that is fitted to the outside of the pile. It can also be used with a running tool or in a custom-built device to perform an internal cut. (An Assessment of Techniques for Removing Offshore Structures, 1996)

There are a few downsides, which need to be considered. If an external charge is used, explosive energy will be transferred into the soil. If the thickness of the pile structure is unknown, the pile is out of round or the charge is not in direct position, the cutting may fail. The manufacturing of cutting charges takes more time and cost approximately 5 times more than bulk charges. A diver needs to be used in the method, if cutting is performed below water level. The safety of the diver needs to be considered alongside the economic aspect. Lastly, the cutting outcome depends on the air gap between the liner of the charge and the pile; thus, water infiltration reduces the cutting effect. (An Assessment of Techniques for Removing Offshore Structures, 1996)

6.6.4 Shockwave Refraction Tape

Shockwave refraction tapes (SRTs) are also called cutting tapes. The basic idea is that tape is concentrated with shockwave effects. When explosives detonate the surface of the target material, the compressive shock waves reflect from free surfaces as tension waves causing a tensile failure of the target material. (Explosive cutting, 2012; Evaluation, Selection and Development of Subsea Cutting Techniques, 1997)

Tape is manufactured of rubber, which is filled with magnetic particles, for example barium ferrite. The rubber band is covered with a layer of high detonation velocity explosive (Figure 34). The use of the tape has shown that the effect falls off below water level. It can also be difficult to attach the tape to its place in cramped areas. (Explosive cutting, 2012; Evaluation, Selection and Development of Subsea Cutting Techniques, 1997)

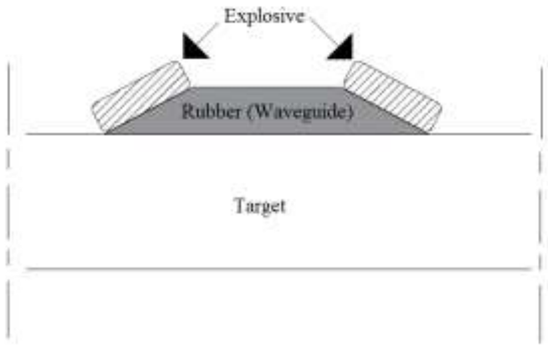

Figure 34. Shockwave refraction tape. (An Assessment of Techniques for Removing Offshore Structures, 1996

7 Conclusions

There are many factors a person needs to consider in piling works. It is important to know the properties of the area where piles are planned because it will define properties that piles need to have. After choosing the pile type, also machinery is in an important role. It is important to follow the provided guidelines and good construction practice in all phases and pay extra attention to safety.

There are mechanical methods like traditional grinder available, but a person should consider other mechanical methods like guillotine saw or diamond wire saw as well. Another method is abrasive cutting which has taken considerable steps in the cutting industry. It can be used in demanding sites and it does not alter the metallurgical properties of steel. The abrasive cutter can also be controlled remotely, which is desirable in terms of safety. In thermal cutting methods, traditional oxyfuel cutting is still effective, but there are also laser cutting and plasma cutting, which should be considered for different works and which are better for precision cutting or for cases when heat damage should be in the minimum. Explosive methods are disruptive but can be used in offshore cutting very effectively. Table 8 presents a small summary of cutting methods and their operational features. Table 9 provides information about the methods' typical applications and significant advantages and disadvantages.

Table 8. Summary of cutting methods discussed in the work.

Method	**Cutting/ Splitting**	**Above/Below water**	**Handheld/ROV**	**External/internal**
Grinder	YES/YES	YES/YES	Handheld	YES/YES
Diamond wire saw	YES/NO	YES/YES	ROV	YES/NO
PCM	YES/YES	YES/-	ROV	YES/NO
Guillotine saw	YES/NO	YES/YES	ROV	YES/NO
Abrasive water jet	YES/YES	YES/YES	ROV	YES/YES
Flame	YES/YES	YES/YES	Handheld	YES/YES
Plasma	YES/YES	YES/YES	ROV/Handheld	YES/YES
Laser	YES/YES	YES/*	ROV/Handheld	YES/YES
Explosives	YES/YES	YES/YES	Varies	NO/YES

*under development

Table 9. Typical wall thicknesses, applications, advantages and disadvantages classified by the method.

Method	**Typical wall thickness (mm)**	**Applications**	**Advantages (A) Disadvantages (D)**
Grinder	varies	pile head cutting small and quick cuts general-purpose tool	A: price, versatile D: handheld, causes injuries
Diamond wire saw	varies	tubular structures standard steel shapes monopiles for structures in spacious areas	A: wire length can be adjusted D: demands a lot of space and preparations, difficult to handle
PCM	-	singular structures pipe piles	A: machine holds the pile, changeable blade D: rolling blade demands space
Guillotine saw	0.8-610	pipelines bracings beams	A: quick to set up D: relatively slow cutting speed, needs space around the pile
Abrasive water jet	< 600	pile walls pipe piles sheet piles multilayer structures precision cutting	A: no spark or heat, complex shapes and radiuses, no alteration of metallurgical properties D: produces abrasive waste, price
Flame	152.4-304.8	pile walls pipe piles sheet piles	A: price, versatility D: heat causes damage around the cut, selection of suitable gas
Plasma	< 25.4	precision cutting industrial manufacturing small cuts	A: can operate solely on electricity and compressed air, can be used for rusty materials D: heat causes damage
Laser	304.8	precision cutting	A: precise method, small kerf width D: price, can’t be used underwater yet
Explosives	varies	remote areas monopoles offshore applications	A: easy to set up D: damages the pile, small deviation of the pile caused by explosion
Refraction tape	varies	remote areas monopiles offshore applications	A: simple method, price D: difficult to attach, effect falls off underwater

While more demanding sites are taken into use, also cutting methods need to follow the development. When it comes to steel pile cutting, there are also aspects that need to be considered (Figure 35). The first step is to evaluate the needs of the location. Cutting can be executed outside or inside the pile. The next step is to establish the attachment of the pile so it can be lifted after cutting.

After defining the factors related to location, the cutting method needs to be chosen. Factors influencing the chosen method are wall thickness, pile's diameter, possible interlocking systems, economic aspect, depth of cutting level and accessibility on site. A person also needs to consider whether cutting should be executed by a diver or ROV.

Figure 35. Considerations in pile selection.

The growing variety of available cutting and splitting methods is a sign of increasing demand. Pile structures evolve, and cutting methods need to continue developing at the same rate as the pile structures and be able to cut more complex shapes. Taking new methods alongside traditional flame cutting and grinder can raise awareness of alternatives and create more effective outcome from the economical but also from the environmental point of view.

Information about the subject is limited in various sources and also difficult to find. If the information would be centralized in one source, companies with recent information could update a database concerning experiences about the execution of different methods for splitting and cutting piles. That would help companies to face new challenges but also accelerate selection process in the cutting industry. Deficiencies and development areas would be easier to detect. The database would keep all the information under control and easily accessible.

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Appendix 1: Process of RGL’s Water Jet Cutting and Case Studies

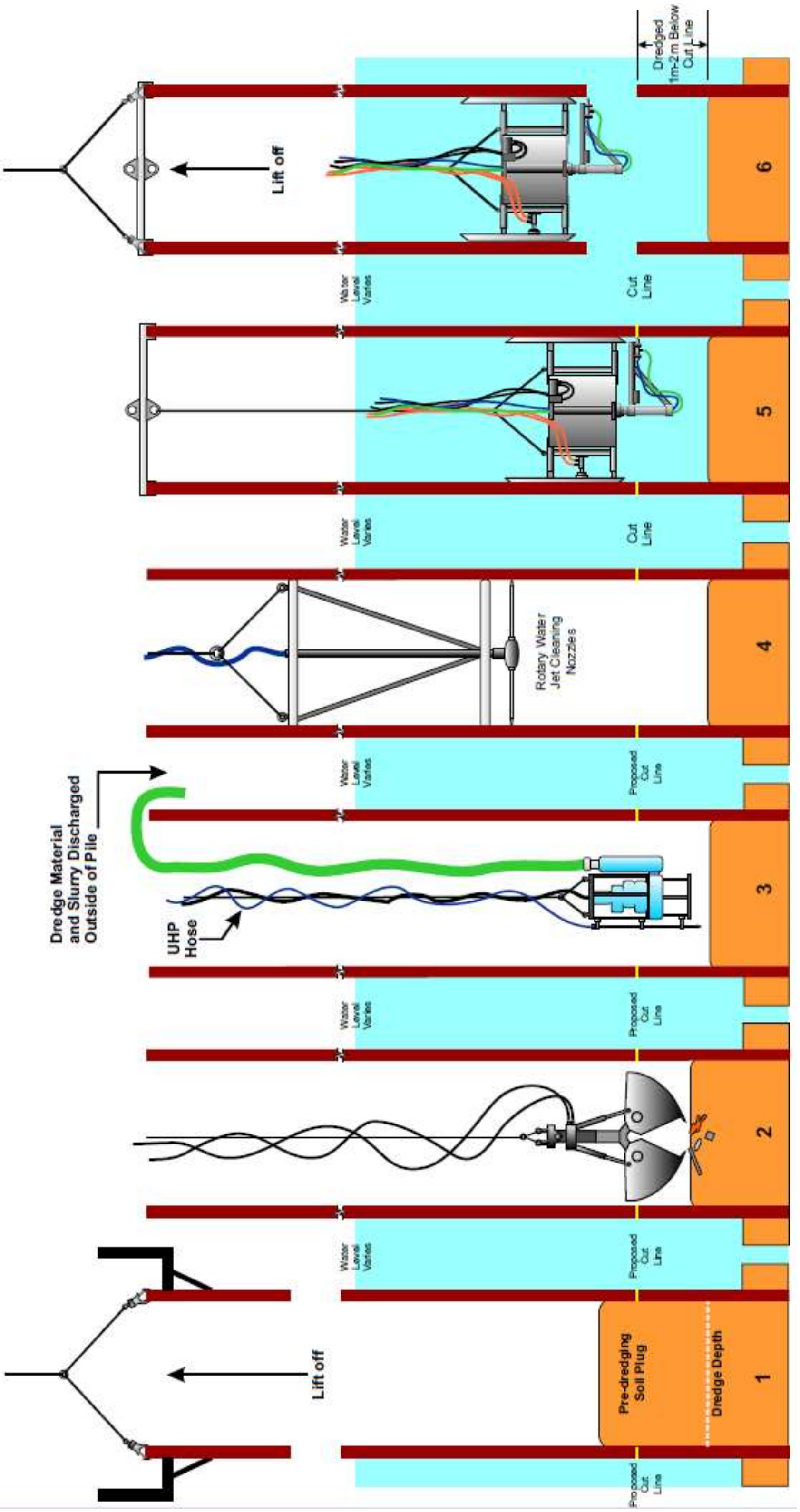

Figure 36. General process of cutting. (Process Illustration Underwater Internal Pile Cutting, 2015)

RGL's abrasive water jet cold cutting has been used for cutting a monopile in Horns Rev, Denmark. The cutting level was below seabed, and the pile's diameter was 1800 mm and wall thickness 45 mm. A survey was executed in advance to ensure a mutual understanding of both parties. RGL was responsible for dredging the material from the pile, and proving and cleaning it to the cutting depth of 24.2 m.

First, the steel deck plate was removed from the head of the pile. The dredging was executed approximately 1 m below the designed cutting level. The dredging was executed with a clamshell excavator bucket and a dredger pump. After the dredging, the pile's surrounding was cleaned from fine material. Some steel coupons were found in the cleaning process, which caused additional investigation that had to be executed with the clamshell excavator. After the investigation, the dredging process around the pile was completed.

After the dredging, a proving rig was used to confirm that the pile did not have any internal obstructions. The proving rig was attached to a high pressure water jet nozzle, which was used to clean the internal bore at the same time with proving the diameter of the pile. After the proving, the rigging of the pile was executed with a total rigging weight of 1.5 t.

Next step was the actual cutting. The cutting rig was lowered into the pile and a test cut was executed. After successful test cut, the cutting rig was lowered with service hoses and lines, which were attached together. Water depth was 14 m; therefore 10.2 m of the pile was above water level. The cutting process took 8 hours which included lifting the pile, which weighted 44 t. The test cut, pile lifting and cut pile on the barge deck are shown in Figure 37. Both RGL and the client were very happy with the result of the cutting process.

Figure 37. The test cut, pile lifting and the cut pile on barge deck. (RGL, 1998-2013)

Another case study was a removal of a wall of Larsen sheet piles from around an ornamental glass house (Figure 38) about 300 mm below a river bed in Laverstock Mill, Hampshire. The length of the wall was 30 m. The piles were supposed to be cut; thus, they would not detract the overall appearance of ornamental glass house. The challenge on site was the brand new glass house, and the fact that it was built on river bed. Another challenge was limited space to carry out the cutting. An ultra high pressure water jetting unit and bespoke tooling were used.

Figure 38. The site of the cutting. (RGL, 1998-2013)

First step was to perform surveys on site, and to hold a project meeting. It was decided, that an abrasive water jet cutting track would be bolted to each group of Larsen piles. This way horizontal cuts were possible to execute in the out-pan flat faces of the piles. The bespoke tooling was used for the in-pan flat faces, and a rotating nozzle with adjustable radius was chosen. The rotation speed wasn’t settled yet in the first meeting.

The preparation work included marking the cutting level and drilling holes at a predetermined distance above the cutting level. The next step was the actual cutting process. Test cuts were made for flat out-pan pile face and in-pan pile face, but also for two clutches. The test cut determined the speed of the actual cutting.

The actual cutting was initiated from in-pan cuts closest from the glass house, because those cuts were the most time consuming and hardest to execute, because of the thick clutches. The cutting was executed successfully. Only little amount of material was removed and limited river water pass back to the work area, where water pumps were installed before cutting.

The in-pan cutting consisted of 30 individual cuts. The good preparation work enabled all the cuts to be performed on the designed cutting level. The cutting process of in-pans took 4 days and out-pans 3 days. After, it was time for vertical cuts, because piles were welded together. The welded sections above water level were gas burned. The cutting below water level was executed by RGL and the cutting process took 2 days. After nine days of cutting, the removal of pile cut sections started. The sections were 1.5 m in length. The lifting of the piles was made by hand or with a machine. Some working phases and outcome are shown in Figure 39. The cutting process was successful and it was done within the budget.

Figure 39. Phases of cutting and the final outcome. (RGL, 1998-2013)