Manish Jaiswal

Design Implementation of Pile Foundation

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The objective of this Bachelor's thesis was to design pile of foundation for a residential building. The aim was to identify aspects affecting pile foundation design in a challenging environment because the building was to be built on a reclaimed land from the Baltic sea and almost half of the foundation slab would extend into the sea, resulting in very high lateral forces due to ice loading during winter. The site was to be stabilised using deep soil mixing columns.

To enable the design, different foundation types were studied. Types of foundation and various categories of pile foundation were considered, together with the with the Geotechnical aspects involved in foundation design. The details of the project such as the structural and natural loadings, as well as forces acting on the building structure were studied.

SCIA software was tool used to perform the finite element analysis of the structure. The loading of the analysis model was done per the corresponding Eurocode. With the designed compressive strength capped at around 10 MN and tension anchoring capacity at 2.2 MN, suitable design layout was achieved with 75 piles. This thesis provides outline of the various aspects involved in the design of pile foundation for the beginners in the field of foundation design.

keywords	foundation, FEM, load bearing capacity, Eurocode, SCIA

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1 Introduction

In general, the term foundation can be defined as the part of the structure which bears the weight of the structure as well as several direct and indirect loads, and transmits them to the underlying soil or rock. The process of designing a foundation involves geology, soil mechanics, rock mechanics and structural engineering. (Day 2005.) A Foundation is the connecting link between the structure proper and the earth. A foundation can also be defined as an artificially laid base on which the superstructure is built (Jumikis, 1971.) The principle aspect of foundation design is to identify the most suitable type of foundation, such as whether to use shallow or deep foundation for the proposed structure. Another fundamental aspect is to develop and understand the governing parameters such as the bearing capacity of the soil or rock underneath and the estimated settlement of the foundation over time. The design of a foundation structure also involves the reinforcement detailing which includes the diameter of the reinforcement bar, the steel grade and the spacing between the reinforcement bars. In most cases, the design of a foundation involves both a geotechnical engineer and a structural engineer. In the initial phase, the geotechnical engineer provides the details regarding the soil bearing capacity and the structural engineer performs the actual design of the foundation. The fundamental structure of the foundation can be divided into two broad categories i.e. shallow foundation and deep foundation. Further, these two types can be divided into several sub-categories depending upon their physical form and structural properties. The geotechnical works and initial planning phase depend upon factors such as the surrounding structures, previous history of the site, and corrosivity levels. (Day 2005.)

The first step in the design of a foundation requires some basic knowledge about the location of the site, known geological hazards, fault lines, landslides or deposits of liquefaction prone sand which is not common in Finland. The knowledge about the projects size also helps in the initial planning phase to avoid budget over-runs. The determination of the scope of the work, such as possible subsurface exploration, laboratory testing to determine the feasibility of the project and compaction testing, minimises any possibility of surprise shortcomings during the actual design and construction phase. For a simple structure, the design and construction could be fully based on the preliminary design in most cases, but for large scale projects, the initial design and plan could be optimised as design and construction progress. (Day 2005.)

In Finland, the most usual concern while designing the foundation used to be the frost protection. Since the bedrock level can be found within a very comfortable piling range, the load bearing issues are usually simple. Primarily in Northern Europe, the foundation is done to mitigate the effects of frost penetration adequately. If this problem is ignored, it may cause damage under and around the foundation, which could require a costly repair procedure. In general, the depth of the foundation should extend well below the depth of frost penetration level in frost-susceptible soil. (Farouki 1992.)

2 Types of Foundation

2.1 Shallow Foundation

A shallow foundation distributes the load of the structure to the upper surface of the ground. The precise definition and range of the depth for a shallow foundation may vary from region to region, but in general, the depth from the field level to the underside of the foundation is less than five time the thickness of the foundation is deemed as a shallow foundation. (Seismic Resilience 2012.) If the soil layer at shallow depth usually less than 3 m can support the structural load and the action forces without exceeding the critical settlement level, then a shallow foundation is constructed. (The Constructor 2015.) Shallow foundations are to be avoided when the surface soil is highly compressible. (Faculty of Environment and Technology 2011.) Shallow foundations are vulnerable to three general failure modes, namely general shear failure, local shear failure and punching failure. In the design of the shallow foundation, the possibility of the failures must be taken into consideration. It is worthwhile to note that shallow foundation can be susceptible to any seismic actions that changes the contour of the ground. A change in the settlement and a lateral translation may alter the bearing capacity of the upper strata of the soil, or result in soil liquefication causing grave consequences to the structure. (Seismic Resilience 2012.) In countries like Finland and other countries with a harsh and long winter, shallow foundations must be protected against freezing. The water in the soil near the foundation can freeze and expand causing damage to the structure. So, to mitigate this problem, the foundation must be built below the frost line protected by insulation, whichever is feasible and cost effective. (Building Construction 2014.) There are several types of shallow foundations. The best one depends upon the project requirements, the soil bearing capacity of the building site, the cost and the efficiency of the construction project. Some of the shallow foundations types are introduced briefly below.

Pad Foundation

A Pad foundation is usually used to support a single point load coming from a support column. The geometrical shape of the padding could be anything circular, square or rectangular depending upon the requirements. The pad could either be of uniform thickness or stepped or hunched if it is required to spread the load from a large column to the maximum surface area underneath. There could be several singular paddings below the structure each supporting a load from a single structural column. Pad foundations are usually considered a very efficient shallow foundation type. (Faculty of Environment and Technology 2011.) The thickness of the paddings should be enough to distribute the load across the planned surface area. Pad foundations in general, are reinforced on all except small structures. The reinforcement allows the structure to take on a higher imposed load. A higher load bearing capacity permits to the construction of shallower pads which involves less excavation and uses less concrete. The arrangement and placement of the paddings depend upon the nature of the structure, the type and magnitude of the imposed loads, the bearing capacity of the ground and the space available at a constructions site. (Designing Buildings Wiki 2017.)

Strip Foundation

Unlike the pad foundation that supports a high-intensity point load, a strip foundation supports line load which may or may not be high in intensity. The strip foundation can be used in most subsoils, but the better a result is yielded if the subsoil has a relatively good load bearing capacity. The depth of the and width of the strip foundation can be changed per the intensity of the line load on it, but the width of a strip foundation that is always either equal to greater than the thickness of the wall it is supports. (Designing Buildings Wiki, 2017.) A strip foundation is very common in cases where structural load bearing wall is used as the load bearing structure instead of the column. A strip foundation is also used if the column to column distance is small, and a pad foundation is not a feasible option. A strip footing is also known as continuous foundation due to the continuous nature of the footings, unlike pad foundations. (The Constructor 2015.)

Mat Foundation

A mat foundation can be defined as a large slab, which supports the columns and walls transferring the load from the structure. This type of a foundation is usually used when the allowable soil pressure is too low and exceeding pressure could result in a major settlement with severe consequences to the structure. This type of a foundation is useful when columns have significantly varied loadings or when the column to column distance is too small for a pad foundation. (The Constructor 2015.) The construction of a raft foundation can be fast and very inexpensive compared to other types of shallow foundations. The ground slab and the foundation are combined, resulting in less use of material. These types of foundations are suitable for structures with a uniform load distribution. When the load is a concentrated high-intensity line load, the area can be thickened, and further reinforced to avoid cracking.

2.2 Deep Foundation

A foundation is classified as a deep foundation if the depth of the foundation. (d) is greater than twice the width. (B) of the base of the foundation footing i.e. if, d>2B. This type of a foundation is usually used if the load bearing capacity of the underlying soil layers is very poor and a shallow foundation wiould not be a viable option (Jumikis, 1971.) Pile foundations are the part of a civil structure designed to carry and transfer the load and other forces arising from the superstructure above, to the bearing ground. The same pile also helps to transfer the forces to the ground surfaces around as friction forces, if the pile is a friction pile. These are mostly seen in desert structures where there is no bedrock available. The primary component in this type of a foundation is the pile, in some cases a pile cap and a slab on the piles. The most used piles are wooden piles, concrete piles and steel piles depending upon the size and other factors involved in the project. The piles are driven, drilled or jacked into the ground, and the top of the pile is connected to the pile cap. A pile cap is not required with the use of additional reinforcement or several custom components available to avoid the punching shear failure. Piles can be categorised into several types depending upon the type of soil, pile material, and load transmitting characteristics of the pile. Cases where the settlement of the soil is high, bearing capacity is low and it is difficult to build heavy structures which require transfer of loads underneath, require a pile foundation. The versatility of a pile foundation makes it possible to design pile foundations of different mechanical characters like end bearing, friction or combination of both depending upon the site. (Designing Buildings Wiki 2017.)

Pile foundations have been in use for several hundred years. The documented history shows that the use of the piling technique can be traced back to the 4th century B.C. When Greek and Roman Engineers utilised the piling technique to build structures on the banks of the Mediterranean coast. Though undocumented, there are references of piling techniques adopted by Swiss lake dwellers to elevate their dwellings to protect the occupants against attacks. (Tritech ground engineering 2011.) in the early days of civilisation, most villages were situated near rivers for defence, strategic, communications or transportations purposes. Therefore, it was important to strengthen the bearing ground with piling. The only types of piles available were the timber pile which was driven to the ground by manual labour, or by first digging a pit, planting the piles, and strengthening the base with sand and stones. A breakthrough in modern piling technique can be attributed to Christoffer Phloem, who in 1740 invented pile driving equipment. Since 1800s, steel piles have been used and the concrete pile was introduced in 1900s. (Smith.) There are several types of pile foundation based on the material properties of the piles, action on the ground, and the load transfer behaviour of the piles.

2.2.1 Classification of piles based on load transfer

Piles can be classified per the effect of the pile on the ground for load transfer mechanism. The ground bearing capacity and other specific requirement of the project site, dictate which types of piles can be used with and what load transfer method. The different types of piles are introduced below

End bearing piles

In general, end-bearing piles have their bottom on a layer of heavy soil or rock. In this system, the load of the superstructure is transferred to the bearing layer through the pile. In a way, the piles act as columns for load transfer, avoiding the instability of the weaker layer upon the solid layer. (Understanding building construction 2017.) Even in scenario when the soil or rock layer is weak, the pile does not fail by buckling. For the pile, not to fail, a part of the pile needs to be unsupported. A layer beneath the pile is then either water or air. The only way to transmit the load to the layer underneath is through either friction or cohesion. In some special cases, the soil around the pile may adhere to the pile surface causing negative skin friction on the pile. This phenomenon may weaken the bearing capacity of the pile substantially. The pile length is determined with the site investigation and soil test. (Smith.)

Friction piles

Contrary to bearing piles, friction piles do not transfer the load of the structure to the underlying bedrock. Instead, the support capacity develops from the resistance of the soil friction and adhesion mobilised along the pile. A friction pile is mostly used where the ground beneath is mainly soft clay where it is difficult to find stable bedrock at a plausible depth. (Day 2005.) Such piles are also known as a floating pile foundation. (Smith.) In sites with medium to low-density sand layers with less cohesion friction piles are often used. The use of friction piles in such circumstances increases the density, which results in the increase of shear strength. At the sites with no bedrock layer at a reasonable depth, end-bearing piles can be extremely long and excessively costly. In such cases, friction piles are driven through the softer layer to a specified depth with enough skin friction required for the desired load bearing capacity. (Civil Dictionary 2015.)

Combined end-bearing and Friction pile

Combined end-bearing and Friction Pile is a pile where, the bearing capacity is developed from combined end-bearing resistance at the bottom tip and adhesion resistance between pile surface and surrounding material surface. In most cases, piles are driven deep enough to gain sufficient frictional resistance. In some cases, the bearing area at the bottom is increased by forcing a bulb of concrete just above the tip to enlarge the area around. (The Constructor 2015.) In this kind of a pile foundation, the total load carried by the pile equals to the sum of the load carried by the pile end and the load carried by the skin friction against the ground. (Katzenbach 2016.) This type of a pile is used when the soil test result show dense soil or bedrock at a feasible depth and the layers above support skin friction. The ultimate load bearing capacity for this type of pile a can be expressed using the equation below. (Engineering Feed 2014.)

$Q_U = Q_S + Q_P$

where Q_U is the ultimate load capacity of pile

Q_S is the load carried by the friction pile and

Q_P is the load carried by the end bearing pile

Batter pile

When a pile foundation is inclined against the vertical, such a pile system is called a batter pile. In a batter pile system, the piles are driven into the ground making a certain angle with the vertical axis so that can provide high resistance to the lateral loadings. (Day 2005.) Within a group of piles consisting of batter piles, the distribution of load can be determined analytically as it is a hyper static structure. When the fill is, loose and has a considerable settlement, the batter pile is laterally loaded. (Civil Engineering World 2011.) Normally, there are 1-5 inclined piles to 12 vertical piles in each foundation deign. During the design phase, it is assumed that the batter pile has the same axial load bearing capacity as the vertical pile if they are of the same material and measurement, and driven to the same stratum. (Sanatkumar 2008.)

2.2.2 Classification of piles based on the types of material used

A use of several materials for piling is a common practice. The use of several materials is influenced by the availability of the material, costs, and project requirements. The advancement in the field of construction material technology has also been a factor in materials used for piles. Some of the most common types of piles based on their material properties are explained below.

Timber

Areas with plentiful of timber available still use timber for piling in construction. Timber piles are most useful underneath embankments. Early settlers around river basins piles in build piling on the swampy land to give stability to their housing structures. Since timber is susceptible to decay caused by water and insects, it is important to have excellent quality timber for piling, to drive it in the right direction. In addition, should not be driven to the firm ground to avoid any structural damage. (Smith.) Timber piles are an economical option for light structures situated in compressive soils saturated with water. Timber piles can have circular or square cross-section. Pile-driving machines are used to drive the timber pile. In the process, the head is blown with a drop hammer. The pile top of the timber pile is enforced with an iron ring, usually little smaller than the diameter of the pile to prevent the pile head from booming. (The construction civil 2008.)

Concrete piles

One of the most commonly used type of piles in all construction is the pre-cast. The cost benefit of concrete piles can be significant depending upon the site condition. The allowable load of a concrete pile depends on the bearing capacity of the stratum below the pile. Cast-in-place concrete piles are not suitable for compressive soil. (Day 2005.) The design load, dimension and length determines the cost of the concrete piles. The fabrication time for a concrete pile is low, usually 14 days after receiving the order compared to steel piles, which might take up to eight weeks from the date of order. (Foundation Pile Driving Concrators 2017.) When high tensile strength and high pile head strength are required additional reinforcement can be applied. The assessment of the soil profile is done with the blow counting method for precast pile driving. (Vanthek partner in piling and drilling 2011.)

Steel piles

Steel piles, with a large diameter, and micro piles, are typical used in construction piling. Sheet metal piles made from steel are common for retaining wall structures. Large diameter piles with a diameter of greater than 220-1200 mm usually have a bearing capacity of over 15 MN in case of 1200mm piles, depending upon bedrock quality underneath. Steel pile designing takes into consideration the lifetime usage of the pile. The design takes the corrosion of the outer wall into account. For renovation purposes and temporary support during the renovation of the foundation and foundation modification, micro steel piles are used. Steel piles provide high bending resistance in case of unsupported lateral length that is loaded. They have also a significantly higher bearing capacity than other piles depending upon pile diameters, the thickness of pile wall, material property and bearing capacity of the earth underneath. (Day 2005.)

Composite piles

Composite piles can also be termed as hybrid piles because of their material properties. Two piles of varied materials are driven one over the other to act together and to perform the function of the single pile. The beneficial property of both materials is well utilised.

The most composite piles are a combination of steel, concrete and reinforcement. Such a combination is effective when the design length of the pile is greater than allowed for cast in situ type of piles. (Day 2005.) Composite piles are not considered an economical option and are only used for exceptional cases. During the piling of composite piles, the joint between the two members must be rigidly constructed to withstand the bending and tensile stresses. These joints between the member add significantly to the cost of the pile. (Michael Tomlinson 1994.)

2.2.3 Classification of piles on their effect on soil

The installation of the piles can be done in several ways. The effect of installation varies based on the process of pile installation. Two most common installation methods with distinct effect on ground are explained below.

Driven piles

Driven piles are also called displacement piles due to the process involved in piling. During the process, the piles are driven, and the soil is moved as the pile enters the ground. The movement of the soil could also be vertical depending upon how loose or compact the soil layer is. A foundation based on driven piles can resist compressive, uplift and lateral loads. Driven piles can also be used to provide lateral support during the construction of earth retaining walls. The most common types of driven piles are precast concrete, steel sheet piles and unconcreted steel tube piles. (Smith.) Several other materials can also be used to build with a high degree of tolerance. Driven piles maintain their shape during the installation process. It is also not likely for a driven pile to be affected by the installation of subsequent piles. (Piledrivers 2007.)

Bored piles

Bored piles, require extra work for boring the earth to make way for the pile. At site, boring is done to make a void and then piles are cast as cast-in-situ concrete piles. Depending upon the soil condition a casing may be required. For example, in unstable grounds like gravel, casing should be used for casting, but only a cloth at the bottom is sufficient where there is hard soil. The length, diameter, shape and quantity of the bored piles used depends on the intended purpose. (Smith.) A bored piling machine is used for casting the drilled shaft. The machine has a specially designed drilling tool, buckets and grabs, used to remove the soil and rock. (The balance 2017.) Modern application is to bore a hollow steel pile and use it as a case for concrete core casing.

3 Geotechnical aspect of a foundation design

For any given construction project, the construction site itself is one of the prime factors affecting the design of the structure. It is even more so in the case of high-rise structure construction. The most important aspects of geotechnical design are the subsoil and groundwater level, load bearing capacity and information about the surroundings. (Day 2005.) These aspects can be studied, and the design can be laid out by following the procedures listed below.

Checking the site history, surroundings, maps

Checking the site history and information about the surroundings in the preliminary and initial phase of foundation design is an important part of a project. The site history and the surrounding structures around the site are a very crucial factor affecting the design of the structure. If the site has any history of a previously built structure or of any geotechnical manoeuvres, it is necessary to have detailed information about the history. Structures underneath, like tunnels, storage tanks or mining shafts should be taken into consideration in the initial planning phase. It is also possible that the site has underground pipelines and utilities, which need to be rerouted. The surrounding structures and habitats may affect the construction process by limiting the allowed vibration and noise levels. Aerial photographs are of use during the initial planning stages to get a detailed of the three-dimensional view of the site, presence of landslides, fault scarps, types of landforms. (Day 2005.)

Knowing the contamination details of the site

It is also necessary to know the chemical state of the site in advance to avoid health safety trouble. The radiation level, as well as chemical contamination from any previous activity and soil contamination from any previous activity and soil contamination due to material left from a previous structure, and the level of radon especially in Finland must be checked before the design phase of a structure. In Finland, the maximum radon concentration must be below 200 Becquerel/m3 for newer buildings and the permitted radon concentration level must not exceed 400 Becquerel/m3 for older buildings. (Eurocode 7 2013.)

Corrosion test of the site

A corrosion test is required to know how much the structural strength of a structure decreases over time. The test is also important when the site has some history of chemical contamination that cause structural damage. If the structure is directly exposed to water the lifetime decrease in the physical form and structural decay is taken into consideration in the initial phase of design. It is necessary to understand how the construction materials like steel, concrete performs under the service conditions to achieve the desired service life of the structure. (Corrosion testing.)

Databases available at Soili, GTK, City Archives

There are several databases with information about geotechnical surveys, history and other vital information of sites provided by the city of Helsinki. Among the database soil is very informative and can provide valuable information, about the properties as well as ground survey reports, cross sections of the soil layers, etc. In 2017 the annual fee of the soil database is 50 €. City archives are also useful in when determining the impact of previous structures on a site. (Helsingin kaupunki 2010.)

Site Investigation

In civil and structural design, the surrounding structures play a vital role in shaping the design process. The surrounding structure determines the level of noise and vibration allowed during the construction. This could lead to change in design or at least the construction process. The soil layer and the mechanical properties of the site influence every bit of the foundation design and may lead to several modifications in the design of the main structure itself. In most areas of Finland, the bedrock level can easily be found within a very comfortable range, and the most commonly used types of pile are the bearing pile foundations. Information about the bedrock level can be obtained from the Geological Survey of Finland. (GTK) or could be calculated from several sounding tests on site by Geotechnical Engineers. The bearing capacity of the soil defines the type of foundation suitable for the structure. This in turn affects the cost and time of construction. (Geological survey of Finland.)

Weight soundings Test

A weight sounding test. (WST) is performed to get a continuous soil profile and layer sequence of a site. Weight sounding test can also be used to estimate the undrained shear strength and density of cohesionless soil underneath. There is a set of rules that needs to be followed to make the test result credible for official use. During the entire process, a device called a penetrometer can be utilized. A penetrometer is manually operated. The testing setup includes a screw shaped point, rods, a loading system and a handle or rotating device. When the soil penetration resistance is less than 1KN, a static sound test is carried out. If the soil resistance in excess is more than 1KN, the number of half turns for the given depth are recorded. (GeotechnicalDesign.info 2011.)

Standard penetration test

A standard penetration tests. (SPT) is used to determine the soil resistance at the base of the borehole. The process is a simple and low cost way to determine the approximate relative density of soils and shear strength parameters. During the process, a thick-walled tube is driven into the ground at the bottom of a borehole by hammering with a standard weight. After the tube is driven 150 mm into the ground, the number of blows to drive it further 150mm and again 150 mm is recorded. The number of hammer blow needed for the last 30 mm is referred to the as SPT blow count. It is also commonly known as the N value of a standard penetration test. A high N value indicates high relative density. (Standard Penetration Test 2016.)

4 Corrosion Protection Methods of Underwater Steel Piles

In average, the external surface of a corrosion-susceptible steel pile surface loses 1.2mm of its wall thickness in 100 years if it is underground. The rate of corrosion can be a lot more if the piles are under contaminated water. The formation of corrosion in piles is due to the contact of water and the surface of the pile. To avoid the contact, the pile is coated with non-porous and anti-corrosive materials which help prevent corrosion. Several types of coatings are available depending upon the needs. Some are described below with the principle on which they work. (Smith.)

Inorganic Zinc Silicates Primers

No cathodic protective layers are applied to the steel structure which is in the splash zone or always immersed in water. Inorganic zinc silicates are suitable for numerous types of anti-corrosive pigmented primers. The best part of using this kind of a primer is that it does not allow the rust to creep further than the damaged part and confines it within and thus avoids it to make any further damage. (Smith.)

High Build Epoxy Coatings

Usually, the resistance of epoxy coatings is higher than that of primers coatings both regarding both chemical and abrasion resistance. The effectiveness of epoxy coatings does not just protect the metals, but also the primer coatings beneath the surface. However, epoxy coatings are vulnerable and have low resistance against sunlight and chalk. The fading of the coatings is highly likely after prolonged direct exposure to sun-light endangers the entire system. (Smith.)

Aliphatic Polyurethane Topcoats

The polyurethane is not an anti-corrosion material, itself but it helps other coatings by providing resistance against ultra violet rays and chemicals. Polyurethane topcoats also help to maintain the cosmetic shine and colour of the material and protect to the overall coating system like zinc rich epoxy primers. As the name suggests, this is the mixture of zinc primers coatings and epoxy coatings. The combination provides a structure with an elevated level of service and resistance against ambient weather conditions. The combination is also effective in containing the damaged area and preserving the coating system. (Smith.)

5 Design of Structural Bearing capacity of pile

The structural bearing capacity of a pile is dependent on the structural strength of the pile structure. An assessment is made to ensure that the structural bearing capacity of the pile structure is high enough to endure the loads from the supporting structure. It is also important to account for any bending moment on the pile structures due to any lateral loading, eccentricities or fixing moments. Apart from these prime actions, the bearing capacity of the pile must also be checked against buckling, negative shaft friction and bending of an inclined pile due to ground settlement. A pile could also experience high a bending moment due to partial soil pressure or lateral resistance. In Finland, it is recommended to use piles with a wall thickness of at least 10 mm for steel pile driven from the upper end. (Finnish National Road Administration 2000.)

5.1 Design for Driving stresses

The allowable driving stress permitted for an unconcreted steel pile is σ_{dall} = 0,9 σ_{sa}, where σ_{sa} is the lower yield strength of the pile material. For driving stress design, the loss of strength due to corrosion is ignored. Driving of pile causes both compression and tension stress to the pile. The force created by the hammer blow to the pile can be calculated by multiplying the area of the pile with the stress on the pile cross section. The formula below can be used to estimate the driving stress.

$$\boldsymbol{\sigma_{max} = f_w f_o v_o \frac{E}{C} = f_w f_o \sqrt{\gamma\, H\, E}} \quad . (1)$$

where,

f_w = factor for the reflection of stress wave dependent on the soil condition
f_0 = pile driving rig coefficient $f_o = e_f \sqrt{2}$, where

e_f = is the effectiveness factor of the pile driving hammer

v_0 = hammer velocity, [m/s]

E = Young´s modulus of elasticity for steel = 2.1 x 10^8 kN/m2

c = stress wave velocity in steel ≈ 5100 m/s

γ = unit weight of the steel = 77 kN/m3

H = drop height of the hammer, [m]

When the information available is not precise, then the range factor for the pile driving hammer f_0 can be from 0.7 to 0.85. The reflection factor of the stress wave ranges between 1.5 to 1.5, when the steel pile is driven against rock. When the soil density is higher, the factor for the stress wave few is between 1,3 and 1,5. A PDA measurement is performed to determine the effectiveness of the pile-driving hammer and the driving stresses. (Finnish National Road Administration 2000.)

5.2 Design for Service State Stresses of steel piles

The pile driving category classification on steel piles is used to determine the allowable central compression stress on unconcreted piles. In most cases, large diameter piles, also called RD piles, are designed for pile driving categories 1A or 1B. For the pile driving category 1A, the maximum allowable compression stress on the pile is 58% of the lower yield strength of the pile material. In the pile driving category 1B, the value is only 50%. The Finnish National Road Administration manual is used to determine the structural bearing capacity of a pile for normal, bending and shear forces when the pile is subjected to bending or shear loadings. During the serviceability state stresses calculation, the designer must consider the loss of structural strength of the pile due to top corrosion. (Finnish National Road Administration 2000.)

For the structural resistance of composite piles against compression, normal force, bending and shear force, The Finnish National Road Administration have outlined instructions. (Composite structures, Design Instructions.) A detailed guideline allowing for the reduction in pile strength due to corrosion can also be found in the same instruction. (Finnish National Road Administration 2000.)

5.3 Design for Buckling Resistance of steel and composite piles

Finnish piling code LPO-087/16/, paragraph 3,475 explains how to determine steel pile resistance against buckling. The paragraph also takes into consideration the shortcomings in the pile strength due to corrosion in unconcreted steel piles. (Finnish National Road Administration 2000.)

The bending strength of a pile can be determined with the equation presented below. (Finnish National Road Administration 2000)

$$EI = E_{cd} * I_c + E_s * I_s + E_r * I_r \quad . (2)$$

E_{cd} = Young's modulus of elasticity for concrete
I_c = moment of inertia for concrete cross section
E_s = Young's modulus for reinforcement steel
Is = moment of inertia for reinforcement
E_r = Young' s modulus for steel pipe
I_r = moment of inertia for steel pipe

6 The Westpro Portus Project

The final thesis explores the several aspects involved in the design of the foundation. The thesis was done for Sipti Consulting. The Westpro Portus Project is a part of an elaborate development scheme for the Kalasatama area of Helsinki by the city. By the time the whole area is developed, there will be 20,000 residents living in the area. (Helsingin kaupunki, 2010) The Westpro Portus Project envisions a multipurpose building consisting of both residential and commercial spaces. The whole building complex will have a construction footprint of around 7800 square meters including the area occupied by retaining walls. The building itself and the parking space will have a built area of around 5300 square meters. As shown in figure 1, the whole building complex is subdivided into six parts from Part A to Part F, during the design phase. Among these, parts A and F are a special case as they extend further from the land surface to the sea surface. The foundation is specially designed to take the lateral forces caused by a ice into consideration. In the figure 2 below, the construction site is the one surrounded by quadrilateral drawn in red. The building extends from the shoreline to the sea.

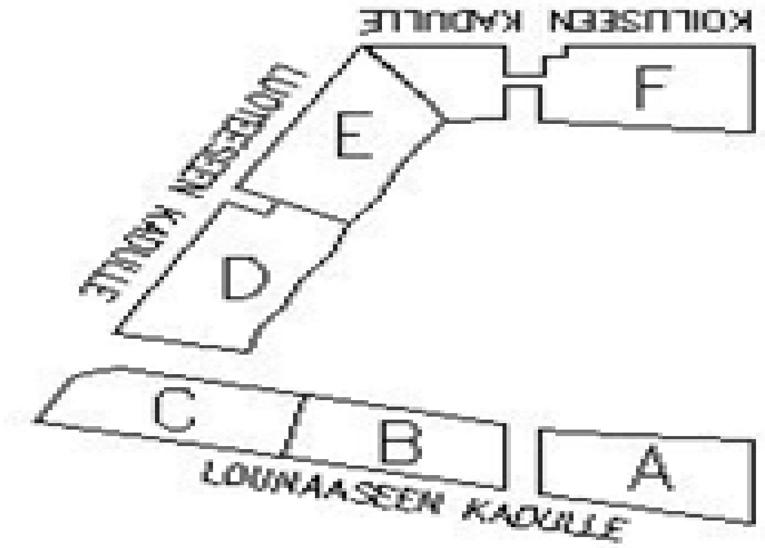


Figure 1 . Sub division of the building

Part F of the building will be tallest, 53 meters from the sea level. It is, therefore, categorized in the Eurocode as consequence class 3. The other parts of the building belong to consequence class 2.

Figure 2. Schematic layout of the Verkkosaari area

As for the complexity class, the part F of the building falls under the class Exceptionally demanding complexity, and the rest under the class less than demanding complexity. The building facades and outer shell are designed to have a 100 years’ lifetime. The basement will be watertight to avoid any seepage or damage due to water.

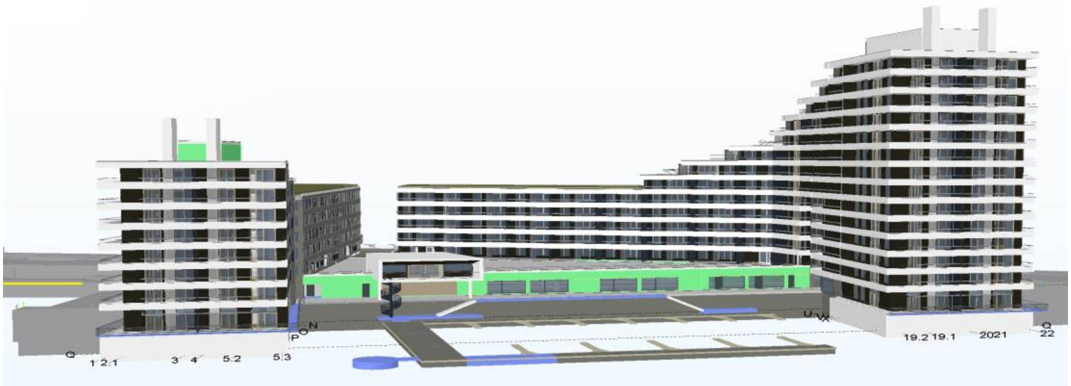


Figure 3. An architectural model of the Westpro Portus project.

The piles for the foundation are composite piles and drilled in-situ. The foundation is designed to take the lateral loading by ice into consideration. The building exterior walls are pre-fabricated concrete walls designed as load bearing structures with a thickness of 200 mm – 300 mm. The separating wall between apartments is also reinforced concrete with a thickness of 150 mm – 180 mm. The foundation slab is cast in-situ and the intermediate floor slabs are hollow core slabs.

7 Project Design Phase

The design requirement of the Westpro Portus project is complicated and the pile layout must be precise both in terms of compressive force capacity and tension capacity. Therefore, the design progressed through trial and error. First, a simple pile map with an approximate idea of combined compressive strength greater than that of the requirement was created. Tension forces on the pile are not considered at this phase. The pile plans were drawn in AutoCAD. After a preliminary pile layout, a 3d model was done using Tekla Structures to get a view of the pile positions. From Tekla Structures, the information was imported as an IFC. (Industry Format Classes) to SCIA for structural analysis after converting them to the native structure. The main reason for using Tekla structure in between the AutoCAD layout and the SCIA analysis model was to ease the modelling. It was easy to place the piles in an inclined position and the conversion to IFC and the subsequent import to SCIA did not add to much extra work. The details of the procedures are explained below.

7.1 Layout and pile plan on AutoCAD

In figure 4, each circle represents a hollow steel pile of a diameter of either 600 mm or 700mm and the wall thickness is 16 mm. The green line in figure 4 shows the area dividing the slab into two zones. The left side of the line represents the area with 600mm piles and the right side represents the slab zone with 700 mm piles. The parallel lines originating from the circumference of the circles represent the direction of the pile inclination. The cyan colour represents the slab and beam. The importance of the pile plan is quite significant because it is the prime document required on site for the piling. The x and y coordinates are as precise as possible. Since most of the piles are inclined and during the piling process there will be an alteration in the z coordinates. The AutoCAD file is used as a reference model in Tekla structure as a reference for 3D modelling of the structure.

In the beginning, the design process started with 92 piles with a varied height. The top end level depends upon the position of the pile and bedrock level, but all piles have the same diameter of 600mm, the wall thickness is 16 mm and the material is steel S355. The combined designed compressive strength of the piles is 920 MN when loaded axially, i.e. 10 MN each.

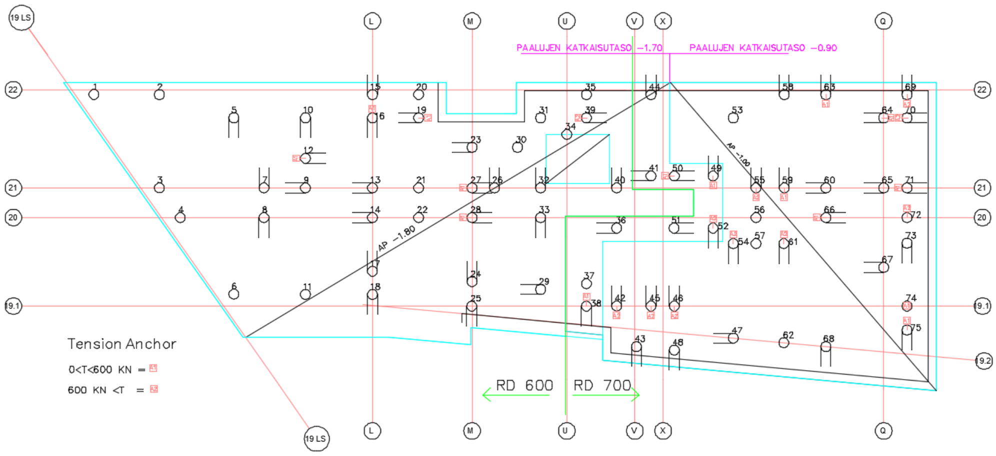


Figure 4. AutoCAD drawing showing the Layout and pile plan.

The maximum axial load resultant for any given combination is around 302 MN during SCIA analysis. The optimisation of the pile layout not only makes the structure structurally reliable but also to reduces costs and avoids unnecessary waste of material. As the analysis progressed further the model could achieve the required result even after cutting the pile number from 92 to 75 with estimated cost reduction of 340,000 €, the approximate cost of piling including pile cost 20,000 € per pile.

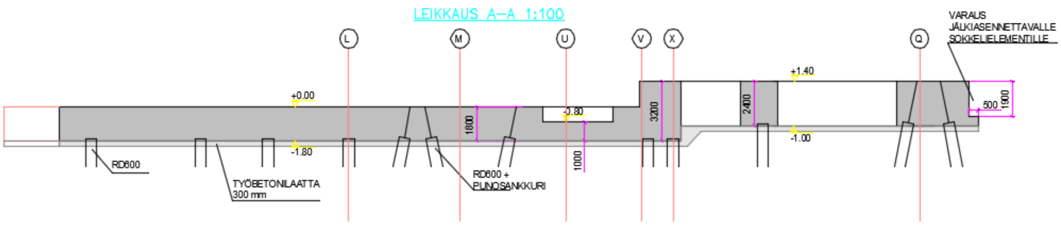


Figure 5. Cross section of the foundation showing slab thickness variation and respective elevation.

Figure 5 shows three separate concrete slab and beam structures with a thickness ranging from 1.8m to 3.2m. The elevation of the top level of the slab with the thickness 1.8m is +0,00 m. The elevation of the top level of the slab with the thickness 3.2m is +1,40 m. The elevation of the top level of the slab with the thickness 2.4m is +1400 m. The bottom level of the slab is -1.80m, -1.80m and -1.00m respectively. There will be a working slab of 300mm throughout the structure below the foundation slab.

7.2 3D Modelling with Tekla structures

Once the AutoCAD pile plan is ready, the plan layout is imported in Tekla structures as a reference model. In Tekla modelling, it is not necessary to care for the precise global location of the structure since it is only needed for importing it as the model an IFC model in SCIA for structural analysis. Slabs were created as they were in the AutoCAD reference file, and piles were created to be placed in the same position in the x-y coordinate but z coordinates varied per the bedrock level. The inclined piles were rotated so that the inclination was in the ratio of 1.5. (Horizontal Vertical) axes.

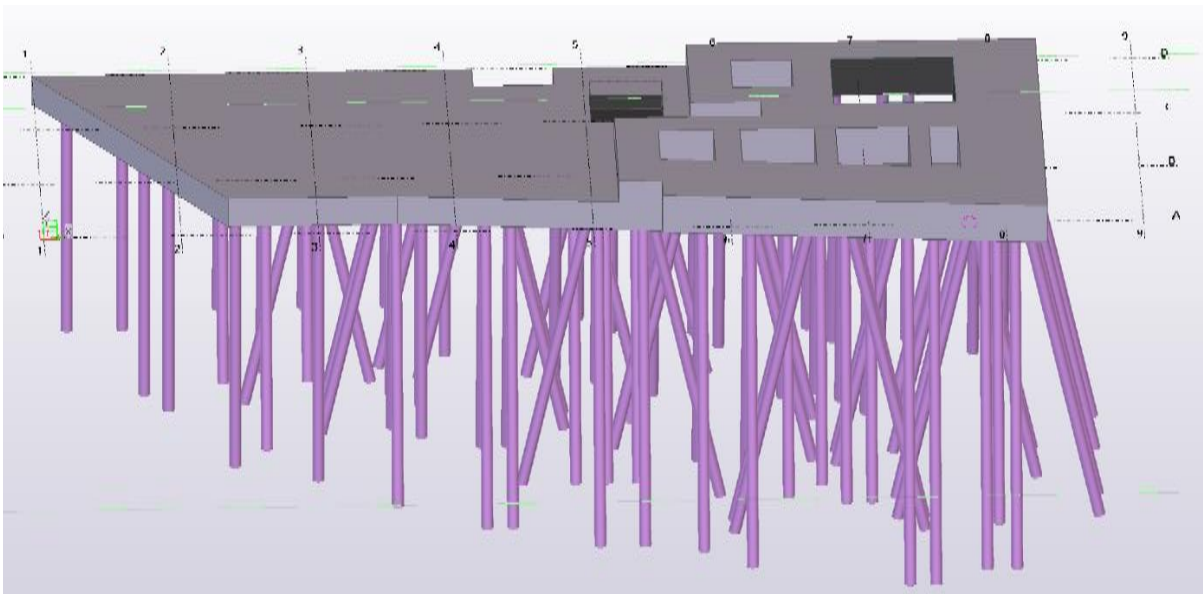


Figure 6. Tekla model of the structure showing the slab and piles position

During the modeling phase, some critical problems were found in the structure, like a collision of piles and narrow safety distances in the pile surfaces. These issues were later resolved by changing the pole position. The entire process of 3D modelling with Tekla was done to get a clear view of the piles below the structure and to easily replicate the pile positions and inclinations in the analysis model.

7.3 SCIA modelling and analysis

The IFC file of the Tekla model, is easy to import to SCIA. However, an IFC file import only imports a general shape and the shapes must be manually given their native structural properties. The slab material properties were set as C35/45 and pile property was set as steel S355. SCIA does not recognize any hollow parts, so they need to be re-defined. All bottoms of piles were provided with fixed support and were rigid in all three axes, x, y, and z. The piles are to be filled with reinforced concrete and tendons in life but were avoided in SCIA modelling. The critical issue at this stage was to identify the piles with high tension so that the correct type of anchoring can be allotted. SCIA was used to check for the internal forces, stresses, compression, and reinforcement requirement. Since the pile used in SCIA was a simple hollow steel pile instead of a composite pile which will be used, the deformation and stresses developed in the piles during analysis are somewhat too high. Taking corrossion into account, the wall thickness of the pile wall was set at 12.7 mm instead of 16 mm. The analysis also considers that the piles are fixed to the bedrock by anchor. The anchoring capacity is calculated theoretically and specific anchoring arrangements are made depending upon the tension in the pile. The movement of the support and the pile bottom is also rigid in X and Y direction.

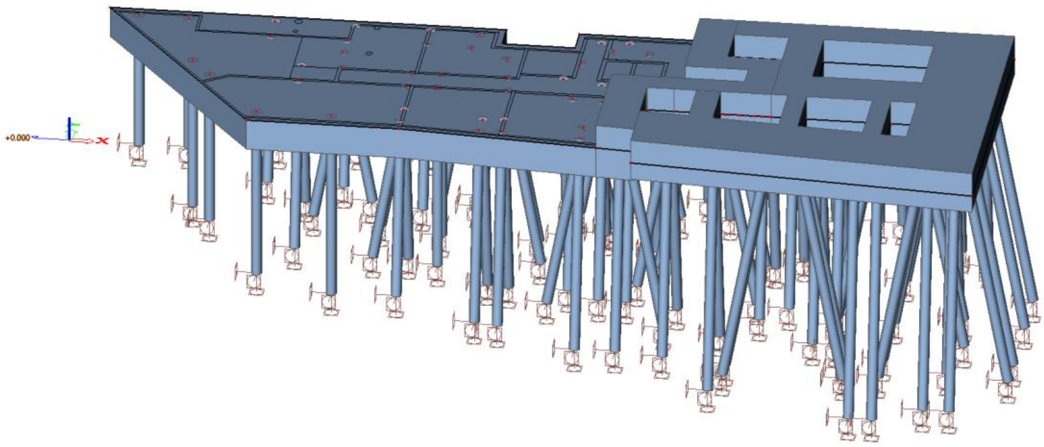


Figure 7. SCIA model with pile support

Apart from the self-weight of the structure i.e. slab and pile, there are several loads and forces that are to be taken into account in the analysis. Furthermore, partial safety factor, types of loads, the direction of load and duration of loading determines the outcome of the result. In the analysis phase, twelve load cases the self-weight, characteristic load from the load bearing wall in the z direction, design load from the load bearing wall in the z direction, characteristic and design load from the load bearing wall in +x, -x, +y and -y direction. Ice forces in z, +x, -x, +y and -y direction. All forces included the dead load, imposed load, snow load and wind load in all possible directions. The loads were classified in two load groups i.e. permanent and variable. 18 load combinations were made from those load cases, out of them 16 were based on the direction of the load and forces. The load combinations were classified based on the four-cardinal direction and middle directions in a clockwise order N, N-E, E, S-E, S, S-W, W, N-W. Each have two combinations, one for the maximum and another for the minimum. The maximum combination includes all the forces acting in one direction and the load in z direction with a maximum partial factor to identify the piles with maximum compression or support reaction. The minimum combination avoided the loads acting in z direction other than the self-load, the partial factor for the loads in z direction was minimum since this helps in the stabilisation against tension. Identification of piles with maximum tension was carried out. The other two combinations took only the permanent load with factor 1.0 and 1.1 into account.

8 Finite Element Analysis in SCIA

Total loadings on the foundation in the SCIA analysis model were divided into 12 load cases. Each load case was divided based on their direction. The load types are divided into two groups i.e. permanent load and temporary load. The self-weight of the structure is called LC1 i.e. load case 1. Load case 2 and load case 3, also referred to as LC2-WALL Vg and LC3 WALL Vq represent the vertical loading on walls which are permanent and temporary in nature. Horizontal loadings like wind, another structural load is divided into four load cases. LC4-WALL HXG represents permanent horizontal loading along x-axis. LC5-WALL HYG represents permanent horizontal loading along y-axis. LC6-WALL HXQ represents temporary horizontal loading along x-axis. LC7-WALL HYQ represents temporary horizontal loading along the y-axis. Within a single load case from LC2 to LC7, there are several line loads with varying magnitudes calculated per Eurocode.

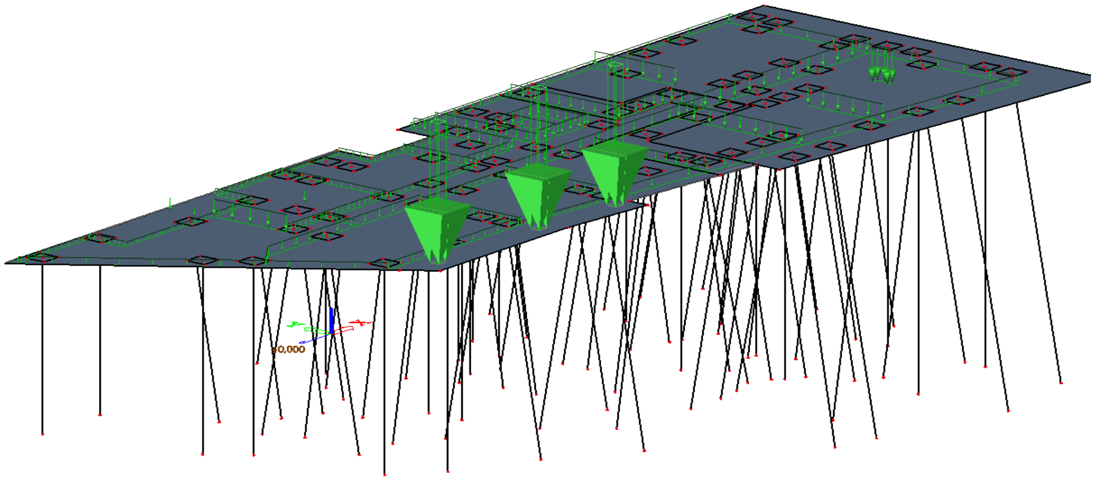


Figure 8. Vertical permanent loading. (wall Vg)

Imposed loads were per the purpose specified by the owner with Eurocode and National annex compliance. Load cases from 8 to 12 represent the ice force loading in Z direction, +x, -x, +y and –y direction respectively. The magnitude of the intensity of ice force acting in the z-direction is 85 KN/m. The magnitude of the ice force acting along x-axis or y-axis is 50 KN/m if it is acting as friction force and it is 180 kN/m if it is acting perpendicular to the surface. 19 different load combinations were used for the analysis.

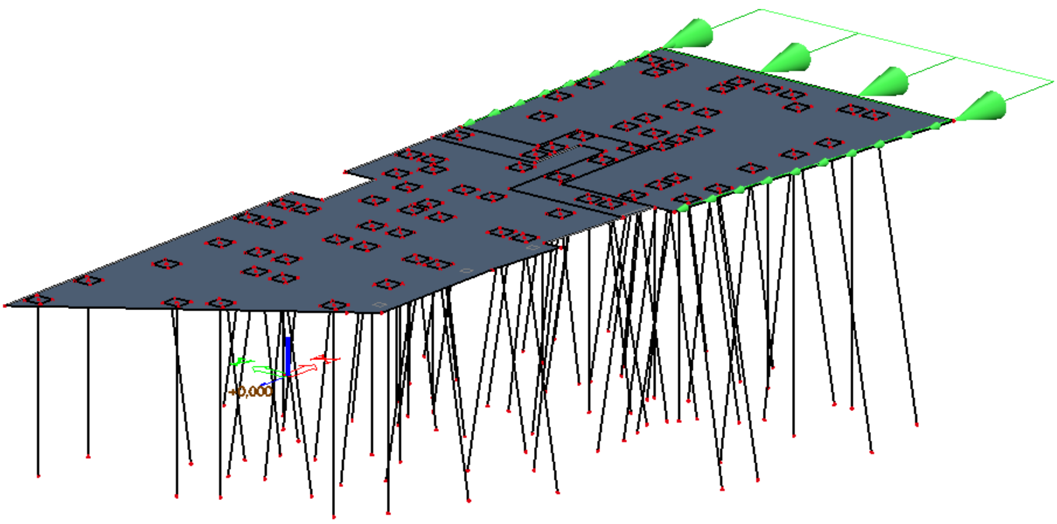


Figure 9. Ice loading perpendicular to the surface and along the surface as friction force

Because an analysis of the whole building complex as a single model would have been challenging, the analyses for the foundation part F and A were done separately. Since part F was the more demanding one, its results are presented in detail here. The critical results for design like the reactions or resultant of reactions, displacement of nodes, internal forces, internal stresses and the reinforcement requirement are presented. The results cover both the piles and the foundation slab. The reinforcement requirement for the foundation slab are also analysed with the SCIA Engineers programme.

Support reactions and resultants of reaction

After the analysis with all the loadings, the maximum for both positive and negative magnitudes support reaction in x, y and z direction for single pile are 1115 KN, -1234 KN in x direction, 1707 KN, -1380 KN in y direction and 8462 KN, -1856 KN in z direction for class of all ULS combination.

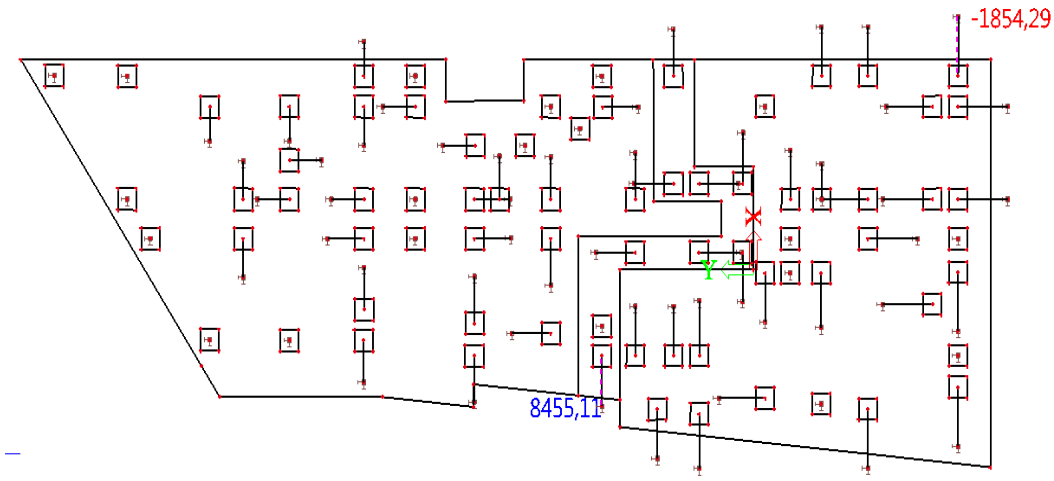


Figure 10. Maximum compression and tension exerted on a pile for any given ULS combination.

Similarly, the maximum and minimum moment reaction around the x, y and z axis for a single pile is 623 kNm and 721 kNm around x-axis, 808 KNm and 789 kNm around y-axis and 116 kNm, 128 kNm around z-axis for the class of all possible ULS combination. The maximum compression force and tension force exerted on any single pile is found in combination 8 and combination 11. The design compressive strength and tension capacity of the pile are above the calculated loadings. The resultant of the force in the z direction is 31,84 MN and resultant moment around Z-axis is 97,134 MNm.

Internal forces on piles

Apart from compression and tension, the supporting piles are subject to several mechanical phenomena. The structural stability of the supporting structural elements is important to ensure the safety and stability of the building. The result of the analysis of the internal forces on piles showed the maximum positive shear force around z-axis on a single pile to be 158,86 KN for the combination number 8 and the maximum negative shear force around the z-axis on a single pile was 160,36 KN. The maximum moment on a single pile around the x-axis was too low to account for, but the maximum positive and negative moment on a single pile around the y-axis was 807 KNm and 796 KNm, respectively, in the same combination number 15. Whereas the maximum positive and negative moment around the z-axis on a single pile was found to be 718 KNm and 679 KNm, respectively, for combinations number 12 in both cases.

Member stress on piles

The maximum normal stress against the pile body in a negative direction is - 471,1 MPa in class load action, and no positive stress is seen in the negative direction. The maximum positive stress against a pile body is 221,8 MPa and -134 MPa, respectively. The range of maximum shear stress on the piles varies from 5.2 MPa to 12.7 MPa.

Internal forces on Slab

The internal forces on a slab, the internal moment, shear force and normal force are critical aspect of structural design. A local failure may lead to severe consequences. The slabs are not of uniform depth and are not loaded uniformly. This causes a very distinct load action and internal forces.

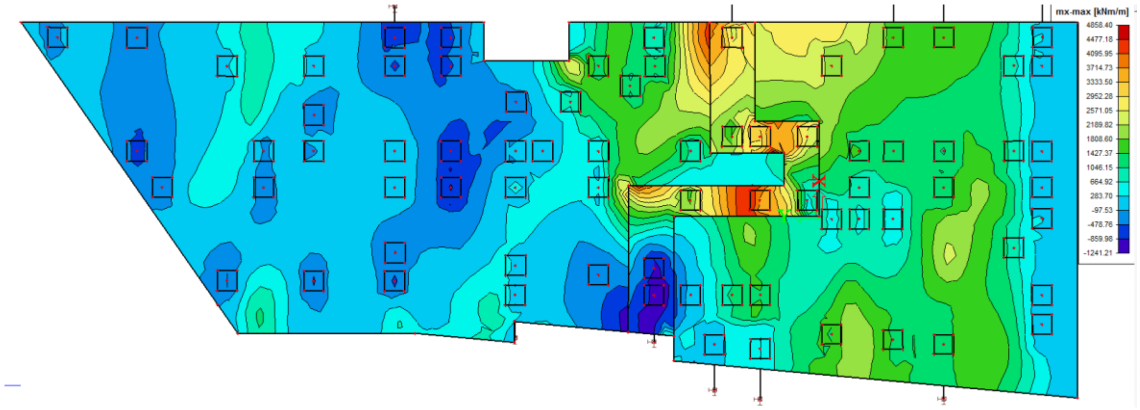


Figure 11. Internal Forces on Slab.

It is evident from figure 11 above that the moment in the x direction is negative. The moment intensity around the x-axis ranges from -1241 kNm/m to 4858 kNm/m. The moment intensity around the y-axis is found to be far lower and much more uniform. It ranges from -1350 KNm/m to 1978 KNm/m. The moment intensity in xy-axis is in the range of -554 kNm/m to 3048 kNm/m. In all three cases of x-axis, y-axis and xy-axis, the maximum moment is in the middle of the central beam which is 3200mm thick. The range of the shear force intensity in the x-axis on the slab is from -1395 kN/m to 5693 kN/m. The range of the shear force intensity in the y-axis on the slab is from -2778 kN/m to 5240 kN/m. The range of intensity of the normal force on the slab in the x-axis is from -407 KN/m to 2609 kN/m and in the y-axis from -395 kN/m to 2125 kN/m, whereas, the range of the normal force in the xy-axis is from -65 kN/m to 1547 kN/m.

Internal stresses on slab

The internal stress on the positive face of the slab along the x-axis is shown to be -8.4 MPa to 2.2 MPa for the minimum envelope case. In figure 12 the result is notated with x+. The maximum internal stress on the positive face of the slab along the y-axis marked in the analysis results with y+, is from -2,8 MPa to 2.8 MPa. The maximum internal stress on the positive face of the slab along xy-axis notated in the analysis results as sign xy+ was found to be in the range of -2,9 MPa to 1.8 MPa. The range of the same but in the negative face of the slab was from -7,1 MPa to 1.3 MPa, -6,9 MPa to 0,6 MPa and -4,6 MPa to 0,6 MPa in the x-axis, y-axis and xy-axis respectively.

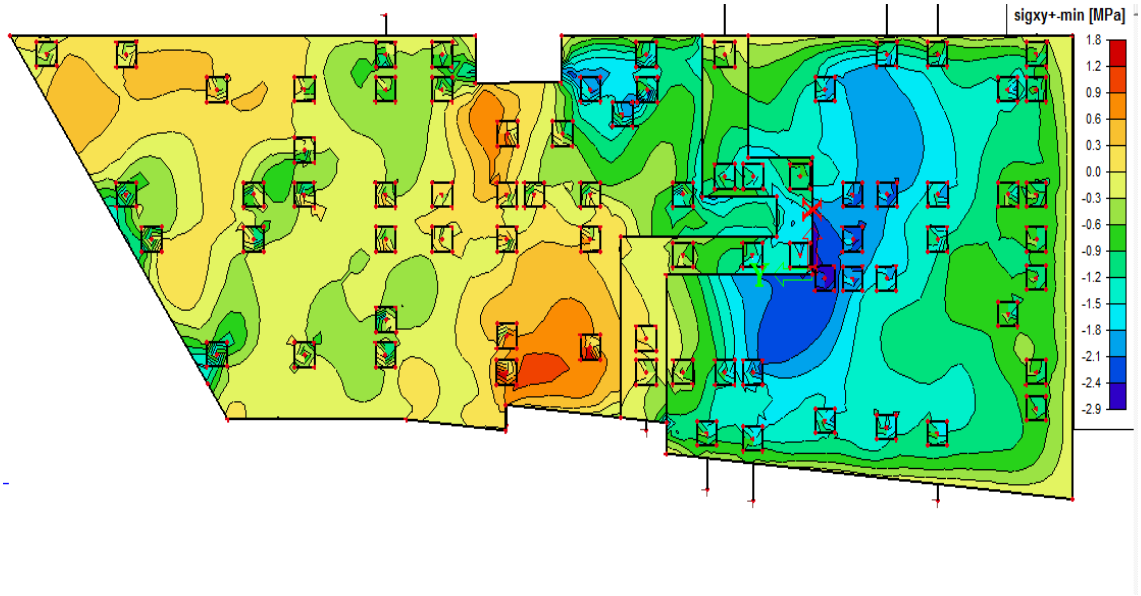


Figure 12. Internal stress on the positive face of the slab in xy-direction for minimum envelope case.

The internal stress on the positive face of the slab for maximum envelope case along x-axis notated in the analysis results as sign x+ was found to be in the range of -1.3 MPa to 7.4 MPa. The maximum internal stress on the positive face of the slab along y-axis notated in the analysis results as sign y+ was found to be in the range of -0,8 MPa to 7,6 MPa. The maximum internal stress on the positive face of the slab along xy-axis notated in the analysis results as sign xy+, was found to be in the range of -0,6 MPa to 4,6 MPa. The range of the same but in the negative face of the slab was from -2, 2 MPa to 7.8 MPa, -2, 8 MPa to 3,1 MPa and -1,7 MPa to 3,1 MPa respectively in the x-axis, y-axis and xy-axis.

9 Selection of the Piles

According to EN 1997-1 : Eurocode 7 about Geotechnical design – Part 1, there are in three piling classes PTL1, PTL2, and PTL3. The categorization of the piling classes is based on two classifications of the consequences class of the planned structure and geotechnical class of the site. In general, permanent structures like buildings and other public spaces fall in classes PTL2 and PTL3, depending upon the scope of the structure and the condition of the site. Light and temporary structures like a household storage area, garage etc. fall under piling class PTL1. It is recommended to use piling class PTL2 for family house projects so that correct pile loads and geotechnical resistance can be ensured.

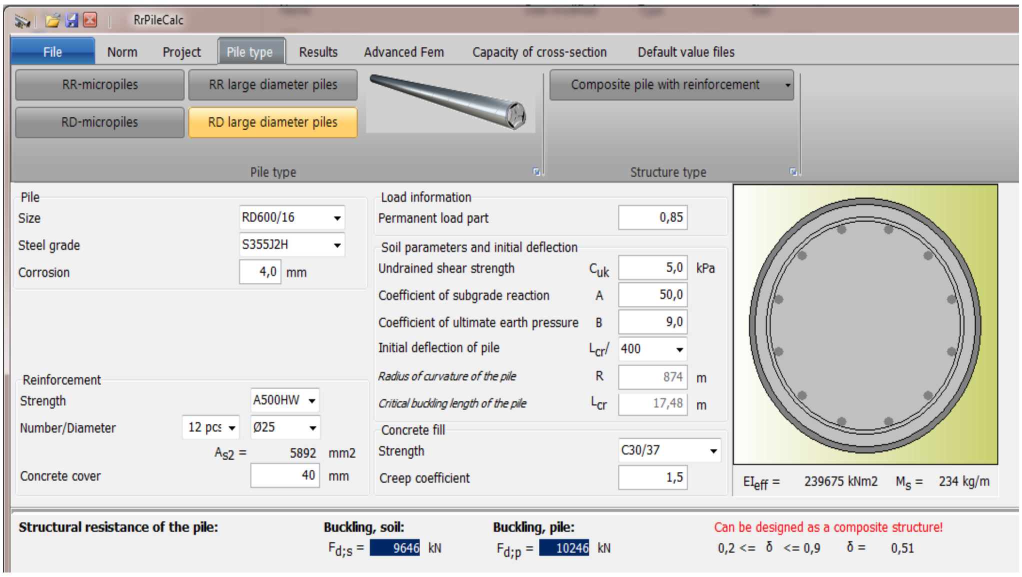


Figure 13. RrPileCalc software used to calculate the pile capacity.

Even in a family house project, if the soil condition is too demanding or many piles are used then piling class PTL3 is used to optimise the structure. The Eurocode explains in detail the general ideas of pile foundation design, limit states design of pile foundation, actions and design situation of the pile foundation, design methods and design consideration, pile load tests, axially loaded piles, transversely loaded piles, the structural design of piles and supervision of construction.

Figure 13 shows the assumed geotechnical coefficient and structural model of the pile that are used for calculations. The software is specifically designed to calculate the pile design capacity of piles produced by Rukki. The structural design of the pile in the software is based on the relevant Eurocode and National piling code of Finland. (PO 2011), Sweden and Norway. The piles used for the Westpro Portus project are concrete filled reinforced steel piles with a diameter of 600 mm and 700 mm and a wall thickness of 16 mm. 12 reinforcement bars of grade A500 HW with a diameter of 25 mm each are used for pile reinforcement. The concrete cover is at 40 mm thick. The concrete strength used for filling the piles is will be C30/37. The soil parameters for the calculations were provided by geo technicians.

10 Retaining Wall with Sheet Pile and Anchoring

The main purpose of constructing a retaining wall is to provide lateral support for soil or rock. In marine and offshore structures or on construction sites partly in water, a retaining wall is made to make the sites clear of water for a convenient construction process. In some cases, the wall may also support vertical loads if the wall is a wall. Retaining walls could be made from sheet steels or concrete. In normal cases with heavy concrete retaining wall, the self-weight of the structure acts against overturning or sliding of the structures. If the retaining wall is sheet metal, the wall can be anchored to the bedrock to provide enough resistances against lateral forces. (W. Day.)

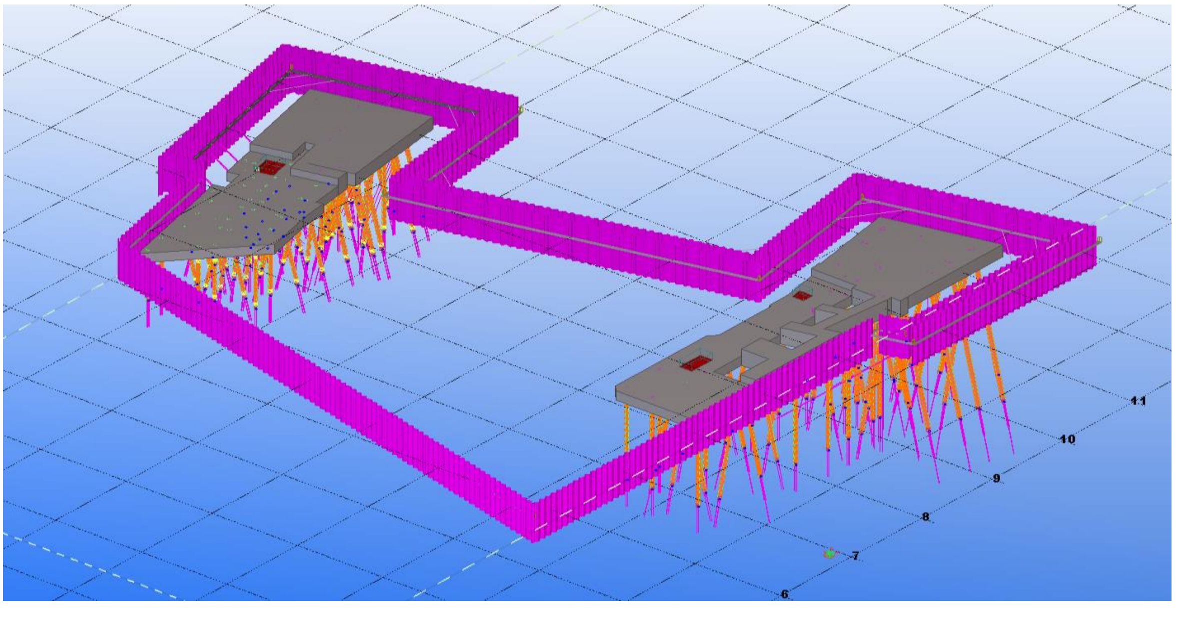


Figure 14. Tekla model of the foundation with sheet pile retaining wall and anchoring.

In the Westpro Portus project, the outer layer of the sheet piles is drilled to the bedrock and supported by a continuous HEB 300 beam. They are also anchored to the bedrock. The inner layer of the sheet piles is not deep drilled to the bedrock. The two separate layers of sheet piles are stiffened with a HEB 200 beam as a truss in some areas. The anchoring system used for the retaining wall anchoring is a GEWI thread bar system with a 50-mm nominal diameter and a yield strength of 500 N/mm^2.

10.1 Sheet pile anchoring

After sheet piling, the area is filled and that causes a very high earth pressure on the sheet. Due to the lateral earth pressure, the sheet pile will fail if no anchoring is provided. The support at the bedrock is not enough since the layers of soil filling can be several metres high. In addition, the corners need to be reinforced. It will be done using three layers of a GEWI 50 mm threaded bar system with the centre to centre distance of 2.4 m. The sheet piles will be anchored to the bedrock by using a DYWIDAG thread bar anchor system. (DYWIDAG Threadbar Anchors, 2014.)

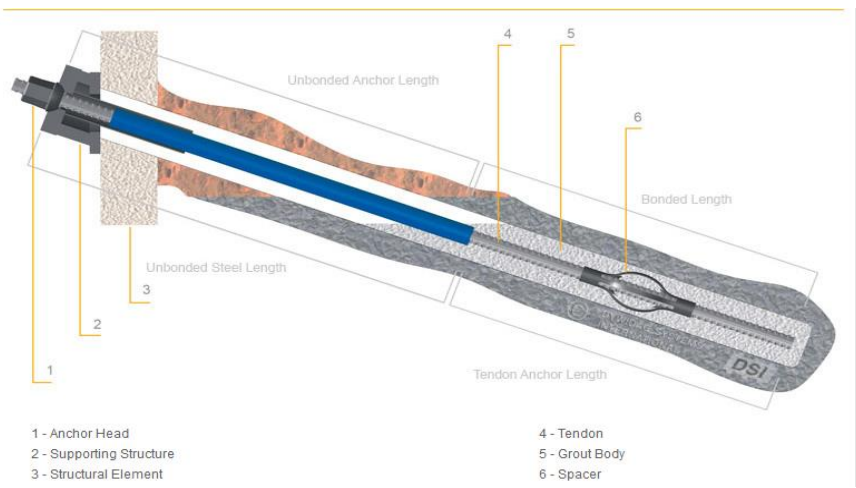


Figure 15. DYWIDAG Thread bar anchor system.

According to the current plan, 20 such anchors are used. The system consists of three main parts bonded length, unbounded length and anchor head. Skin friction between the bonded length and the grouted cement transfers the load to the bearing soil. The unbounded length can freely extend so that tension can be applied to the anchor system. Anchor force is transferred to the substructure by an anchor head. During the approval test, the load bearing capacity of each anchor is tested once the grout is sufficiently hardened. (DYWIDAG Threadbar Anchors, 2014.)

10.2 Stabilisation of clay with Lime-Cement Piles

Stabilisation of the soil can be done with several techniques but the most common one is deep mixing. (DM). This is used to increase the bearing capacity of the soil and thus a decrease in the total settlement of the soil layer. The process involves mixing binders like lime and cement with clay using a special machine to create cylindrical piles with required diameter. A single pile does not have a very high compressive or tensile strength but a group of piles acts together to make the area stiff.

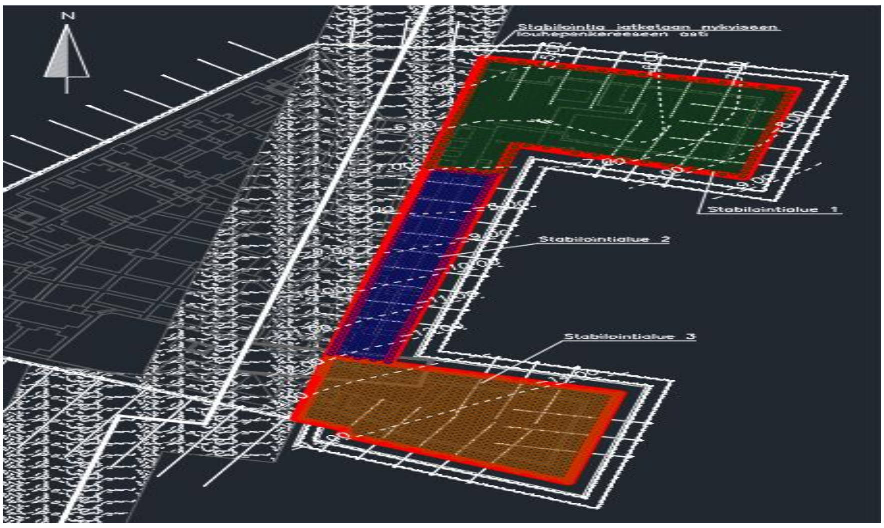


Figure 16. Plan view of project.

Before the construction of the foundation slab starts, a 300-mm construction slab is constructed. The slab is supported by the soil underneath. Since the clay underneath is not stiff and could displace significantly resulting in the failure of the construction slab, the clay will the ground underneath is stabilised with roughly 2100 pieces of 700 mm diameter lime-cement piles. The centre to centre distance between the stabilisation piles and the length of the pile will depend upon the stiffness of the soil and depth of the clay layer underneath. The construction site will be divided into three regions depending upon the distribution of the stabilisation piles.

Figure 16, shows the three stabilisation regions, indicated with three colours. The stabilisation region one with an approximate area of 930 sqm is stabilised using 667 lime-cement piles with a diameter of 700 mm and a centre to centre distance of 1200 mm. The average length of piles in this zone will be 3 m. The stabilisation region two with an approximate area of 405 sqm is stabilised with 427 lime-cement piles with diameter of 700 mm and a centre-to-centre distance of 1000 mm. The average length of piles in this zone is 6.5 m. The stabilisation region three with an approximate area of 760 sqm is stabilised using 966 lime-cement piles with a diameter of 700 mm and a centre-to-centre distance of 900 mm. The average length of piles in this zone is 10.5m.

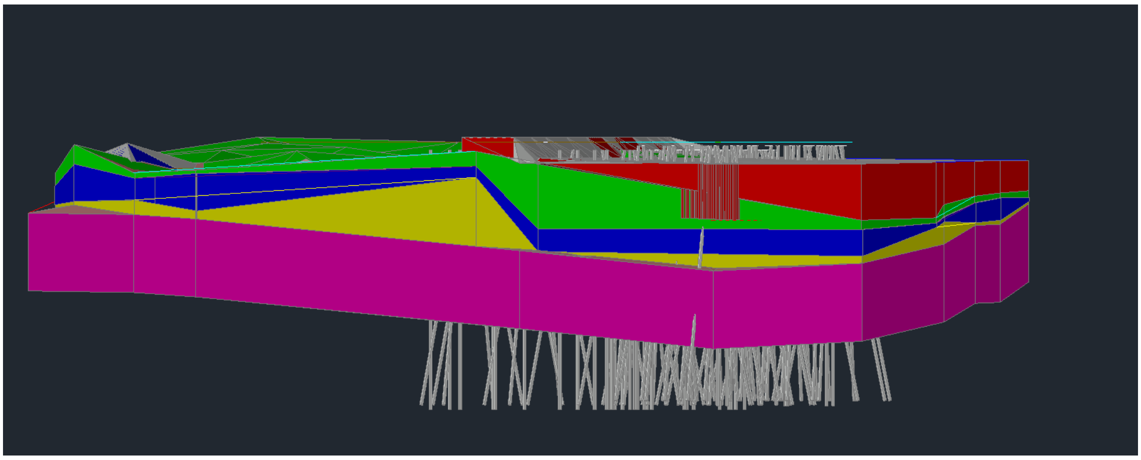


Figure 17. Sectional View of the bedrock with pile position

Figure 17 shows the cross section of the site. In the figure, red layer represents the layer of clay the green layer represents the layer of sand, the blue layer represents the layer of silt, the yellow layer represents the layer of moraine and the magenta layer represents the bedrock. The red piles represent the stabilisation piles and the white piles represents the structural load bearing piles driven to the bedrock. This visualisation was done using AutoCAD 3D civil software tool. Sound testing was used to determine the type of soil layers.

11 Conclusion

Ultimately, the structural integrity of a structure depends upon the stability of its foundation. It is crucial not only to think about the superstructure, but also the surroundings, the ground on which the structure is built and the layer underneath. Since the design of a foundation is affected by several factors, it is worthwhile to give it enough time during the planning stage. When designing the foundation, the cooperation between the geo technician and the structural engineer is crucial. Due to a rapid progress in the field of structural analysis software, it is easy to cross-check the design. The design must fulfill the requirements set by the current national code. In the Westpro Portus project, the initial design phase for the pile layout was mostly done with the trial and check method that is by changing the positions of the piles and number of the piles, and checking the results obtained from the structural analysis of the model.

In the Westpro Portus case, with a very high ice force and wind loading, many piles experienced a significant uplift force. Since the bedrock lies within a piling range, it was easy to design for bedrock anchoring. It was also crucial to estimate the settlement and place two different sizes of piles. It helped designers to achieve the proper design, and the total number of piles used was decreased significantly compared to the very first pile plan. The use of 3D modeling software helped in detailing the exact pile positions even below the bedrock level and change the positions to mitigate conflicts and keep the safety distance between the pile ends. Designers were also able to fix the anchoring position of the sheet pile anchor to avoid any collision with the piles. The workflow from AutoCAD through Tekla Structures to SCIA was done several times due to the changes in the pile arrangement. Nevertheless, there are several shortcomings when using different modeling software and analysis software. It was not possible to import objects directly from software to another. The conversion to IFC resulted in a loss of fundamental properties of the material, which were to be redefined.

Finally, for the end bearing pile foundation design, it was important to check for the bending moment in the pile and tension in the pile due to horizontal loading. It was decided to stabilise the site by using deep soil mixing columns so that the foundation slab can be laid. The main aim of this thesis was to give a clear insight into the design of pile foundation. The calculations and analysis were used for the Westpro Portus project. The results from the analysis will be submitted to the City of Helsinki for construction permit.

Since the Westpro Portus project is still in design phase, there might be several changes in the design in the future.

References

Building Construction (2014.) Types of Foundation. [Online] URL.http.//www.understandconstruction.com/types-of-foundations.html
Accessed 1st May 2016.

Civil Dictionary, 2015. Classification of piles n the basis of load transfer. [Online] URLhttp.//www.aboutcivil.org/types-classification-of-piles.html
Accessed 18th Feb 2016.

Foundation, Concrete and Earthquake Engineering, (2011.) What is Batter Pile?. [Online] Civil Engineering world, May 2011 URL.https.//civil-engg-world.blogspot.fi/2011/05/what-is-batter-pile.html
Accessed 15th Feb 2017.

Corrosion testing, n.d. Corrosion testing. [Online] URL.http.//www.intertek.com/corrosion/testing/ Accessed 15th March 2017.

Day, R. W., 2005. Foundation Engineering Handbook. 1 ed. NewYork. The McGraw-Hill Companies.

Designing Buildings Wiki, (2013.) Pile Foundations. [Online] URL.https.//www.designingbuildings.co.uk/wiki/Pile_foundations Accessed 15th Jan 2017

DYWUDAG Threadbar Anchors, (2014.) DYWIDAG Threadbar Anchors. [Online] URL.https.//www.dywidag-systems.com/emea/products/geotechnic/dywidag-bar-anchors.html Accessed 18th Jan 2017.

Engineering Feed, 2014. Pile foundation selection based on soil conditions. [Online] URL.http.//engineeringfeed.com/pile-foundation-selection Accessed 1st May 2017.

Eurocode 7, (2013.) Geotechnical design. [Online] URL.http.//eurocodes.jrc.ec.europa.eu/doc/2013_06_WS_GEO/report/2013_06_WS_GEO.pdf Accessed 12th April 2017.

University of the West of England, (2011.) Types of foundation. [Online] URL.http.//environment.uwe.ac.uk/geocal/foundations/Fountype.htm
Accessed 15th Feb 2017

Farouki, O., (1992.) European Foundation Designs for Seasonally Frozen Ground, s.l.. office of the chief of engineers.

Finnish National Road Administration , (2000.) Steel Pipe piles, Helsinki. Finnish National Road Administration .

Foundation Pile Driving Concrators, (2017.) Concrete Piles. [Online] URL.http.//www.foundationpiledriving.com/concrete-piles/
Accessed 9th Feb 2017.

Geological survey of Finland, n.d. Bedrock of Finland. [Online] URL.http.//en.gtk.fi/informationservices/palvelukuvaukset/suomenkalliopera.html) Accessed 15th Dec 2016.

GeotechnicalDesign.info, (2011.) Weight Sounding Test. [Online] URL.https.//geotechnicaldesign.info/ec7p3/g7-1.html Accessed 14 01 2017.

Helsingin kaupunki, (2010.) Helsingin kaupunki. [Online] URL.http.//www.hel.fi/www/helsinki/fi Accessed 1st Jan 2017.

Jumikis AR, (1971.) Foundation Engineering. 1 ed. New Jersey. Intest educational publisher.

Katzenbach, R., (2016.) Foundation system for high rise structures. 1st ed. CRS press.

Tomlinson Micheal, J. W., (1994.) Composite piles. In. Pile Design and Construction Practice. London. Taylor and Francis Group, p. 47.

Piledrivers, (2007.) Benefits of driven piles. [Online] URL.http.//www.piledrivers.org/benefits-of-driven-piles/
7th May 2017.

Sanatkumar, M., (2008.) behaviour of rigid batter piles and pile gropus subjected to horizontal load in sand. Indian Geotechnical Journal.

BRANZ Seismic Resilience, (2012.9 Shallow Foundations. [Online] URL.http.//www.seismicresilience.org.nz/topics/foundations/residential-foundations/shallow-foundations-residential/ Accessed 12 04 2017.

Smith, A. A. &. D. I. G., n.d. Pile Foundation Design. A Student Guide, Edinburgh. Napier University.

Standard Penetration Test, (2016.) Standard Penetration Test. [Online] URL.http.//www.geotechdata.info/geotest/standard-penetration-test.html
Accessed 7th Jan 2017.

The balance, (2017.) Bored piles. [Online] URL.https.//www.thebalance.com/bored-pile-advantages-also-referred-as-drilled-shafts-844753 Accessed 13th April 2017.

Mishra Gopal, The construction civil, (2008.) Timber Piles. [Online] URL.http.//www.theconstructioncivil.org/timber-piles/
Accessed 28th Jan 2017.

The Constructor, (2015.) Types of shallow foundation. [Online] URL.https.//theconstructor.org/geotechnical/types-of-shallow-foundations/5308/
Accessed 11th March 2017.

Tritech ground engineering , (2011.) History of Piling. [Online] URL.http.//www.aeyates.co.uk/tritech-piling-and-foundations-ltd/about/history
Accessed 15th March 2017.

Understanding building construction, (2017.) PILE FOUNDATIONS. [Online] URL.http.//www.understandconstruction.com/pile-foundations.html
Accessed 12th Feb 2017.

Vanthek partner in piling and drilling, (2011.) Precast concrete pile. [Online] URL.http.//www.vanthek.com/en-GB/78/precast-concrete-pile.html
Accessed 9th March 2017.

Appendix 1

The Appendix 1 consists of simple pile calculation for the “Westpro Portus” Project. The calculation from RrPileCalc have been presented alongside theoretical calculation based on Finnish Piling code RIL 254-201

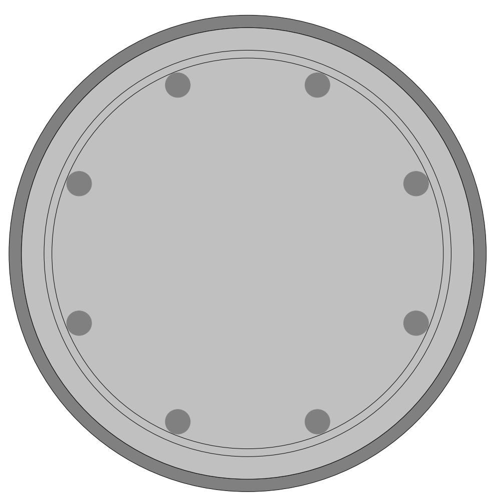
Calculation information

Project:	Westpro Portus
Designer:	Ville Salo
Pile tag:	RD600_20m_f0=30mm
Date:	8.4.2016
Code:	Finnish code, YM talonrakennus
Safety factors	
- pile material:	1.00
- reinforcement material:	1.15
- concrete material:	1.50
- soil material (against buckling):	1.50
Pile data	
- size:	RD600/16
- steel strength:	S355J2H
- corrosion allowance:	4.0 mm

Concrete fill data		Reinforcement data	
- strength class:	C35/45	- strength:	A500HW
- creep coefficient:	1.5	- number and size of bars:	8*Ø32
- proportion of dead load:	0.8	- concrete cover thickness:	40 mm

Soil data	
- characteristic value of undrained shear strength:	6 kPa
- coefficient of subgrade reaction A:	50
- coefficient of ultimate earth pressure B:	9
- radius of curvature of the pile R:	500 m

Cross-section



Capacity of the pile

Design resistance of the pile:	**F_d**	**8697 kN**
- buckling, soil:	$F_{d;s}$	8697 kN
- buckling, pile:	$F_{d;p}$	10360 kN

Calculation values

Pile pipe				
- outside diameter:	d_1	610.0 mm	d_{eff}	602.0 mm
- wall thickness:	t_1	16.0 mm	t_{eff}	12.0 mm
- cross-section area:	A_{s1}	29858 mm2		
- effective inertia:			EI_{eff}	203327 kNm2
- effective axial stiffness:			EA_{eff}	4671 MN
- steel strength:	f_{yd}	355.0 MPa		
Concrete				
- strength class:	f_{cd}	23.3 MPa		
Reinforcement				
- cross-section area of bars:	A_{s2}	6432.0 mm2		
- strength:	f_{yd2}	434.8 MPa		
Composite structure				
- effective inertia:	EI_{eff}	247234 kNm2		
- effective axial stiffness:	EA_{eff}	7194 MN		
Buckling, soil				
- modulus of subgrade reaction of soil:	k_s	498 kPa/m		
- ultimate earth pressure (ultimate limit state):	p_{md}	36.0 kPa		
- buckling length and radius of curvature of the pile:	L_{cr}	16.83 m	R	500.0 m
- geometrical curvature of the pile:	δ_g	70.8 mm		
- fictive curvature of the pile:	δ_f	21.9 mm		
- buckling load of the straight pile:	F_{cr}	17224 kN		
- design resistance of the pile when soil fails:	$F_{d;s}$	8697 kN		
Buckling, pile				
- total initial curvature ($\delta_0+\delta_f$)	δ_0	92.7 mm		
- moment capacity of the pile:	M_u	2074.5 kNm		
- buckling load of the straight pile:	$F_{c;u}$	16441 kN		
- design resistance of the pile when pile structure fails:	$F_{d;p}$	10360 kN		

Advanced FEM

Soil data

Nr	Top level [m]	Bottom level [m]	Soil type	Shear strength C_{uk} [kPa]	Friction angle Φ´ [°]	Unit weight γ´ [kN/m3]	Subgrade reaction k_s [kPa/m]
1	0.00	16.00	cohesive soil	6.0	-	6.0	498.3
2	16.00	20.00	friction soil	-	32.0	10.0	10927.1

- in friction soils below ground water the subgrade reaction is 60% of the value shown in table.

- distance of groundwater level from ground level: 0.00 m
- critical buckling length: 16.83 m

Support types of the pile ends

	Vertical displacement	Horizontal displacement	Rotation
top end	free	fixed	free
bottom end	fixed	fixed	fixed

Loads on the top end of the pile
- normal force (vertical force): 9000.0 kN
- shear force (horizontal force): 0.0 kN
- moment: 500.0 kNm

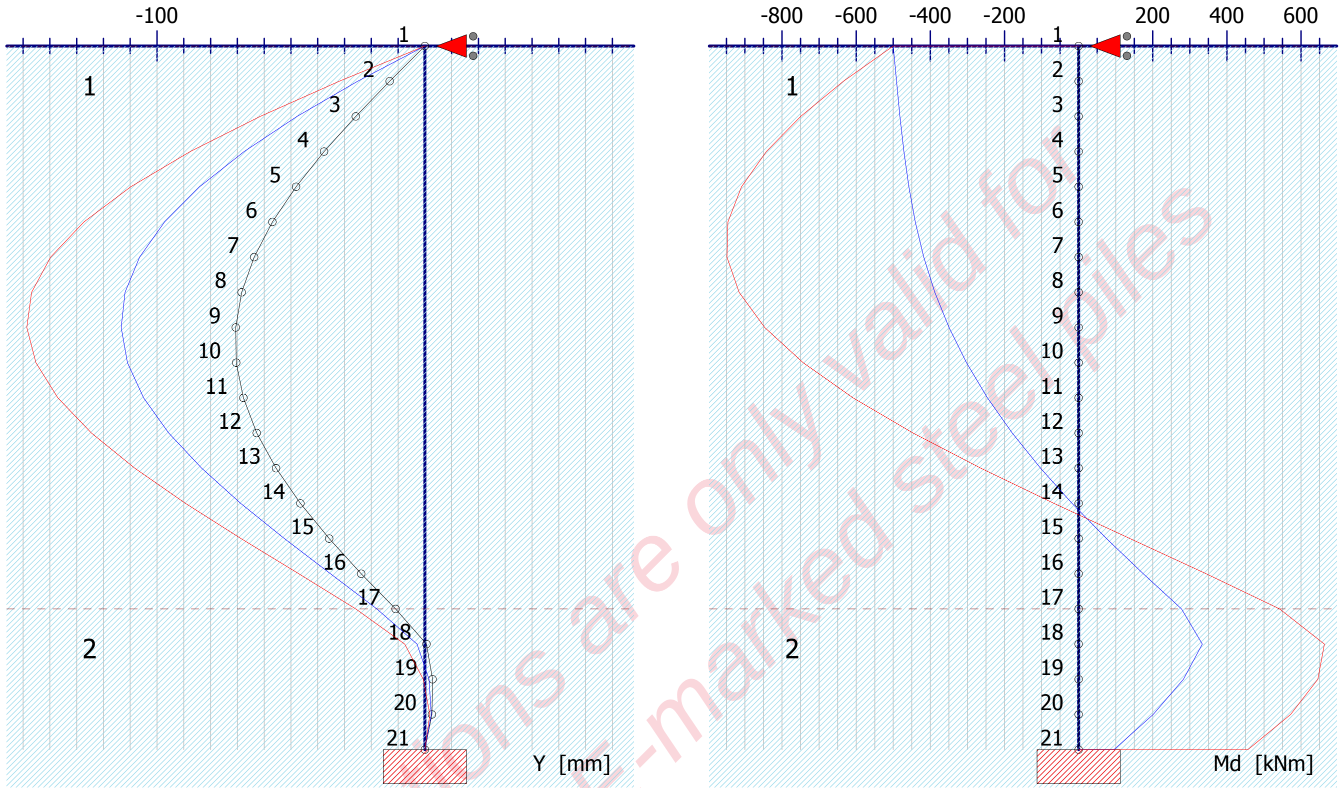
Results of 2. order calculations

Forces and capacity values at decisive node
- decisive node: 7 Nd 9000.0 kN
  Md 948.6 kNm Mu 1399.2 kNm

Deflection value at decisive node
- decisive node: 9 Y -148.6 mm

Displacement of top end of the pile
- horizontal/vertical direction: 0.0 mm 22.5 mm

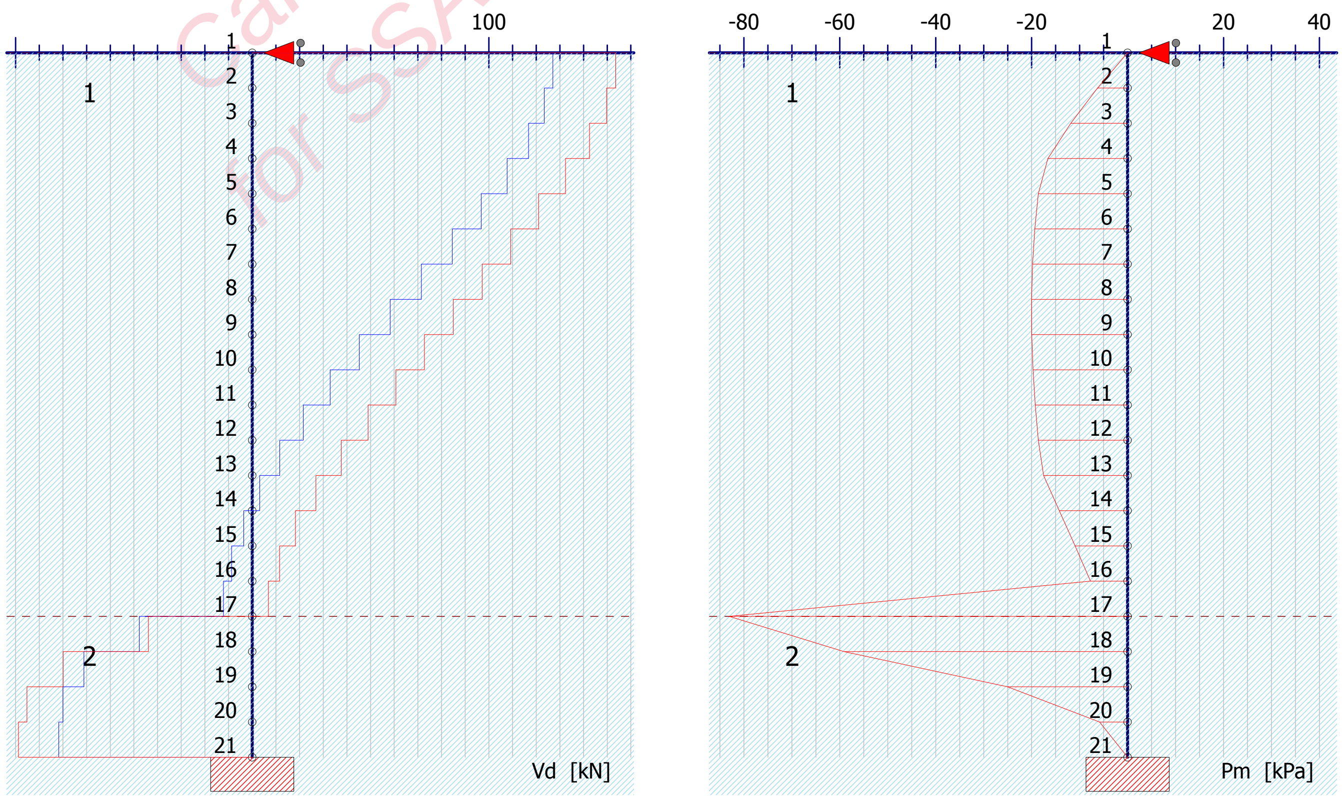
Deflection and moment graphs of the pile



YForces and capacity values at decisive node/Ymin: 2.38/-148.63 mm

MdForces and capacity values at decisive node/Mdmin: 662.9/-948.6 k

Shear force and soil pressure graphs of the pile



VdForces and capacity values at decisive node/Vdmin: 153.58/-98.77 kN

PmForces and capacity values at decisive node/Pmmin: 662.9/-948.6

N / M capacity graph of the pile cross-section

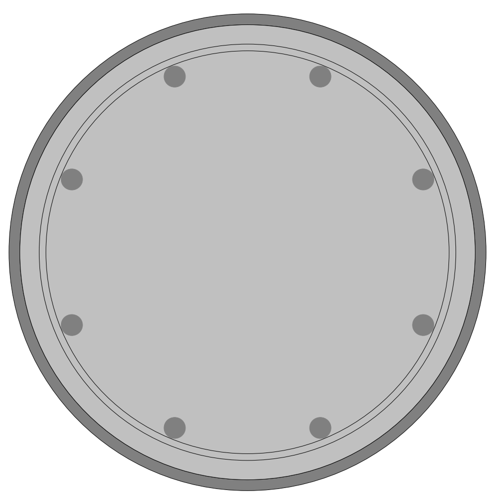
Calculation information

Project:	Westpro Portus
Designer:	Ville Salo
Pile tag:	RD700_23m_f0=48mm
Date:	8.4.2016
Code:	Finnish code, YM talonrakennus
Safety factors	
- pile material:	1.00
- reinforcement material:	1.15
- concrete material:	1.50
- soil material (against buckling):	1.50
Pile data	
- size:	RD700/16
- steel strength:	S355J2H
- corrosion allowance:	4.0 mm

Concrete fill data		Reinforcement data	
- strength class:	C35/45	- strength:	A500HW
- creep coefficient:	1.5	- number and size of bars:	8*Ø32
- proportion of dead load:	0.8	- concrete cover thickness:	40 mm

Soil data	
- characteristic value of undrained shear strength:	6 kPa
- coefficient of subgrade reaction A:	50
- coefficient of ultimate earth pressure B:	9
- geometrical initial deflection of pile:	Lcr/200

Cross-section



Capacity of the pile

Design resistance of the pile:	F_d	**10360 kN**
- buckling, soil:	$F_{d;s}$	10360 kN
- buckling, pile:	$F_{d;p}$	12659 kN

Calculation values

Pile pipe				
- outside diameter:	d_1	711.0 mm	d_{eff}	703.0 mm
- wall thickness:	t_1	16.0 mm	t_{eff}	12.0 mm
- cross-section area:	A_{s1}	34935 mm2		
- effective inertia:			EI_{eff}	326607 kNm2
- effective axial stiffness:			EA_{eff}	5471 MN
- steel strength:	f_{yd}	355.0 MPa		
Concrete				
- strength class:	f_{cd}	23.3 MPa		
Reinforcement				
- cross-section area of bars:	A_{s2}	6432.0 mm2		
- strength:	f_{yd2}	434.8 MPa		
Composite structure				
- effective inertia:	EI_{eff}	405410 kNm2		
- effective axial stiffness:	EA_{eff}	8633 MN		
Buckling, soil				
- modulus of subgrade reaction of soil:	k_s	427 kPa/m		
- ultimate earth pressure (ultimate limit state):	p_{md}	36.0 kPa		
- buckling length and radius of curvature of the pile:	L_{cr}	19.05 m	R	476.2 m
- geometrical curvature of the pile:	δ_g	95.2 mm		
- fictive curvature of the pile:	δ_f	24.8 mm		
- buckling load of the straight pile:	F_{cr}	22057 kN		
- design resistance of the pile when soil fails:	$F_{d;s}$	10360 kN		
Buckling, pile				
- total initial curvature ($\delta_0+\delta_f$)	δ_0	120.0 mm		
- moment capacity of the pile:	M_u	2824.3 kNm		
- buckling load of the straight pile:	$F_{c;u}$	20120 kN		
- design resistance of the pile when pile structure fails:	$F_{d;p}$	12659 kN		

Advanced FEM

Soil data

Nr	Top level [m]	Bottom level [m]	Soil type	Shear strength C_{uk} [kPa]	Friction angle Φ´ [°]	Unit weight γ´ [kN/m3]	Subgrade reaction k_s [kPa/m]
1	0.00	17.00	cohesive soil	6.0	-	6.0	426.7
2	17.00	23.00	friction soil	-	32.0	10.0	10927.1

- in friction soils below ground water the subgrade reaction is 60% of the value shown in table.

- distance of groundwater level from ground level: 0.00 m
- critical buckling length: 19.05 m

Support types of the pile ends

	Vertical displacement	Horizontal displacement	Rotation
top end	free	fixed	free
bottom end	fixed	fixed	fixed

Loads on the top end of the pile
- normal force (vertical force): 9000.0 kN
- shear force (horizontal force): 0.0 kN
- moment: 700.0 kNm

Results of 2. order calculations

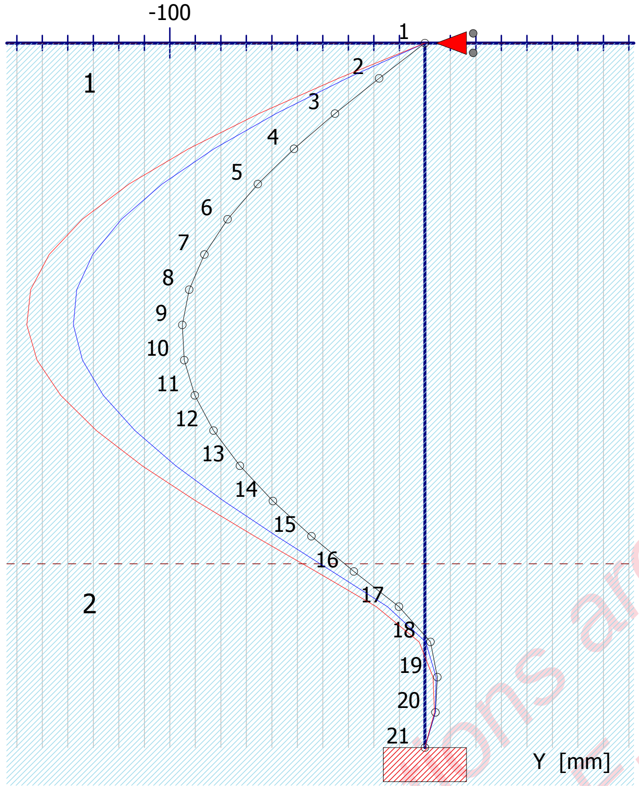
Forces and capacity values at decisive node
- decisive node: 6 Nd 9000.0 kN

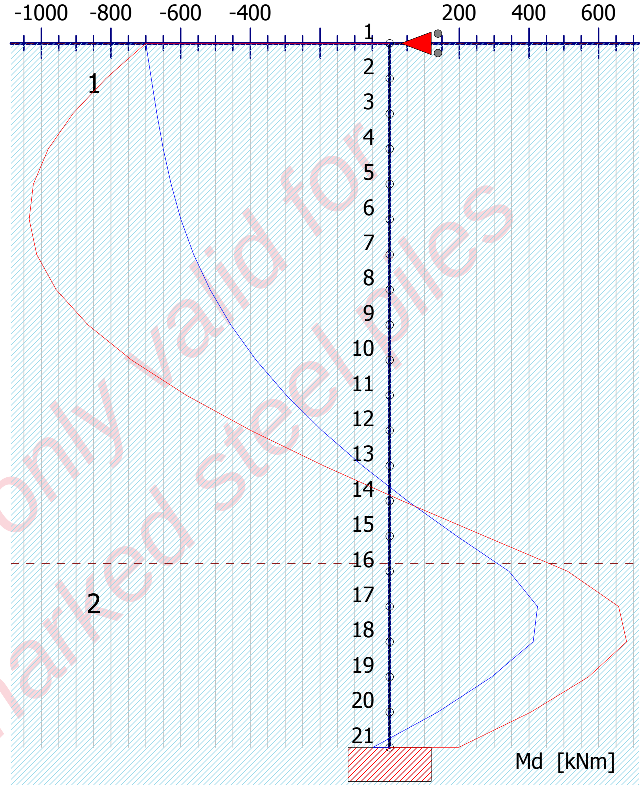
  Md 1034.9 kNm Mu 2354.6 kNm

Deflection value at decisive node
- decisive node: 9 Y -156.1 mm

Displacement of top end of the pile
- horizontal/vertical direction: 0.0 mm 20.0 mm

Deflection and moment graphs of the pile

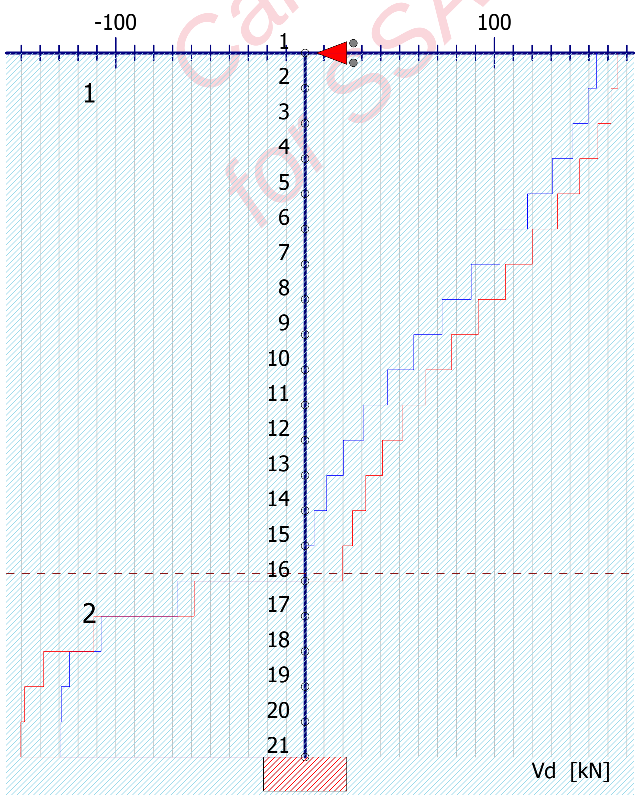


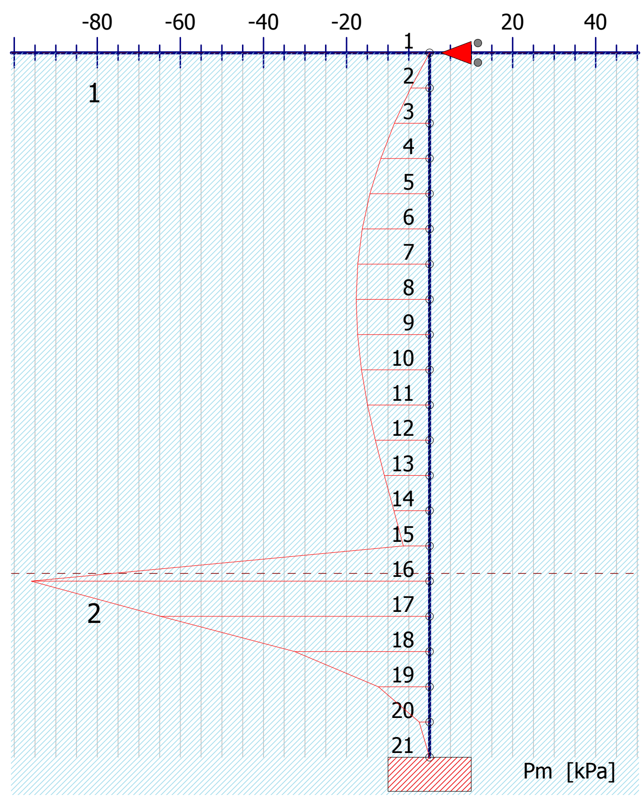


YForces and capacity values at decisive node/Ymin: 4.39/-156.11 mm

MdForces and capacity values at decisive node/Mdmin: 680.2/-1034.9

Shear force and soil pressure graphs of the pile





VdForces and capacity values at decisive node/Vdmin: 165.31/-150.23 kN PmForces and capacity values at decisive node/Pmmin: 680.2/-1034.9

N / M capacity graph of the pile cross-section

Buckling resistance of Composite pile

Pile Pipe details

Diameter of pile $d_1 := 610\ mm$

Thickness of pipe $t_1 := 16\ mm$

Design yield strength of pile $f_{yd1} := 355\ \dfrac{N}{mm^2}$

Corrosion $4\ mm$

Effective diameter $d_{eff} := 602\ mm$

Effective thickness $t_{eff} := 12\ mm$

Area $A_{s1} := 22242\ mm^2$

Radius of curvature of Pile $R := 874\ m$

Concrete details

Design Compressive strength of Concrete $f_{cd} := 20\ MPa$

Concrete cover $40\ mm$

Reinforcement details

12 pcs of 25mm diameter

$$A_{s2} := 12 \cdot \pi \cdot \left(\frac{25\ mm}{2}\right)^2 = \left(5.89 \cdot 10^3\right)\ mm^2 \qquad f_{yd2} := 434.8\ MPa$$

Composite Structure

Bending stiffness

$$EI := 276741\ kN \cdot m^2$$

Effective Bending stiffness

$$EI_{eff} := 239675\ kN \cdot m^2$$

Soil parameters

Undrained shear strength $c_u := 5\ kPa$

Coefficient of Subgrade reaction

$$A := 50$$

Impact factor of reinforcement bar

$$K_s := \frac{50\ c_u}{d_{eff}} = 415.282\ \frac{1}{m} \cdot kPa$$

Critical buckling length of pile

$$L_{cr} := \pi \cdot \sqrt[4]{\frac{EI_{eff}}{K_s \cdot d_{eff}}} = 17.481\ m$$

Critical Force for buckling

$$F_{cr} := 2 \cdot \sqrt{K_s \cdot d_{eff} \cdot EI_{eff}} = \left(1.548 \cdot 10^4\right)\ kN$$

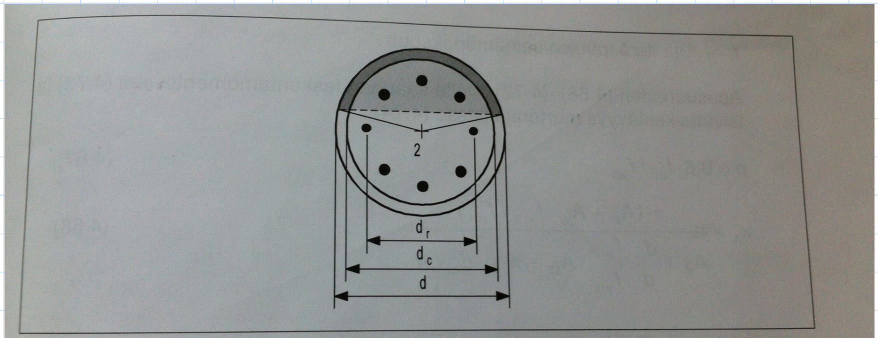
Geometrical Initial deflection of pile

$$\delta_g := \frac{{L_{cr}}^2}{8\ R} = 43.706\ mm$$

$$\rho_m := 6 \cdot c_u = 30\ kPa$$

Design buckling resistance of Soil

$$F_{d.s} := \frac{F_{cr}}{1 + \frac{K_s \cdot \delta_g}{\rho_m}} = \left(9.646 \cdot 10^3\right)\ kN$$



Kuva 4.16. Liittorakennepoikkileikkauksen taivutuskestävyyden laskennassa käytettävät merkinnät.

$$d_r := d_1 - 2\ t_1 - 2 \cdot 40\ mm - 25\ mm = 473\ mm$$

$$d_c := d_1 - 2 \cdot t_1 = 578\ mm$$

$$P := \frac{0.8 \cdot f_{cd}}{f_{yd1}} = 0.045$$

$$K_1 := \frac{\pi \cdot \left(A_{s1} + \frac{A_{s2} \cdot f_{yd2}}{f_{yd1}}\right)}{A_{s1} + \frac{d_r}{d_1} \cdot \frac{f_{yd2}}{f_{yd1}} \cdot A_{s2} + \frac{\pi \cdot P \cdot {d_c}^2}{4}} = 2.333$$

$$K_2 := \frac{P \cdot {d_c}^2}{4 \cdot \left(A_{s1} + \frac{A_{s2} \cdot f_{yd2}}{f_{yd1}}\right)} = 0.128$$

$$\theta := K_1 \cdot K_2 \cdot \sin\left(K_1\right) + \frac{K_1}{2} = 1.382$$

$$e_s := \frac{\sin(\theta)}{3\ \theta} \cdot \frac{\left(d_1^{\ 3} - d_c^{\ 3}\right)}{d_1^{\ 2} - d_c^{\ 2}} = 0.211\ m$$

$$e_c := \frac{2 \cdot d_c \cdot \sin(\theta)^3}{3 \cdot (2\ \theta - \sin(2\ \theta))} = 0.152\ m$$

$$e_n := e_c + \frac{2\ \theta}{\pi} \cdot \left(e_s - e_c\right) + \frac{0.8\ \theta \cdot A_{s2} \cdot f_{yd2} \cdot d_r}{\pi \cdot A_{s1} \cdot f_{yd1}} = 0.258\ m$$

Ultimate bending resistance of cross section of pile

$$M_u := A_{s1} \cdot f_{yd1} \cdot e_n = \left(2.038 \cdot 10^3\right)\ kN \cdot m$$

Area of concrete

$$A_c := \left(\pi \cdot \left(\frac{d_{eff}}{2}\right)^2 - A_{s1} - A_{s2}\right) = 0.256\ m^2$$

Frictional initial deflection

$$\delta_f := 0.0013 \cdot L_{cr} = 22.726\ mm$$

$$\delta_0 := \delta_g + \delta_f = 66.431\ mm$$

Pile cross section restistance for ULS

$$F_{c;u} := A_c \cdot f_{cd} + A_{s1} \cdot f_{yd1} + A_{s2} \cdot f_{yd2} = \left(1.559 \cdot 10^4\right)\ kN$$

Pile cross section of concrete compressive strength in ULS

$$F_{c;u;c} := f_{cd} \cdot A_c = \left(5.13 \cdot 10^3\right)\ kN$$

$$B := F_{cr} + F_{c;u} + \frac{0.5 \cdot F_{cr} \cdot \delta_0 \cdot \left(F_{c;u} - F_{c;u;c}\right)}{M_u} = \left(3.371 \cdot 10^4\right)\ kN$$

$$C := F_{cr} \cdot F_{c;u} = \left(2.413 \cdot 10^8\right)\ kN^2$$

Ultimate buckling resistance of Pile cross section

$$F_{d;p} := \frac{B}{2} - \sqrt{\frac{B^2}{4} - C} = \left(1.032 \cdot 10^4\right)\ kN$$