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Foundations of the Gothenburg Cable Car Towers

A Geotechnical Feasability Study for Two Cable Car Towers on Deep Deposits of Soft Clay

Bachelor Thesis in Civil Engineering

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Cover: The image shows an early animated vision picture of the cable car tower planned at Lindholmen (UNStudio, n.d.).

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Abstract

To prevent a possibly overburdened public transit system, a cable car was supposed to be built in Gothenburg, a city largely situated on deep deposits of soft clay. The soil conditions together with the large and heavy cable car towers, results in a geotechnical challenge. The two cable car towers investigated in this Thesis, are located at Järntorget and Lindholmen. For the towers to be able to stand stable on the clay, it is essential with a suiting adequate foundation. In this Thesis, an investigation to find a suitable foundation for the towers is conducted by gathering information from literature, such as scientific papers, reports and books. Calculations on geotechnical and structural capacity is performed as well. It is found that concrete displacement piles will be the best option for the foundation of both towers. A sustainability aspect is considered in the Thesis and it is shown that longer piles require less concrete with fewer piles and are, therefore, more sustainable than shorter piles. Furthermore, the most suitable foundation option for tower A is 66 square-sectioned displacement jointed pre-cast concrete piles with a width of 350 mm and length of 60 m. These dimensions generate a total concrete volume of 485 m^3 for the piles. For tower B, the most suitable foundation is 100 square-sectioned displacement jointed pre-cast concrete piles with a width of 350 mm and length of 55 m. These dimensions generates a total concrete volume of 663 m^3 for the piles.

Contents

1 Introduction

The city of Gothenburg is expanding rapidly and thus the need for a larger capacity and more developed public transport system has emerged (Göteborgs Stad Trafikkontoret, 2014). Communications between key points within the city is one of the main goals brought forward by the city council in Gothenburg's traffic strategy. The strategy also states the need to eliminate barriers within the infrastructure and create a more tightly knitted city. One of the major barriers within the city is the Göta River that divides the city into two parts. One of the key points in the city, which is expanding on the northern banks of the river, is Lindholmen. It is a modern area with a science park and schools and is about to expand further with a new district called Karlastaden, which surrounds the soon to be tallest building in Scandinavia, Karlatornet. The expansion of Lindholmen will contribute with more job opportunities and attract tourists, which means that more people than ever will be looking to take public transit to the area. Today the options are fairly limited and will in time be insufficient for the number of people travelling with public transport to the area, with only a few bus lines going from the city centre and a ferry, Älvsnabben, arriving from across the river at Stenpiren. Therefore, the traffic strategy mentions a possible solution to this problem; a cable car. A zoning plan was made on behalf of the City of Gothenburg where a cable car system was planned.

1.1 Background

A cable car is a transportation system that transports units forward by being connected to a cable or a line (Tyréns, 2013). This Thesis will focus on hanging cable car systems, since the cable car in Gothenburg are passing over several districts as well as the Göta River. In the hanging type of cable car there are some components that are included in every type of cable car. These are gondolas, cables, towers and attachments. Moreover, there are some differences depending on what system is used, such as the number of gondolas and their size, detachable cars and the number of cables. A cable car system usually has one cable but can have up to three cables. Since the cables need to carry the weight of the gondolas, systems with larger loads can use several cables to distribute the vertical load. The number of cables also influences how far apart the towers can be placed.

According to the zoning plan, the Gothenburg cable car will consist of four stations between Järntorget and Wieselgrensplatsen. Figure 1 shows a map of Gothenburg where the placement of the stations are marked with yellow circles. One of the towers, holding up the cable, is supposed to be placed at Järntorget, from now on called tower A, and in the Göta River at Lindholmen, from now on called tower B (Göteborgs Stad, 2019). These spots are marked with red shapes in Figure 1. The two sites have similar geotechnical conditions since they are both located in Gothenburg and they are placed on each side of the Göta River. At Lindholmen, however, the tower is supposed to be built in the water which is not the case at Järntorget. Gothenburg is located on deep deposits of very soft clay, which brings risks and challenges when it comes to constructing the foundation for tall and heavy buildings, bridges and other infrastructure projects (Göteborgs Stad Fastighetskontoret, 2017). Nonetheless, because of geotechnical difficulties, a project can become very expensive and this has led the

City of Gothenburg to postpone the cable car project (Trafikkontoret, 2019). Despite of that, this Thesis will still include an investigation for what methods could be used and if a solution would be possible to achieve.

Figure 1: Map of Gothenburg. Red and yellow shows critical parts of cable car. (Google, n.d.)

1.2 Problem

The cable car in Gothenburg will stretch from Järntorget to Wieselgrensplatsen. In this Thesis, a feasibility study will be conducted on the possible solutions for the foundation of cable car tower A at Järntorget and tower B in the basin at Lindholmen. The towers are placed on soft clay with a substantial depth and the tall, slim and heavy tower constructions causes significant loads upon the foundation. Loads imposed by weather could lead to an overturning moment which could lead to collapse of the tower foundations. The combination of deep deposits of soft clay and large loads results in a geotechnical challenge.

1.3 Aim

The aim of this Thesis is to investigate which type of foundation and what design of the foundation is suitable for the cable car towers located at Lindholmen and Järntorget in Gothenburg. To meet the aim, the following objectives are composed:

- The foundation must be designed to function in deep deposits of soft clay and be able to handle the vertical and horizontal loads, as well as the overturning moment.

- The ecological footprint should be minimized and this will be achieved by minimizing the amount of material for the foundations.

1.4 Limitations

In this Thesis, several limitations has been set for the study. Those limitations are:

- Only floating piles will be considered.
- Only dead load will be considered when calculating the bearing capacity of the foundation.
- Downdrag from settling soil and accidental loads will not be considered in the pile design.
- Calculations will be performed on concrete piles without taking buckling effects into consideration.
- Settlement analysis will not be included in the study.

1.5 The Structure of the Thesis

This Thesis consists of 7 chapters, including subsections. To get a further understanding of the structure, the following list describes the content of the chapters:

- **Chapter 1 - Introduction** describes the background of the project and specifies the problem and aim, divided into several objectives.
- **Chapter 2 - Theory** contains general theory about foundations, soil conditions and soil mechanics to get a deeper insight into these subjects.
- **Chapter 3 - The Gothenburg Cable Car** consists of a description of the Gothenburg cable car project. It is divided into different parts of the project, including sustainable development, specific loads and soil properties on site at Järntorget and at Lindholmen. It also describes other projects with similar conditions and methods, to be able to compare with the Gothenburg cable car in the discussion.
- **Chapter 4 - Method for Designing the Foundation** describes the designing method, including calculations on geotechnical and structural capacity of piles.
- **Chapter 5 - Results** presents the results.
- **Chapter 6 - Discussion** consists of discussions and comparisons of the findings in the Thesis.
- **Chapter 7 - Conclusion** concludes the Thesis.

2 Theory

A foundation is the part of a structure that transfer loads from the superstructure above ground to the underlying soil (Craig & Knappet, 2012). The foundation has to meet requirements regarding ultimate limit states (ULS) and serviceability limit states (SLS). ULS requires that the foundation is designed with the capacity or resistance to withstand applied loads without collapse. SLS requires that the foundation is designed to avoid deformations that could damage or cause loss of function in the supported structure. Foundation methods are usually divided into the categories shallow and deep foundations.

2.1 Shallow Foundations

Shallow foundations are used when the relation between the horizontal and the vertical loads are relatively small (Craig & Knappet, 2012). Therefore, the area of the foundation is a critical restriction when choosing to build with a shallow foundation.

2.1.1 Footing

When building with shallow foundations, a footing or a raft is created beneath the upper structure (Baban, 2016). The purpose of the foundation is to distribute the loads over a wide horizontal area near the surface. The basic methods for shallow foundations are:

- **Spread footing** - Transfers the load from a single column into the footing and to a wider area in the ground, the footing is often made of concrete and the shape is circular, square or rectangular.

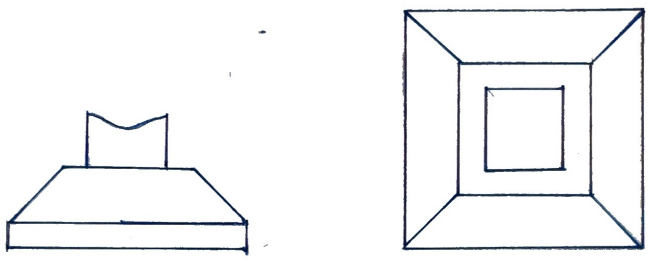


Figure 2: Spread Footing. Left: Side view. Right: Overhead view (Baban, 2016)

- **Combined footing** - The loads are transferred from two or more columns into the footing. The load is spread equally between the columns.

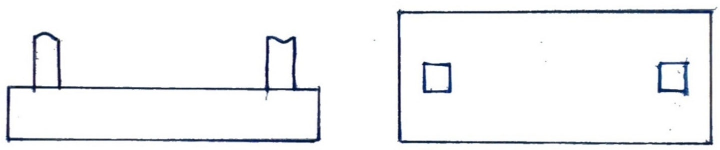


Figure 3: Combined Footing. Left: Side view. Right: Overhead view (Baban, 2016)

- **Mat or raft foundation** - The loads are transferred from all the columns into a footing that covers the entire area beneath the upper structure.

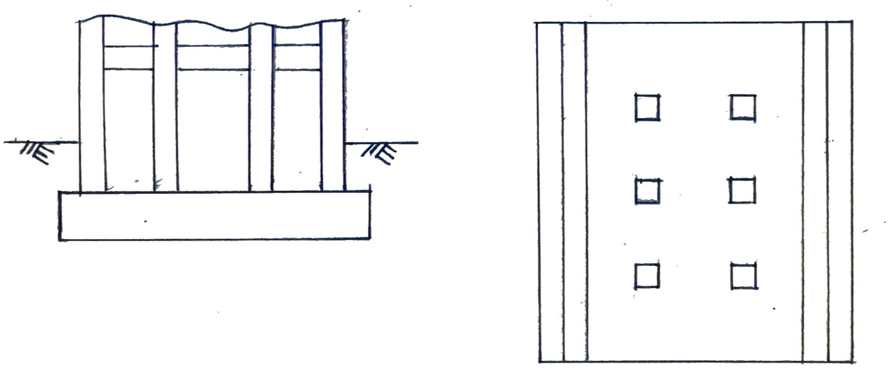
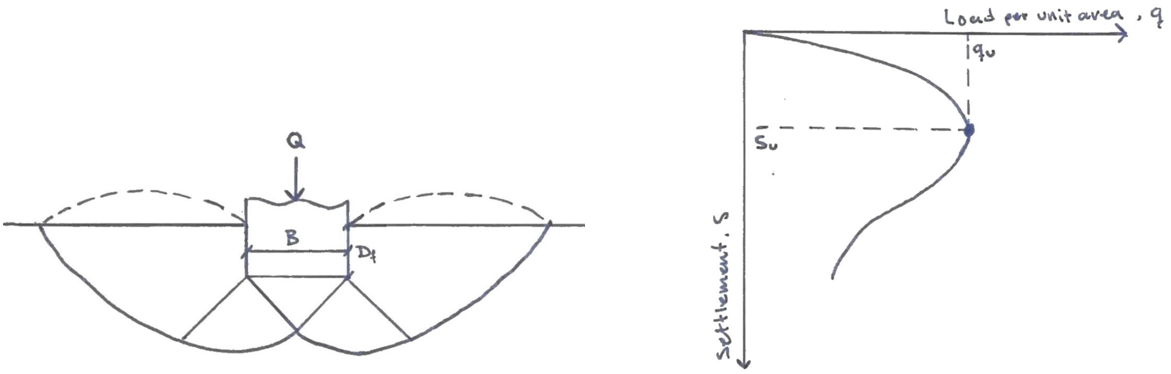


Figure 4: Mat Foundation. Left: Side view. Right: Overhead view. (Baban, 2016)

2.1.2 Soil Behaviour

Soil conditions are an important factor influencing how efficient shallow foundations can be (Das, 1999). On stiffer soils the settlements are lower than on less stiff soils, such as clay. Therefore the ultimate stability of the structure is greater on stiffer soils. Furthermore, the type of soil also determines how and at what stress the soil succumbs to failure.

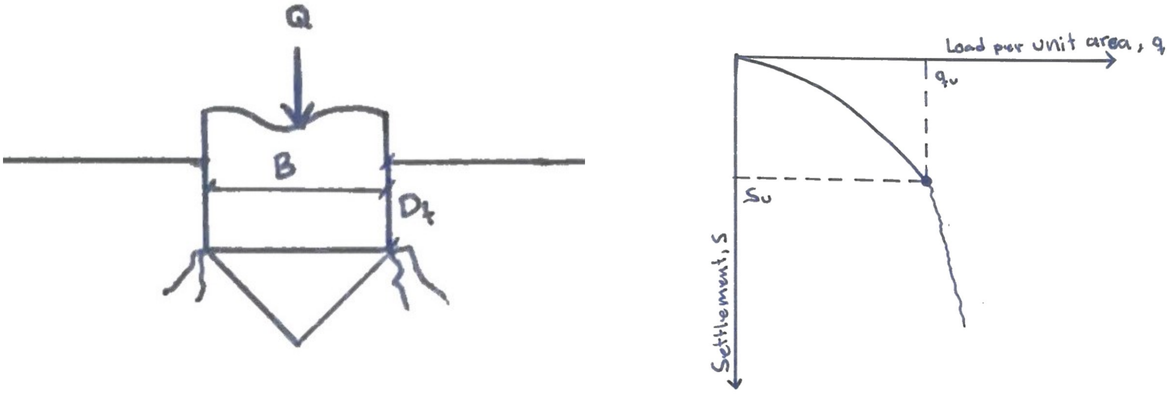
Shallow foundations on dense sand or stiff clayey soil have what is called a general shear failure (Das, 1999). This is illustrated in Figure 5a. Here, the settlement (S) becomes larger when the load per unit area (q) increases. However, when q becomes equal to the ultimate bearing capacity (q_u) the soil undergoes failure beneath and around the foundation area. After this, q can be lowered while the foundation continues to settle, which is shown in Figure 5b.



(a) (b)

Figure 5: General Shear failure (Das, 1999)

Loose sand or soft clayey soils behaves quite differently compared to stiff soils (Das, 1999). This is illustrated in Figure 6. While q is still increasing with S, the soil failure occurs after it has settled more than in dense sand or stiff clayey soil. When q reaches q_u the soil experiences a punching shear failure. In this case the failure never reaches the surface. After this point, q barely needs to become greater for settlements to continue, which is shown in Figure 5b.



(a) (b)

Figure 6: Punching Shear failure (Das, 1999)

2.2 Deep Foundations

The deep foundation methods are used when loads need to be transferred to more competent materials, deeper beneath the surface (Craig & Knappet, 2012). The foundation is defined as deep if the height of the foundation is larger than the width of the foundation. The most common method of deep foundations is piling, which is when a member of steel, timber or concrete is installed in the ground. Piles are often of square or circular cross-sections and will always have a much smaller diameter or width than its length.

Piles are widely used since they transfer loads from the superstructure into deeper layers of soil with higher strength and stiffness than the top layers of soil (Alén, 2009). The reason that the deeper soil layers have higher strength and stiffness is normally because of its stress history. The way piles transfer loads to deeper layers of soil can be classified into two types of piles, floating piles and end bearing piles or as a combination of the two (Fleming, Weltman, Randolph, & Elson, 2009). The floating piles are used when it is not possible to place the piles on a firm layer underneath a soft soil layer. The piles are called end-bearing piles when placed on a firm layer and they majority of the capacity of these piles are therefore obtained from their base capacity. The shear strength between the pile and the soil depends on both the exterior geometry and on the method of installation (Craig & Knappet, 2012). The installation methods are divided into two main categories, displacement piles and non-displacement piles.

2.2.1 Displacement Piles

Displacement piles is a collective name for piles that are driven and makes the soil move radially when a pile enters the ground (Fleming et al., 2009). These types of piles can lead to heave in clay and small volume changes occur as the soil is displaced. The piles can either be pre-fabricated or constructed on site. Displacement piles can be organized into the following subcategories:

- **Driven cast-in-place displacement piles** - A void is created by driving a tube, made by either steel or concrete, into the ground.

- **Vibrated concrete columns (VCCs)** - A vibroflot displaces the soil creating space for a pile, usually made of concrete.

- **Totally preformed displacement piles** - These piles can be solid or hollow and are driven or screwed into the ground. They can be made out of tree, concrete or steel and if made out of concrete they can be pre-cast reinforced or pre-cast pre-stressed.

- **Auger screw displacement piles** - These piles are made by screwing an auger into the soil and concreting while retrieving the auger.

Totally preformed displacement piles can be constructed in several different materials depending on whether the piles are tubular or solid (Fleming et al., 2009). Sections that are tubular and hollowed can be composed of concrete or steel while the solid parts can be built in timber, concrete or steel.

Pre-cast reinforced concrete piles is one type of pillars in the category totally pre-formed displacement piles (Fleming et al., 2009). Due to economical reasons the pre-cast jointed concrete piles are the most commonly used pile of this type. If the conditions allow it, the piles can be pre-cast on the constructions site, which is preferred since it can make transportation easier. The piles are usually square-sectioned with a width up to 600 mm. The pre-cast non-jointed concrete piles can manage loads up to around 3 000 kN, depending on what soil they are installed in. It is important to align the sections of piles accurately since redoing the installation of the piles can lead to large bending stresses. Concrete piles can be pre-stressed with the advantages that their resistance against tensile stresses are improved and are less likely to be damaged at the construction site. On the other hand, they are more sensitive to destruction during transportation and it is challenging to shorten their length if needed.

As mentioned earlier, jointed piles are widely used since they often are the most economical solution when using totally pre-formed displacement piles (Fleming et al., 2009). Jointed piles are not pre-stressed, which usually is not a problem since handling stresses are reduced due to the fact that each unit is shorter compared to a pile without joints. The joints need to be aligned and well constructed so that no excess loads are created. The piles can be made in many different shaped sections, varying from square to triangular, and can manage loads from 700 kN up to 2 500 kN. If the pile is square-shaped the width normally ranges from 250 mm to 450 mm but it can also be either smaller or larger. Most commonly they are installed in soil depths up to about 30 m but it has also been done in soil with a depth of 100 m. A sketch of a jointed pile is shown in Figure 7.

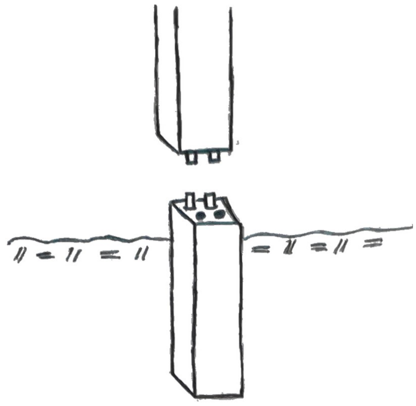


Figure 7: Jointed pile

Hollow tubular-section pre-cast concrete piles are constructed with a diameter varying from 600 mm to 1 500 mm (Fleming et al., 2009). The pre-tensed tubular parts of reinforced concrete can withstand the double moment of resistance compared to if it were solid. These types of cylindrical piles are good to use in marine environments, if they have a large diameter, since they have a good capacity to handle loads. The concrete in the piles, when used in marine environments, normally does not have problems with corrosion but this can change over time if freezing occurs. When the piles are installed it will lead to extensive displacements in the soil and therefore if large amount of piles are needed it is favourable to build in loose soils. Even if these types of piles have been driven to great depths, up to 80 m, they are not widely used since it is difficult to extend their length. Hence, they can be used if the length they are to be driven is pre-determined. A sketch of a hollow tubular concrete pile is presented in Figure 8.

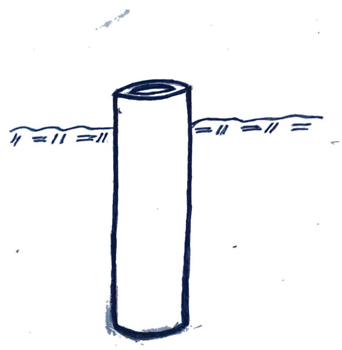


Figure 8: Hollow tubular concrete pile

Pre-formed steel piles are also in the category of totally pre-formed displacement piles (Fleming et al., 2009). Pre-formed steel piles can be constructed with various sections and in Scandinavia piles with X-sections has been on the market. One disadvantage with steel piles is that the risk of fast corrosion is feared but in many cases that fear is not justified. On the other hand, the advantages of steel piles are that the risk of over-stressing is low, it is easy to alter their length and they are simple to handle.

Timber piles can be used if the soil depth and loads are modest and they are not commonly used in depths larger than 12 m (Fleming et al., 2009). Working loads for timber piles are usually not higher than 500 kN, since it is hard to construct sets that can handle larger loads and timber piles usually have small cross-sections and a low compressive strength.

Driven cast-in-place piles can be constructed with various methods (Fleming et al., 2009). For smaller loads it is common to create a pile of this type by driving a tube into the soil and then filling the created void with concrete, as the tube is removed from the ground. For larger loads another method is used where the driven tube is used as a permanent shell. To withstand larger loads the concrete can be reinforced. A risk with these types of piles is that they can be damaged if driving neighbouring piles to close, which means they have to be driven down with caution.

Screw cast-in-place displacement piles can be created with a method, known as the Atlas Piling System, that screws an auger down in the ground to the needed depth, with a maximum of 22 m (Fleming et al., 2009). The head of the auger is attached to a hollow stem that is closed with a disposable tip. When the auger is at the right depth the reinforcement is put in place before concrete is disposed through the hollow stem. At the same time as the concrete is put in place the auger head is removed. One disadvantage with these piles is the limitations of the reinforcement cage as there is a restricted diameter which can cause problems if the piles need to resist great bending stresses. A sketch of how the Atlas Piling system method works is shown in Figure 9.

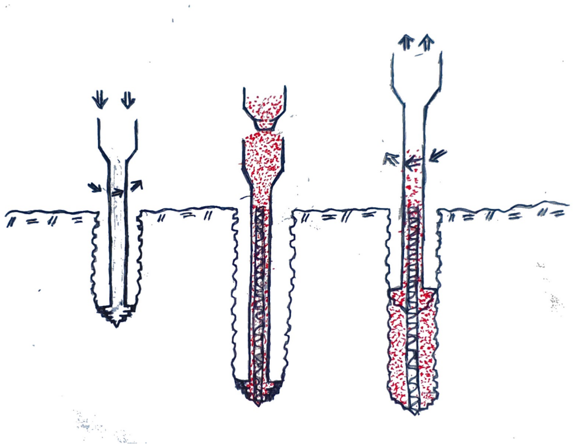


Figure 9: The Atlas Piling System method.

The screw cast-in-place displacement piles have a higher capacity compared to traditionally constructed bored piles with the same size and volume of concrete (Fleming et al., 2009). Another positive aspect with this method is that it combines the benefits of displacement piling while it is also less noisy and causes less vibrations, which are benefits with bored piles.

Regarding sustainability, the screw cast-in-place displacement piles are good in the way that the need to dispose soil, which can be contaminated, is reduced. However, compared to a classic auger pile machine the piling machine needed for this method demands more power and therefore the air pollution may be increased.

Another pile type using almost the same method is the Omega pile (Fleming et al., 2009). This piling method is different from the Atlas piling system in the way the auger is removed, as it is screwed in the same direction as it was screwed during installation. This method, unlike the Atlas piling system, leaves a small amount of spoil. Fundex piles also uses a similar method but with the difference that a flighted casing is used to create a straight pile. The case can also be left in the ground to protect the concrete if the ground conditions are harsh.

Vibrated concrete columns (VCCs) are much alike **vibro-displacement stone columns (VSCs)** that adds cement to a stone feed, which creates piles (Fleming et al., 2009). The difference, however, is that when constructing VCCs concrete is instead added through the stem of the vibroflot when the required depth is attained. If needed, a reinforcement cage can be installed in the pillar while the concrete is still wet. The most suitable ground conditions for VCCs and VSCs are if weak deposits lays upon dense gravel or weak rock. This method is not suited for ground conditions with stiff clay since the vibroflot will have issues with penetrating this type of soil. One of the most relevant parameters to mention with VSCs is standard depths and diameters. They are very effective between 4-10 m depth, but after 10 m the borehole can loose stability (Patel, A., 2019). It can also occur problems with stone contamination in larger depths. The standard diameter of VSCs lies between 0.8 and 1.2 m.

2.2.2 Non-displacement Piles

Non-displacement piles are installed without soil displacement and instead the soil is normally removed by boring or drilling to form a shaft and concrete then being cast in the shaft to form the pile. Advantages with this technique is that it creates minimal soil disturbance in the nearby area and are quiet during installation. They can thus be used close to existing structures and congested areas. Since they are also cast-in-situ, complex formed piles can be shaped, included that an under-ream can be formed to enhance base capacity (Craig & Knappet, 2012).

In non-displacement piles lateral stresses are reduced during excavation and only partly reinstated by concreting, which can eliminate problems that may arise from soil displacement (Fleming et al., 2009). However, a problem with non-displacement piles is that spoil will be produced and can become costly to remove, especially if it is contaminated. For some soils, for example stiff clays, forming piles with the non-displacement method is particularly beneficial, since the borehole walls do not require support, except close to the ground surface. Depending on the soil and the pile diameter the non-displacement piles can be be divided into two categories, bored cast-in-place piles and continuous flight auger (CFA) piles.

Bored cast-in-place piles are piles where the installation method depends on the diameter of the pile (Fleming et al., 2009). The diameter is referred to as small-diameter when less than

600 mm and as large-diameter when between 600 mm and up to 2 100 mm. Smaller-diameter piles were in the past usually installed with percussion methods but today CFA rigs are more common to use. The larger-diameters are generally bored with rotary or sometimes percussive methods.

A tripod rig with a clay cutter is used when installing percussion bored cast-in-place piles with smaller diameters (Fleming et al., 2009). The winch for raising the clay cutter and spoil can be driven by a diesel or a compressed air motor. The hole is advanced by repeatedly dropping the clay cutter, that consist of an open cylinder with a hardened cutting edge, in the soil. Clay is then either extruded past the cutting rig or passed into the cylindrical cutter and shaken out at the surface. The tripod rigs are light, easily transported and minimal soil disturbance occurs during boring. To install a pile with a larger diameter the difference is that a semi-rotary down-hole percussive hammer is often used. For those rigs, larger quantities of compressed air is required and larger sites for those are therefore also needed. On the other hand, the set-up is often adaptable in its arrangements.

The majority of piles with larger diameters are bored using rotary methods (Fleming et al., 2009). For rotary methods the auger rig is usually crawler mounted and the auger is driven from the ring gear and is suspended from the crane by a winch rope. The auger is penetrating the ground by a screw action and raised when loaded with spoil. The spoil is then removed by spinning off, which is illustrated in step one and two in Figure 10. This process is repeated until the required depth is reached. Step three in Figure 10 illustrates a temporary casing getting lowered into the bore hole. This becomes necessary for the upper portion of the pile bore if the soil is loose or weak. When the bore hole is completed the reinforcement is placed, illustrated in Figure 10 in step four and then the concreting can start, in step five. The concreting can be done with several methods depending on soil and hydrogeology. Regardless of method, the temporary casing is withdrawn during the concreting and is illustrated as step six in Figure 10, while step seven illustrates the finished pile.

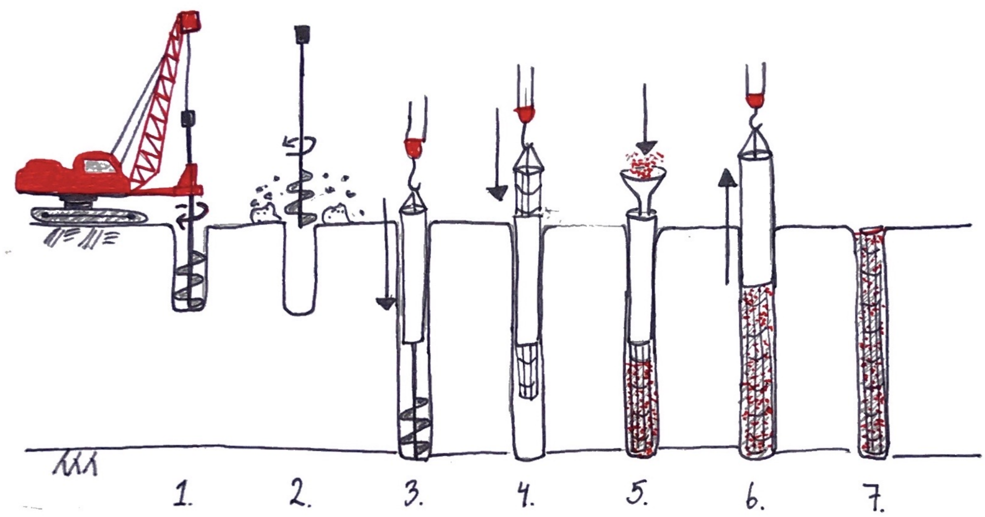


Figure 10: Piling installation process with the rotary method.

This method can bore diameters of at least 3 000 mm and the depth can vary from around 25 m to as much as 60 m with the larger crane-based auger rigs (Fleming et al., 2009). Typical design loads are from 1 000 kN to 20 000 kN in suitable ground conditions.

Continuous flight auger (CFA) piles are available in sizes up to 1 200 mm but the most common are 300-750 mm (Fleming et al., 2009). The CFA piles offer considerable environmental advantages during construction since the vibrations are minimal and noise outputs are low and the method is suitable for sand, gravels and clays. The auger is full length and has a hollow stem. The base machine can be a crane or purpose-built crawler unit and the auger is top driven. The piles are installed by rotating the auger into the ground to the required depth, up to approximately 30 m (Fleming et al., 2009). This is illustrated in Figure 11 step one. In the second step concrete is injected and the auger stem is withdrawn. In this process spoil is removed as well. When the grouting of the pile is completed the reinforcement cage is lowered, which is illustrated in step three. Step four illustrates the finished pile installed with the CFA-method. Typical CFA-pile loads are from 350 kN for a pile diameter of 300 mm to 1000-2 500 kN for a pile diameter of 750 mm.

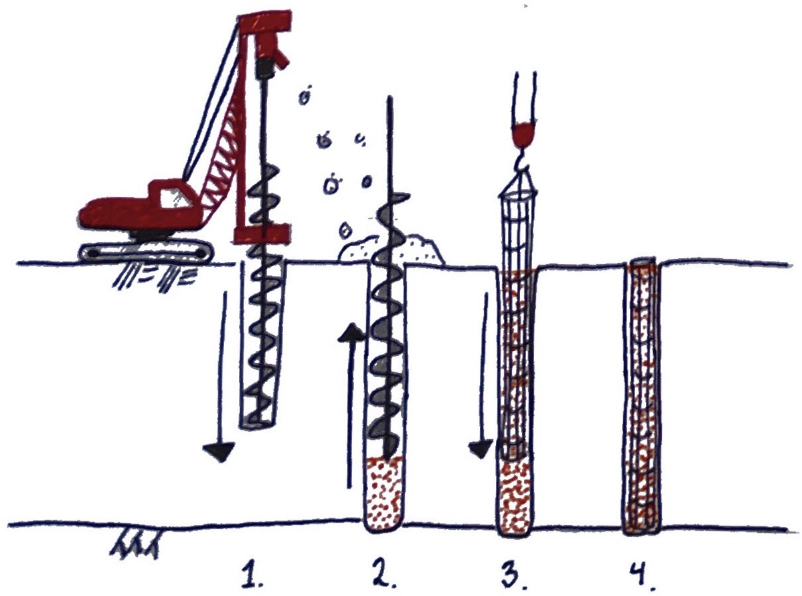


Figure 11: Installation process of a CFA-pile.

2.2.3 Design Methods

The design method for piles is based on three concepts and their relations to each other (Alén, 2009). Those are actions, action effects and resistance. The actions, more commonly known as loads, are the applied forces to the foundation and need to be known before calculations can be performed. Examples of loads are permanent loads such as self weight and variable loads such as wind. The action effects are the effects that occur in the structure, the internal forces such as axial stresses and bending moments of pile elements. The overall design criteria for the geotechnical structure is that the action effects must be less or equal to the resistance. The concept resistance can be related to a number of different failure modes like the structural capacity of the pile or the geotechnical bearing capacity of the pile.

Figure 12 illustrates how two behaviours govern the capacity of a pile depending on if the pile is end-bearing or floating. The end bearing resistance (Q_s) is a function of the nominal compressive strength of the soil at the toe at ground failure and the area of the pile section at the toe (Alén, 2009). The shaft resistance (Q_m) depends on how the installation of a pile is performed and what type of soil the pile is surrounded by (Craig & Knappet, 2012). There are two methods on how to calculate the shaft resistance, the alpha-method and the beta-method. The alpha-method consists of an adhesion factor with a value between 0 and 1, which is a function both of the surface condition along the pile and the method of installation. The beta-method uses a beta-factor that is a function of both horizontal stress and the frictional capacity along the pile (Alén, 2009). In general the two behaviours are combined and the pile resistance or capacity (Q) is the sum of the end bearing resistance and the shaft bearing resistance (Alén, 2009). This means that the actions on the structure governs the design of the piles.

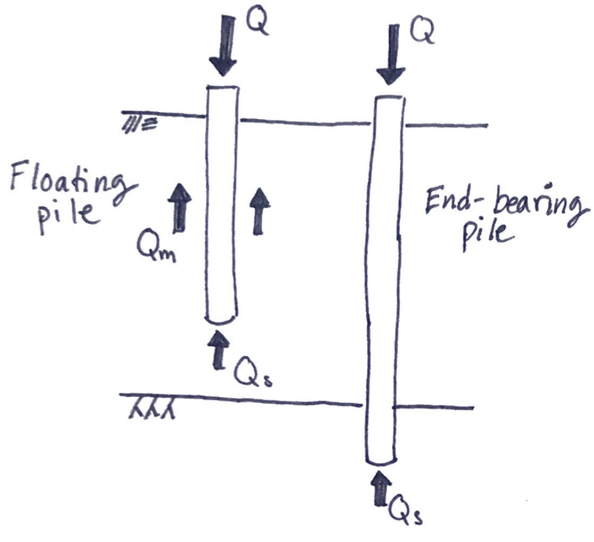


Figure 12: Floating pile and end-bearing pile.

2.3 Soil Conditions and Soil Mechanics

There are different types of soil that have their own properties and therefore affects the foundation differently. The hydrogeology also have a large impact on the foundation and it is hence important to perform soil investigations to get a better understanding of the site.

2.3.1 Soil Types

Non-cohesive soil is a type of soil that exist underneath and/or above the clay in Gothenburg, depending on if the first clay layer is underneath water or not (Statens geotekniska institut, 2019). The water content determines the shear strength of a non-cohseive soil (Sällfors, 2013). Usually, if non-cohesive soil occurs above the ground water it has a high shear strength, the same can not be said about the non-cohesive soil that occurs just above the rock bottom. It consist of sand or gravel and to decide the shear strength, the friction angle needs to be known. The friction angle is determined by piling up the soil and measuring the angle of the cone that forms. In cohesive soils, such as clay, it is not only friction forces that acts between the soil particles but cohesion forces as well.

2.3.2 Hydrogeology

The ground water level has a large impact on the effective stress since water has the ability to reduce stress due to pore pressure (Bondelind, M and Häggström, S, 2018). Pore pressure means that the free space between particles in the soil is filled with water and increases with depth by the bearing capacity of the water of 10 N/m^3.

If there is a layer of clay or other materials with low hydraulic conductivity, it may divide the stratigraphy and create two aquifers. One of the two aquifers will be an open aquifer at the top, which depends on precipitation and diffusion. The other one is called a closed aquifer and occurs in the non-cohesive soil between the rock bottom and clay layer, reducing the shear strength, which that part of the layer can resist.

The Gothenburg clay is a fine grain soil with high water content (Geological Survey of Sweden, 2015). It has a very low hydraulic conductivity. The hydraulic conductivity is defined as how fast water can move through the soil (Espeby & Gustafsson, 1998). Coarser soils has a higher conductivity. In Table 1, approximate values of hydraulic conductivity are presented.

Table 1: Hydraulic conductivity.

Material	**Hydraulic conductivity [m/s]**
Coarse silt	$10^{-5} - 10^{-7}$
Moraine	$10^{-6} - 10^{-9}$
Muddy moraine	$10^{-8} - 10^{-11}$
Clay	$< 10^{-9}$

Even if clay has a conductivity of at least 10^{-9} m/s or less, aggregation and cracks in the soil creates pathways for water to run though (Espeby & Gustafsson, 1998). In those parts, there are less tensions since the water works as a lubricant for the friction between the particles.

2.3.3 Soil Investigations

When determining the soil layers, there is a need for drilling probe holes (Sällfors, 2013). Those holes are used to evaluate the layers from ground to rock bottom. Similar probe holes can also provide data of the undrained shear strength, using different tests such as a vane test, cone penetration test (CPT) sounding, direct shear attempts and CRS, the constant rate of stress. These are then combined and weighted towards the direct shear attempts for a correct value on the undrained shear strength.

Even if the test values are acceptable when doing the investigations, the aim with the investigations is to locate hard strata that could bear the structure (Fleming et al., 2009). The hard strata could, nevertheless, be false information since it could also be a large boulder, which is tough and expensive to drill through. Data gathered to evaluate the soil and quantities of boulders is important for further construction. Vice versa if the soil is to loose or there are a lot of horizontal cracks in it, one may need to use bentonite or similar fluid to stabilize the casing for the pile.

3 The Gothenburg Cable Car

A cable car is a possible solution for the rapidly expanding city of Gothenburg and its need for a more developed traffic system. Since Gothenburg is located on deep deposits of soft clay, the stabilization of tall infrastructure, such as the cable car towers, is a geotechnical challenge. The most critical tower spots are planned to be located at Järntorget and Lindholmen, which is the reason that foundations for these towers are the focus of this Thesis. To be able to investigate the possibility of different foundation methods while considering different sustainable aspects, there is a need to gather information about both sustainability as well as specific soil conditions and loads affecting the towers. However, to get a deeper understanding of the specifics, it can be educative to study other similar projects first.

3.1 Similar Projects

Since the aim of this Thesis is to choose a foundation method, it can be a useful input to study similar projects to see which methods has been successfully used in similar conditions. Since there are no other cable cars in Gothenburg, other infrastructure and building projects can be studied instead.

3.1.1 The Emirates Airline London Cable Car

The Emirates Airline is Britain's first urban cable car that crosses the Thames river (Bachy Soletanche, 2020). Figure 13 shows a picture of the cable car. It takes passengers from the O2 Arena across the river to the Exhibition Centre London and was built to be in use during the 2012 London Olympics. It crosses the river every 30 seconds and carries up to 5 000 passengers an hour.

Figure 13: Emirates Airline Cable Car, London (Cooper, 2012). CC BY-SA.

Civil engineers have been working with and on the well known London clay for many years (Standing, 2018). The layer of clay is around 100 m thick and can be divided into different layers of clay with some variations of characteristics. In general, the clay as a whole is often described as stiff and becomes very stiff with increasing depth. The clay is convenient for deep excavations since it is able to stand unsupported for periods in which temporary or permanent structures can be built.

The foundation of the Emirates Airline cable car was made by Bachy Soletanche, in joint venture with Red7Marine and was successfully completed within a fixed budget and the short duration of six months (Bachy Soletanche, 2020). Bachy Soletanche installed large diameter piles with the method of bored rotary piling. The south tower, the north compression tower and the north station are built in water and piled from barges provided by Red7Marine. The north station and compression tower consist of 31 no. 750 mm diameters piles that are up to 45 m long with 17 m to 18 m long permanent casings. Those piles were constructed from a 42 m by 17 m spud leg barge with a piling rig. All of the south constructions are built close to water. The south station and compression tower consist of 43 no. 750 mm diameter piles that are up to 40 m long and were constructed with a rotary piling rig. The south main tower required 4 no. 1 800 mm diameters piles that are up to 51 m long with 24 m long permanent casings and were constructed with a rig from a 200 t jack-up barge.

3.1.2 Karlatornet in Gothenburg

Serneke, a Swedish construction and development company, is building a 245 m tall building, called Karlatornet, in Gothenburg (Serneke, n.d.-b). This tall building, visualized in Figure 14, is built on a 70 m thick layer of clay and will contain 593 apartments and a hotel.

Figure 14: Illustration of Karlatornet, Gothenburg (Serneke, n.d.-a). CC BY-NC.

Because of the tall and heavy building combined with the thick layer of clay, the building had to be piled and anchored into the bedrock and Aarsleff Grundläggning AB, a ground engineering company and subcontractors to Serneke, did the piling (Serneke, n.d.-b). The end-bearing piles were installed with the non-displacement method and 58 bored cast-in-place piles with a diameter of 2 000 mm were bored into the ground. Each pile is supposed to carry a load of 44 130 kN. Generally the drilling was through 40-50 m of clay, followed by 6-10 meters of cohesive soil and anchored 4-7 m into the bedrock. All the spoil was removed, a reinforcement cage submerged and the hole was then filled with about 200 m^3 of concrete. When the piles were installed, 3 500 m^3 of concrete became a 3.75 m thick layer as a footing. The machine that installed the piles is German and weighs 250 t.

Since the piles were installed with the non-displacement method, a large amounts of clay had to be taken care of. At this project all the spoil was put in a sedimentation basin at the site to let the water drain. The water then went through a treatment plant before it was released into to the Göta River. The water also went through controls to make sure it was not contaminated before all of the clay got deposited.

3.1.3 Offshore Wind Turbines with Monopile Foundations

Offshore wind turbines are one of the most widely used methods to harvest energy from renewable sources (Thompson, Byrne, & Houlsby, 2003). By locating the wind turbines offshore, turbines with greater capacity can be installed and there is less conflict regarding aesthetics compared to onshore wind turbines. One type of foundation normally used for offshore wind turbines, since it has been proven economical at smaller water depths, is the monopile (Bisoi & Haldar, 2014). A photograph of monopiles is shown in Figure 15. A monopile is made out of steel, normally with an outer diameter between 3 m to 6 m and a length varying from 22 m to 40 m. The water depth is usually between 10 m to 25 m when monopiles are used as a foundation for offshore wind turbines. Vattenfall, the largest producer of fossil free electricity in Sweden, is constructing Kriegers Flak Offshore Wind Farm, an offshore wind farm in the North Sea, outside the Danish coast (Nielsen, 2019). The turbines will be founded on a monopile foundation that can weigh up to 800 t.

Figure 15: Monopile foundations (Wirrwa, 2015).CC BY-NC-ND

3.2 Sustainable Development

It is common to divide sustainable development into three divisions; ecological, social and economical (Nationalencyklopedin, 2020). The importance of each division is a subject of discussion and therefore sustainable development should not be seen as the answer on how to protect our planet, but more as a process where different perspectives meet. The cable car project in Gothenburg will contribute to an extensive infrastructure transformation, not only for people who will use it as transportation, but also for those who live in the city. Therefore, there are several social and ethical aspects to consider. Furthermore, if Gothenburg wants to be in the forefront, infrastructure projects need to be built from a sustainable perspective.

3.2.1 Social and Ethical Aspects

The Gothenburg cable car, as a whole project, entails several social and ethical aspects to consider. The cable car will become a new landmark for the city and will be visible from many spots, which leads to a changed city skyline for Gothenburg (Tyréns, 2018a). For example, when looking from the south and in the direction of "Slottsskogen", the tower at Lindholmen will lead to a changed experience since the tower will be in contrast to the mountain silhouette and a characteristic neighbourhood of wooden houses.

In the zoning plan other ethical problems with the cable car has been discussed (Tyréns, 2018b). Amongst others, problems as insight in buildings from the gondolas, noise from the cable car system, disturbing birds and affects on the maritime transport can arise. Proposed solutions has also been discussed. Insight in buildings can for example be avoided with reflectors or similar solutions. The noise levels from the system has to be further investigated but could in first hand be reduced by choosing a quieter cable or in second hand by improvements at the facades of the buildings. The negative effects on birds caused by the cable car has been evaluated to be limited, such that no further actions have to be taken. To avoid disturbing the maritime transport, a minimum height over the Göta River has been set for the cable car.

The cable car will be a complement to the current public transport and it will be accessible for everyone and, therefore, make it easier for everyone to travel across the Göta River (Tyréns, 2018b). This will also lead to integration between the districts on each side of the river. A problem that possibly could occur is if people become insecure around the stations, towers and in the gondolas. This could be handled by design and configuration, for example with open areas and manned stations.

The zoning plan does not consider any social and ethical aspects either for the foundation or the construction of the foundation. However, as mentioned in Section 2.2, the installation of piles can cause harmful and disturbing noises for humans, which should be considered a social aspect.

3.2.2 Environmental Aspects

An environmental aspect that affects the process of building the foundation of the tower is the risk of contaminated sediments at the bottom of the harbor basin at Lindholmen (Ramböll, 2017). Measurements in the Göta River shows that there are high levels of toxic substances such as tributyltenn, TBT, in sediments, which is toxic to both aquatic organisms and humans. This could be a problem for the construction of the tower and its foundation since piling in the soil could cause the sediment to spread. In the area at Lindholmen where the tower is to be placed, no sediment investigation has been performed. This means that if the cable car is to be built, it will be necessary to conduct such a study to ensure that no maximum limits are exceeded. Decontamination may be required if the study indicates that the area has polluted sediments and this could in turn become costly for the project.

There are several other potential environmental impacts when piling (Westcott, F.J and Smith, J.W.N and Lean, C.M.B, 2003). There are, for instance, many ways that piling can effect the hydrogeology. This could be by creating flow paths between the surface into an underlying confined aquifer or contrariwise, which could lead contaminated water into an aquifer or contamination from the ground into surface water. As earlier mentioned, TBT is an example of a contamination that could contiminate the underlying aquifers below the towers at Lindholmen and Järntorget. It could lead to grave influences on the ecosystems in the area. It is also relevant to consider the fact that contaminated materials can be driven from the surface to a confined aquifer when installing piles.

Another environmental aspect to consider is that 20% of global greenhouse gas emissions are in some way connected to the construction industry (Kirsch, K and Bell, A and Russ, J.C, 2012). The chosen methods and materials used for a foundation are two factors that contributes to the emission of greenhouse gases from the construction industry. The raw material used in foundations has the largest impact on the total emissions caused by the production of a foundation and during its lifetime. The second largest source of greenhouse gas emissions is the fuel consumption by the machinery during installation of the foundation. The displacement pile method can lead to large environmental impact since the machines that drive the piles in place uses more power compared to the machines that bores the non-displacement piles, and therefore produces larger amounts of emissions (Fleming et al., 2009). Even if the machines used for displacement piles produces more emissions during installation the whole process for displacement piling can still be more environmentally friendly compared to non-displacement piling, since no transport for residual soil is needed.

Regarding the choice of material, concrete has a higher carbon footprint than stones, timber and mortar (Kirsch, K and Bell, A and Russ, J.C, 2012). Both displacement and non-displacement pile methods with concrete has a higher total carbon footprint than if other materials, as those earlier mentioned, are used. The most environmentally friendly method, estimated in carbon footprint, is vibro stone columns (VSCs) with gravel, since the raw materials in VSCs are rock and gravel. Both the method and the machinery used to compose VSCs are very effective as well. The alternative that gives the largest carbon footprint is bored piles, due to the large amount of cement used in the piles.

In Sweden, concrete piles are the standard pile type and represent 75-80% of all piles in the country (Holm & Olsson, 1993). This demand for concrete piles has led to the opening of several concrete pile factories around the country, especially around the larger cities. The proximity to factories makes piles cheaper and less straining on the environment. The principle of producing the concrete for the piles as locally as possible also goes for the footing. Timber piles is also an option since Sweden has a large timber industry spread throughout the country, which offers short transportation distances.

Caution needs to be taken during the construction of the foundation due to the risk of harming adjacent buildings, since piling increases the risk of ground movement and damage to adjacent structures (Göteborgs Stad Fastighetskontoret, 2017). The installation of foundations can also cause harm to both constructions and people due to vibrations. These issues could in turn lead to surpassing the SLS requirements for nearby constructions. In a worst case scenario, the ULS requirements could be exceeded and resulting in total collapse of constructions or other types of structural failure. To prevent this from happening, analyzes needs to be performed and appropriate measures have to be taken to stabilize the ground in the area. This means that one aspect to be considered is how the installation of the foundations can be installed without damaging nearby structures.

3.3 Loads

When constructing a building or other infrastructure projects, there is a need to consider the different loads that will be applied to the structure (Craig & Knappet, 2012). There will be both vertical and horizontal loads affecting the towers of the cable car in Gothenburg (Sweco, n.d.). The horizontal loads will also result in an overturning moment that needs to be considered in the design. The vertical loads on the towers will mostly be a result from the self weight of the towers and footings, while the horizontal load on the towers consists of loads from the cable, the gondolas and wind.

Sweco, a multinational consulting company, has designed a hexagonal footing for tower B to stand upon, which is shown in Figure 16 (Sweco, n.d.). Point A-C represents where the load gets distributed from the tower construction. As shown in the same figure, the y arrow points in the north direction along the cable and the x arrow points in the eastern direction. Z is not shown in the figure but represents the vertical direction of the footing.

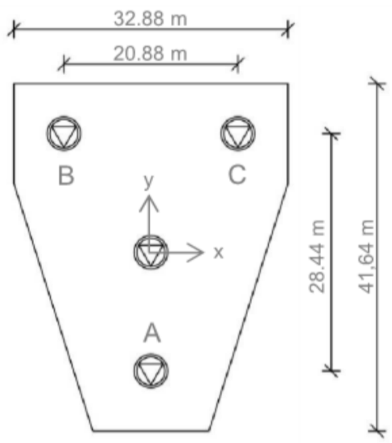


Figure 16: The geometry with Sweco's assumptions. (Sweco, n.d.)

Assumptions and calculations on loads has been done by Sweco and are presented in Table 2 (Sweco, n.d.).

Table 2: Assumptions for vertical loads and overturning moment (Sweco, n.d.).

	Foot	**Pz [kN]**	**Mzz [kNm]**
Dead load	A	19 200	3 500
Dead load	B	7 900	-800
Dead load	C	7 100	1 800
Total Dead load		34 200	
Wind and ice load			6 600

Unlike Sweco that only designed a footing for tower B, NCC, one of the leading construction and property development companies, has calculated approximate volumes of concrete of the footings for both towers (NCC, 2019). The concrete volumes of the footings are presented in Table 3.

Table 3: Volume of concrete in the footing for tower A and B (NCC, 2019).

Footing	**Amount of concrete**
Tower A	1760 m^3
Tower B	2970 m^3

3.4 Soil Properties

There is a the need to determine the properties of the soil and documents from NCC has been used to present soil property values. Test values from NCC shows that tower A has more than 100 m to rock bottom (Pedersen, 2019a). With more coarse clay from 25 m. The stratigraphy from tower A is presented in Table 4 and Appendix A.

Table 4: Stratigraphy for tower A.

Level	**Material**	**Unit Weight [kN/m^3]**	**Undrained shear strength [kPa]**	**Friction angle** [θ]
0	Non-cohesive Soil	18 (table value)	21	
-8	Fine Clay	15	21 + 1.65 [kPa/m]	30
-25	Coarse Clay	15.3	21 + 1.5 [kPa/m]	30
-100+	Non-cohesive Soil	18 (table value)		41

For tower B there are quite different properties since it is located under water, which entails no dry crust, and the first layer is a mix of mud and clay (Pedersen, 2019c). Under the foundation there is 70 m to bed rock and sloping towards Hisingen. The stratigraphy from tower B is presented in Table 5 and Appendix B.

Table 5: Stratigraphy for tower B.

Level	**Material**	**Unit Weight [kN/m^3]**	**Undrained shear strength [kPa]**	**Friction angle** [θ]
0	Water	10		
-4	Clay and mud	15	14.5 + 0.8 [kPa/m]	30
-9	Clay	15.3	20.5 + 2 [kPa/m]	30
-40	Non-cohesive Soil	18 (table value)		41
-70	Bed rock			

4 Method for Designing the Foundations

The cable car in Gothenburg is planned to be located at Järntorget and Lindholmen on thick deposits of soft clay. To be able to investigate what type of foundation would be the most suitable and sustainable for the cable car towers, theory needed to be gathered. First general theory about foundations was studied. Information about what type of foundations that exist, how they are installed and how they function was conducted. The results from site investigations was utilized to decide the soil characteristics that was used for the design of the foundations. Information about other similar projects was also found and studied. To design the foundations, calculations on geotechnical and structural capacity was performed for concrete piles.

4.1 Geotechnical and Structural Capacity

To calculate the bearing capacity of the soil around a pile, the end resistance and shaft resistance of the pile needed to be compiled. The total resistance (R_k) was summed in the following equation:

$$R_k = Q_m + Q_s = f_m \cdot A_m + f_s \cdot A_s \tag{1}$$

where:	R_k	Total resistance.
	Q_m	Shaft resistance.
	Q_s	End resistance.
	f_m	The (average) friction strength at the interface of soil and shaft.
	A_m	The total area of the shaft, length of pile times the circumference.
	f_s	The nominal compressive strength of the soil at the toe at ground failure.
	A_s	The area of the pile section at the toe.

To find the ultimate limit state value for resistance a design value (R_d) had to be calculated. This can be done with different methods and is explained with equations for the alpha- and beta-method below.

4.1.1 Alpha-method

The Alpha-method is used when the piles are driven down in a material with low friction, such as clay (Alén, 2009). The shaft resistance (f_m) of the pile is given by the equation:

$$f_m = \alpha \cdot c_u \tag{2}$$

where:	α	Adhesion factor.
	c_u	Undrained shear strength.

The adhesion factor (α) has a value between 0 and 1 and depends on the soil type and the material of the pile. The undrained shear strength (c_u) for the towers are presented in Table 4 and 5.

The characteristic bearing capacity (R_k) is calculated with the equation below:

$$R_k = \alpha \cdot \overline{c}_u \cdot A_m \tag{3}$$

where: $\overline{c}_u$ The average undrained shear strength for the given pile length.

The design value for the bearing capacity (R_d) for cohesion piles is calculated with the following equation:

$$R_d = \frac{1}{\gamma_{Rd}} \frac{R_k}{\gamma_m \cdot \gamma_n} \tag{4}$$

where: γ_{Rd} Model factor for alpha method.
γ_m Resistance factor.
γ_n Partial factor depending on safety class.

4.1.2 Beta-method

The beta-method is used for friction piles and based on assumptions of the values for the friction factor (β) and the bearing capacity factor (N_q) (Alén, 2009). The resistance in the shaft (f_m) can be expressed by the β-value times the average vertical effective stress along the shaft ($\overline{\sigma}'_v$):

$$f_m = \beta \cdot \overline{\sigma}'_v \tag{5}$$

where: β Friction factor.
σ'_v Vertical effective stress.

The β-factor is a function of both horizontal stress and the frictional capacity along the pile. The end resistance (f_S) is expressed by choosing a value on N_q times the effective vertical stress in the soil (σ'_v):

$$f_s = N_q \cdot \sigma'_v \tag{6}$$

where: N_q Bearing capacity factor.

To calculate the characteristic resistance equation 1 is used to sum up the shaft bearing capacity and end bearing capacity. To calculate the design value for the resistance (R_d) for friction piles the following equation is used:

$$R_d = \frac{1}{\gamma_{Rd}} \left(\frac{f_m \cdot A_m}{\gamma_{mm} \cdot \gamma_n} \cdot \frac{f_s \cdot A_s}{\gamma_{ms} \cdot \gamma_n} \right) \tag{7}$$

where: γ_{Rd} Model factor for Beta method.
γ_{mm} Shaft resistance factor.
γ_n Factors for different safety classes.
γ_{ms} Toe resistance factor.

4.1.3 Number of Piles

By dividing the total load (Q_d) by the capacity of what a single pile can handle (R_d) the number of piles (n) needed to handle the total load was obtained.

$$n = \frac{Q_d}{R_d} \tag{8}$$

When the number of piles where known the pile volume could be calculated and hence the concrete volume needed was obtained. The volume was calculated by multiplying the depth of the piles (z), the base area of one pile (A_{pile}) and the numbers of piles (n):

$$V = z \cdot A_{pile} \cdot n \tag{9}$$

4.1.4 Pile Compressive Strength

To make sure the piles can withstand the force from the structure the compressive strength of the piles had to be evaluated. First, a concrete class needed to be assumed and in this case C40/50 was chosen, which is considered normal concrete, as opposed to high performing concrete (Al-Emrani, Engström, Johansson, & Johansson, 2013). The designed compressive strength (f_{cd}) was calculated with the following equation:

$$f_{cd} = \alpha_{cc} \cdot \frac{f_{ck}}{\gamma_c} \tag{10}$$

where: α_{cc} Strength reduction factor considering prolonged loads.
γ_c Partial coefficient for concrete.
f_{ck} Design compressive strength.

An approximate compressive strength (Q_{cs}) was calculated and expressed as:

$$Q_{cs} = f_{cd} \cdot A_s \tag{11}$$

where: Q_{cs} Structural capacity of a pile.

4.1.5 Overturning Moment

An overturning moment can affect the foundation as is illustrated in Figure 17. The dashed line represents the centre of the footing and e is the distance to the piles subjected to compression- and tension force from the applied overturning moment. The overturning moment occurs where two equal forces are opposite each other with different lengths to the center, also know as force couples. The Tension and compression related from the overturning moment is calculated with the values presented in Table 2 for tower B. The same values has been assumed for tower A as for tower B. The total moment acting on the foundation is calculated by adding the loads from wind and ice to the total dead load, which results in the overturning moment for a worst case scenario.

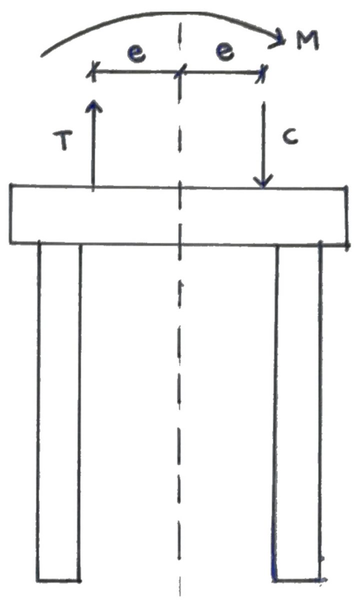


Figure 17: Conceptual model for calculating the resulting tension force, T, and compression force, C, in the foundations arising from the applied overturning moment, M.

Equation (12) is used to calculate the tension force for different eccentricities (e). The compression force, C, has the same value as the value for tension force, T, but in the opposite direction.

$$T = \frac{M_{tot}}{2 \cdot e} \tag{12}$$

where: T Tension
M_{tot} Total moment
e Distance from center

4.2 Design Values, Loads and Geometry

The geotechnical and structural capacity of the piles was calculated using equation 1 to 12 with design parameters and safety factors according to Table 6.

Table 6: Design values used in calculations.

Factor	**Design Value**	**Comment**
Alpha-method		
α	0.7	(Alén, 2009)
γ_{Rd}	1.7	(Alén, 2009)
γ_m	1.6	(Alén, 2009)
γ_n	1	Safety class SKF 1 (Alén, 2009)
Beta-method		
β	0.17	From figure of friction factor β (Alén, 2009)
N_q	10	From figure of bearing capacity factor (Alén, 2009)
γ_{Rd}	1.6	(Alén, 2009)
γ_{mm}	1.45	(Alén, 2009)
γ_n	1	Safety class SKF 1 (Alén, 2009)
γ_{ms}	1.8	(Alén, 2009)
Pile compressive strength		
f_{ck}	40 MN/m^2	Concrete class 40/50 (Al-Emrani et al., 2013)
α_{cc}	1	(Al-Emrani et al., 2013)
γ_c	1.5	(Al-Emrani et al., 2013)

To calculate the loads from the footings, some changes were made compared to the calculations done by Sweco and NCC. Instead of using Sweco's model with the hexagonal footing, shown in Figure 16, a square footing was assumed for the calculations. The geometry was set to contain approximately the same amount of concrete as presented in Table 3. The geometry of the footing together with the unit weight of the concrete used for the calculations are presented in Table 7. By adding the load from the footing with the load from the superstructure, from Table 2, the total load acting on the foundation was calculated and is presented in Table 7.

Table 7: Geometry of footing and loads.

	Tower A	**Tower B**
Geometry of footing		
Width	25 m	28 m
Length	25 m	35 m
Height	3 m	3 m
Volume	1875 m^3	2940 m^3
Density of concrete	25 kN/m^3	25 kN/m^3
Loads		
Dead load - footing	46875 kN	73500 kN
Dead load - construction	34200 kN	34200 kN
Total load	81075 kN	107700 kN

For all the performed calculations, four square-sectioned piles and one circular-sectioned pile has been tested. The width and diameters of the tested piles are presented in Table 8.

Table 8: Pile dimensions that have been tested.

Pile dimension [mm]
275
300
350
750
750 (Circular)

5 Results

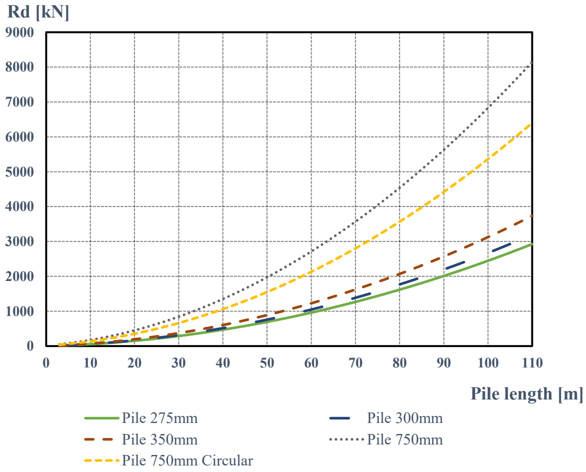
As described in Section 2.1, shallow foundations need to have large surface areas if the structure itself is tall and heavy, which matches the description of the towers at Järntorget and Lindholmen. The fact that the foundations are restricted to a small surface area makes the task even more difficult. With this information it became clear that a shallow foundation is not a feasible option for the foundations of the towers. Therefore, a deep foundation will be used.

Section 2.2 results in a list of different piling methods combined with common pile lengths, diameters and single pile capacity. The list also includes what type of piles that are used in similar projects. The list is presented as Table 9. The conclusion of the table is that it is possible and common with concrete piles with a length between 20 m and 80 m. The diameters varies from around 300 mm up to 2 000 mm and a pile group can consist of as little as 4 piles but more commonly consists of between 30 to 60 piles. The structural capacity of a single pile can vary from 700 kN to 44 000 kN.

Table 9: List of different piling methods as a result of the theory section.

	Pile length [m]	**Diameter [mm]**	**Structural capacity for a single pile [kN]**	**Number of piles**
Deep foundations				
Displacement piles:				
Pre-cast non-jointed concrete piles		<600		
Totally pre-formed, jointed concrete piles	30 (100)		700-2 500	
Hollow tubular-section pre-cast concrete piles	80	600-1 500		
Driven screw cast-in-place concrete pile	22			
Non-displacement piles:				
Bored cast-in-place concrete piles, percussion method		<600		
Bored cast-in-place concrete pile, rotary method	25-60	600-3 000	1 000-20 000	
CFA	30	300-750 (<1 200)	350 (300 mm) 1 000-2 500 (750 mm)	
Emirates Airline London Cable Car (concrete piles installed with rotary method)				
North station and compression tower	45	750		31
South station and compression tower	40	750		43
South main tower	51	1 800		4
Karlatornet in Gothenburg (bored cast-in-place concrete pile, anchored into rock)	65	2 000	44 130	58
Offshore wind turbines with monopile foundations	22-40	3 000-6 000		1

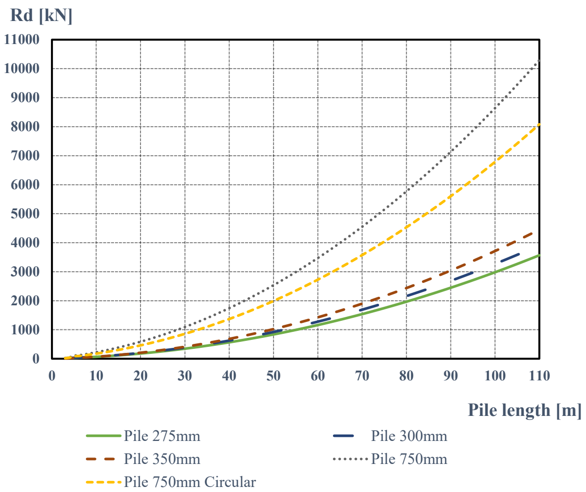
The results for geotechnical capacity of a single pile calculated for square-sectioned piles with widths of 275 mm, 300 mm, 350 mm, 750 mm and a circular pile with a diameter of 750 mm with the alpha-method for both towers, is shown in Figure 18. The designed resistance (R_d) is plotted on the y-axis and the pile length on the x-axis. Both the square-sectioned pile with the width 750 mm and the circular pile with the diameter 750 mm have much larger geotechnical capacities than the smaller piles. The two graphs have different pile lengths on the x-axis due to ground conditions of each tower.



(a) Tower A (b) Tower B

Figure 18: Single pile geotechnical capacity with alpha-method.

Figure 19 shows the geotechnical capacity of a single pile, as in Figure 18, but calculated with the beta-method instead of the alpha-method.



(a) Tower A (b) Tower B

Figure 19: Single pile geotechnical capacity with beta-method.

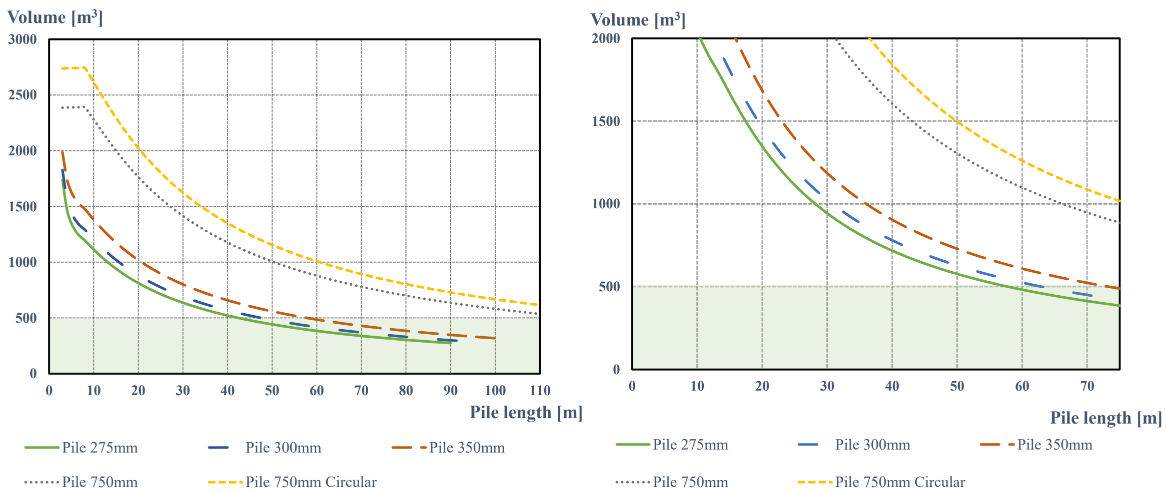
When comparing the alpha-method in Figure 18 with beta-method in Figure 19 there is a larger increase in geotechnical capacity as the piles get longer with the beta-method. The beta-method is also used for several types of soil while the alpha-method is more specified for clay. Therefore, further results are only evaluated with the alpha-method for a worst case scenario.

Table 10 presents the compressive strength for each pile with the concrete class C40/50. The maximum strength is the same regardless of pile length.

Table 10: Compressive strength.

Pile width [mm]	**Compressive strength [kN]**
275	2 017
300	2 400
350	3 267
750	15 000
750 (Circular)	11 794

In Figure 20, the volume of concrete used in a pile group for each pile dimension is plotted on the y-axis with the pile length on the x-axis. Setting a boundary at 500 m^3 concrete volume, marked with a green area, is to minimize the usage of concrete. In Figure 20a, each pile ends at the pile length where the geotechnical capacity of a single pile is lower than the highest compressive strength for that dimension. This is based on Equation (4) where the lower levels in the soil increases the value of R_d, due to the higher c_u-value as the piles get longer. By combining Equation (4), (8) and (9) the value of R_d can be compared with Table 10 and the pile length can be calculated with the equation, resulting in a maximum depth for the pile. For tower B the volume scale is restricted to 2 000 m^3 to make it easier to see where the piles goes below 500 m^3 of concrete. All pile dimensions have a sufficient compressive strength for the pile lengths at tower B, seen in Figure 20b.

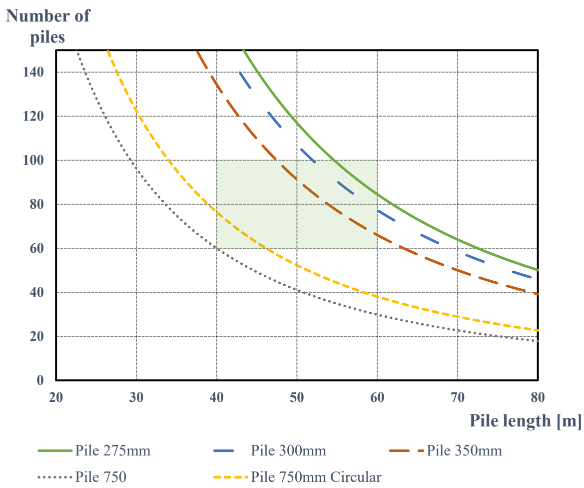


(a) Tower A (b) Tower B

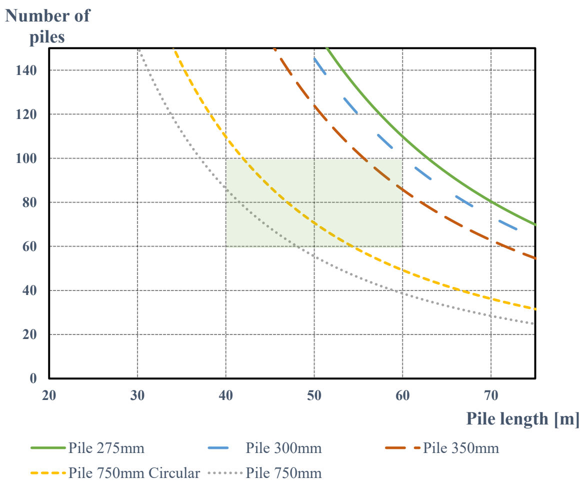
Figure 20: Total concrete volume for pile group versus pile length.

To show the results of how many piles is needed and how long they should be, one must first see the boundary set in Figure 20, narrowing down the results to something reasonable. The number of piles is plotted on the y-axis and the pile length on the x-axis, shown in Figure

21 for both towers. The green area represents the chosen value for the pile length and how many piles are needed. The area is based on Figure 20 and Table 9. At both towers there are significantly fewer piles for the 750 mm dimensions but since they do not meet the criteria in Figure 20, they are neglected but shown for comparison. At tower A, all other pile dimension could be used but at tower B all except the 275 mm pile meet the criteria.



(a) Tower A



(b) Tower B

Figure 21: Number of piles versus pile length.

The overturning moment on the foundation is resisted by axial loads in the piles. The axial load from the overturning moment is decreasing with the increase in distance from the footing center, see Figure 22. It shows that the further away from the center, the lesser the additional load gets, with the minimum of 444 kN when the piles are placed at the edge of the footing, 12.5 m from the center. The axial load is insignificant compared to the total dead load and there is therefore no need to further consider the effect of the overturning moment on the foundation.

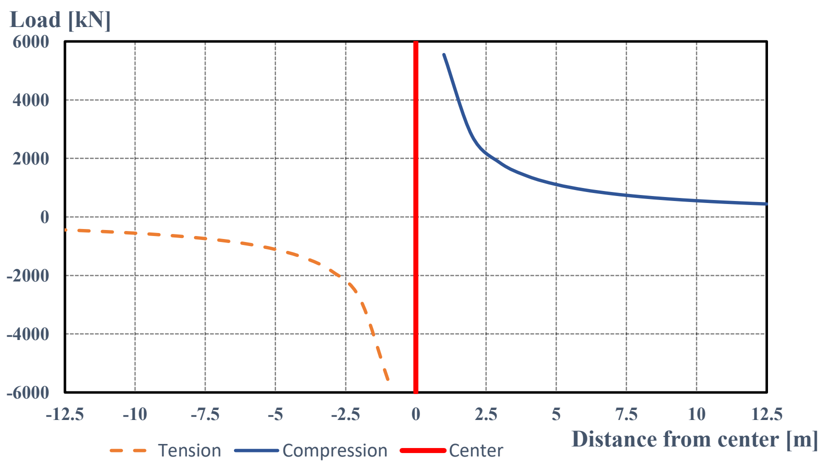


Figure 22: Vertical load due to overturning moment.

5.1 Analysis of the Results

Figure 18 and 19 shows that a wider dimension on piles resists higher loads. This is due to the larger surface area facing soil and creates more friction. It is stated that the volume of concrete in Figure 20 should not be larger then 500 m^3. This limit is based on how the concrete is affecting the environment in a negative manner. Furthermore, the limit separates the piles with the larger dimensions from the ones with smaller dimensions. One could argue that the limit should be higher for tower B due to greater soil depths and loads. The same could be said for Figure 21, where the green zone is the same for both towers. Both of the figures are zoomed in to easier read the values. There is no need to present more than 140 number of piles since a large number of piles leads to an unnecessary use of concrete. For the towers, the pile length limit is from 40 m to 60 m. The lower limit is based on Figure 20 where no pile dimension could be shorter than 40 m and still meet the volume criteria of 500 m^3. For tower B, the maximum limit at 60 m is based on its close vicinity to rock bottom that starts at 70 m and sloping downwards. If the limit was set to longer, there would be no need to use cohesion piles since it would be better to use end-bearing piles. The same can not be stated for tower A since it has more then 100 m down to the bed rock. The limit at 60 m is, however, based on similar projects and specifications for piles with different installation methods.

The overturning moment has an impact on the axial loads. For this project, the axial load had a small influence over the total force from the dead load, even though the worst case scenario with wind and icy weather was applied. The reason for the low impact is that the high dead load and wide footing of concrete counteracts the overturning moment. If the opposite situation was implied, with a low dead load and a narrow footing, the overturning moment would have a large impact on the axial load. In the latter case, a measure would be needed. This could be, adding a row of piles designated to the axial load or sizing for longer piles at the last row on each side. One method that could also be used to counteract the overturning moment is to angle poles out from the last row. However, this method is inferior in urban spaces due to other structures in the vicinity. With the results from Figure 22, 444 kN is distributed over the last row of piles on each side. Such small force could be neglected due to high safety factors used in equation (5).

The pile dimension chosen for Tower A is a square-sectioned pile with a width of 350 mm. It would be possible to choose piles with a width of 275 mm or 300 mm as well and still meet the set criteria. The main reason a 350 mm pile will be used for tower A is that the 350 mm pile is well within the green areas in both Figure 20 and 21, compared to the 275 mm and 300 mm piles. Another reason the 350 mm pile would be a better option is that fewer piles would be needed, compared to the other two, which is preferred when using displacement piles.

The result for tower B is the square-sectioned 350 mm pile. This pile went over the criteria for the concrete volume due to the stratigraphy. After 40 m, there is a layer of non-cohesive soil down to rock bottom. The evaluation of using more concrete for shorter piles and also increasing the amount of piles needed for shorter piles is to choose between environmental- and structural aspects. In the case for tower B, the results displayed is a compromise between those two. To meet the criteria for both the volume and length, a lesser load is needed. This could be achieved with a lower density of the concrete, smaller dimension on the footing or another design of the tower.

The gist of this analysis is that longer piles give lower volumes of concrete and that the larger dimensions piles have, the better they are at withstanding larger forces. Generally, twice the dimension size generate twice the load capacity, but also takes up twice the volume. If the concrete volume could be unconsidered, the larger piles would have the advantage. When comparing 275 mm pile with the 300 mm pile, the differences seems to be insignificant. This is a result of the high load used in this project.

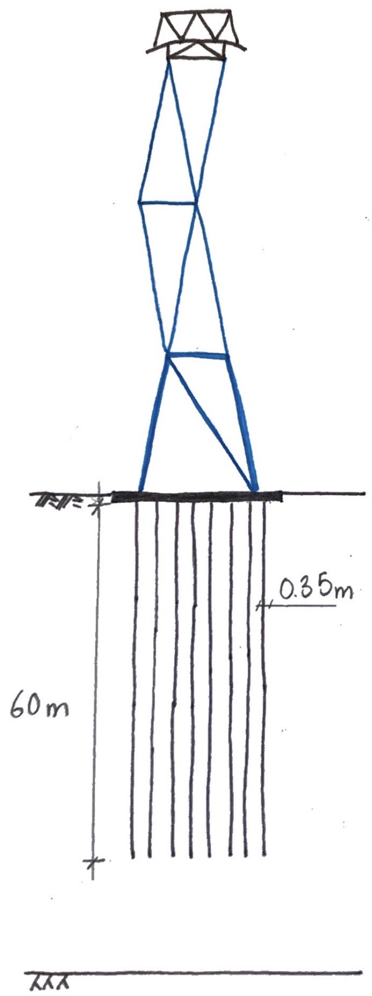
5.2 Final Results

After analysing the results a final proposal for the foundation design is that both towers should be piled with square-sectioned pre-cast concrete piles and installed with the displacement method. Specific result for pile width, pile length, number of piles and concrete volume of the foundation for each tower is based on Figure 20 and 21 and is presented in Table 11. The total volume of concrete for the foundations is the sum of the volume of the footing and the volume of the piles.

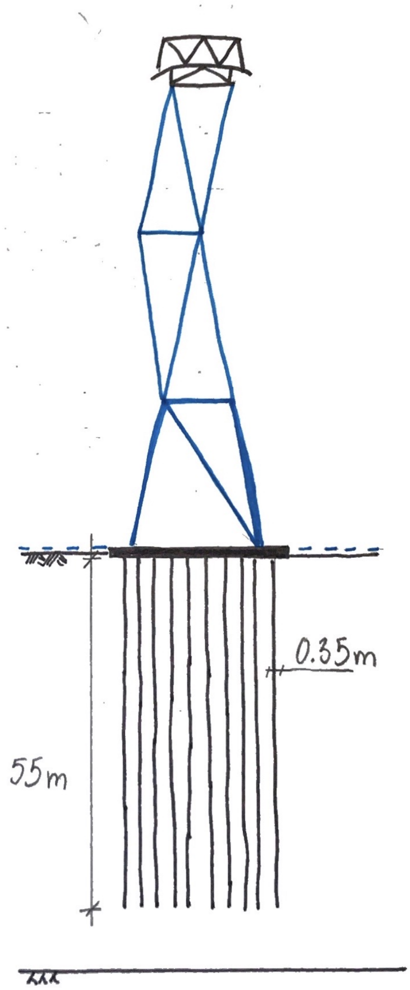
Table 11: Resulting pile dimensions, length, number of piles and volume of concrete.

	Tower A	**Tower B**
Pile width (square) [mm]	350	350
Pile length [m]	60	55
Number of piles	66	100
Volume of concrete for piles [m^3]	485	663
Volume of concrete for footing [m^3]	1 875	2 940
Total volume of concrete for foundation [m^3]	2 360	3 603

The final result of the foundations are illustrated for the towers in Figure 23. Both towers uses the square-sectioned 350 mm pile dimension. Tower A uses 66 piles which adds up to a volume of 485 m^3 concrete for the piles and a total volume of 2 360 m^3 for the foundation. Tower B uses 100 piles which adds up to a volume of 663 m^3 concrete for the piles and a total volume of 3 603 m^3 for the foundation.



(a) Tower A



(b) Tower B

Figure 23: Final result of foundation for the towers.

6 Discussion

To achieve the results, some assumptions and simplifications was made on the design values and the geometry of the foundation to be able to perform the calculations. Several other choices, such as installation method and the material of the piles, had to be made when designing the foundation. It is also useful to make comparisons with other projects to get a better understanding of suitable foundations. Further studies could also be conducted on this Thesis to take new aspects into consideration.

6.1 Design Values and Geometry

When calculating the bearing capacity of piles several design values had to be assumed. Different γ-values was tested for both the beta- and alpha-method. No significant difference in bearing capacity was noted while trying the different γ-values and hence the γ-values presented in Table 6 was chosen. Another option is to consistently choose the γ-values that results in a worst case scenario.

In this project Eurocode 2 concrete class C40/50 was used to calculate the compressive strength of the piles. This choice was made arbitrarily and steel reinforcement was not taken into consideration. With this in mind the choice of concrete class may have been too conservative for the foundation structure, since reinforcement most likely would have been used in reality.

The pile dimensions used for calculations, presented in Table 8, was chosen since they are considered as common in Section 2.2. The dimensions used in similar projects, presented in Table 11, has been considered but not taken into account since other aspects, such as loads and soil conditions, have been regarded as more important.

The assumption that the footing for tower B is much larger than the footing for tower A was based solely on the amount of concrete that NCC estimated in their study. In order to simplify the calculations of the number of piles, the geometry of the footings were re-shaped into a square. As a result, the placement of the piles became evenly distributed over the entire area of the footing. The total load from the construction illustrated in Table 7 was calculated for the most critical tower, which is tower B. Since this is the worst case scenario in dead load, tower A will probably have a smaller total dead load.

6.2 Installation Method

It is stated in Section 5 that shallow foundations are not a suitable option for the towers, since the towers are much taller than they are wide and the loads are too great. Instead deep foundations are studied since they have the properties required. The deep foundations are then divided into two categories, displacement and non-displacement piles. In Chapter 5, displacement piles are said to be the most suitable option for both tower A and tower B. In Section 2.2.1 it is stated that the soil will move radially when the piles enter the ground which may disturb nearby buildings. However, the towers are not located closely to other constructions and soil movement should therefore not be a problem. Another factor that should be considered is the fact that displacement piles are the most loud piling method. This would not be socially sustainable if the piling work would be more extensive, but since the construction will only be built in a limited time, it should not be a problem.

There are several different methods to install displacement piles, all with their own advantages and disadvantages. The jointed pre-cast reinforced concrete piles are considered reasonable in several aspects for the foundation of the towers. They can be manufactured in the studied dimensions, carry the needed loads and can be installed in the required soil depths. Since they are pre-cast and jointed at site the transport becomes safer and more efficient. As stated in Section 3.2.2 several factories in Sweden are producing concrete piles, which can lead to shorter distances from factory to site and international transports can be avoided. It is possible to do the piling with the non-displacement method with the advantage that it will not disturb the nearby ground. But as stated in Section 2.2.2 the soil is removed from the excavation and must then be taken care of. It is possible that the soil at the sites is contaminated, which can become costly for the environment and thus considered better to avoid. Another advantage with the non-displacement method is that vibrations and noise during construction is minimal. However, since the towers are not located in densely built areas it should not significantly affect buildings or people in the nearby area.

6.3 Choice of Material

The choice of pile material should be made considering a constructing aspect, but it is also important to discuss the environmental aspects, since the raw material in piles have the largest impact on the carbon footprint of the project. In Section 3.2.2 it is stated that stones, timber and mortar are better alternatives than concrete, when investigated from an environmental perspective. Furthermore, foundation methods that can be made without, or with lesser, concrete is preferable. For example, a totally preformed displacement pile in timber could be used in soft clay and have a much smaller carbon footprint than a similar pile in concrete. However, timber piles are rarely used in larger depths than 12 m and with loads higher than 500 kN. This entails that timber piles are not a viable solution in this project, since the method would probably require an unreasonable amount of piles. A large number of piles would also result in an unnecessary measure of emissions from the machinery required to drive the piles into the ground. Therefore, it would be necessary to perform an investigation to reach a conclusion regarding if it is even possible to use timber piles but the difficulty and quantity of timber piling in this project would, in the end, might not be that environmentally friendly. The same can be concluded from methods such as VSC. The strength of the method comes from stones and gravels, which lead to the method being the most environmentally friendly. However, the piles also contain cement to keep the stones together in piles. But foremost, their effectiveness is limited to only 4-10 m, which will not be nearly enough in this project. Deeper VSC piles can, also, cause problems with stone contamination, which can be transferred to underlying aquifers and contaminate the ground water in the area.

It might be possible to build with other materials than concrete but concrete piles are the most commonly used foundation in Sweden, especially in cities like Gothenburg, with high buildings and soft clay deposits. Moreover, concrete has a high compressive strength which is one of its biggest advantages when using piles. So even though the concrete itself has a high carbon footprint, there are methods that take advantage of the benefits of the material whilst using as little concrete as possible. An example of this is using hollow tubular-section pre-cast piles. The method requires a larger diameter but a lot less concrete, which also contributes to a good capacity to handle loads. The problem in this project is that the required pile lengths are too long to be able to pre-cast and transport the piles to the construction sites.

6.4 Comparison with Other Projects

Since there are no other cable cars in Gothenburg, other infrastructure and building projects was studied. The Gothenburg cable car was compared to the urban cable car Emirates Airline in London. The purpose of building a cable car was the same in London as it is in Gothenburg and the construction above ground would therefore be similar. However, the soil conditions are different since the clay in London is significantly stiffer than the clay in Gothenburg. The foundation method for the Emirates Airline are concrete piles but dimensions and the number of piles are not comparable with the foundation in Gothenburg because of the different soil conditions.

A comparison with Karlatornet have been done in Section 3.1.2, which is interesting to do comparisons with since it is built close to the site for tower B. This means that the there is similar soil conditions as for the foundation of the towers. The foundation for Karlatornet is made with non-displacement piles with a diameter of 2 000 mm. The largest difference between the projects is that the foundation of Karlatornet has to carry significantly larger loads, both vertical and horizontal and that at Karlatornet uses end-bearing piles. The larger loads leads to a need of a bigger pile dimension, which also leads to bigger soil displacement. Presumably, this is one of the reasons to why the piling is made with the non-displacement method and the spoil had to be taken care of. For Karlatornet this was made with a sedimentation basin and a treatment plant. This is a costly process and can be avoided by using displacement piles, since the piles for the cable car towers has a smaller width than piles used for Karlatornet.

The cable car has also been compared with offshore wind turbines since the construction above ground is similar to the towers of the cable car. A foundation method often used for offshore wind turbines are monopiles but these are not an option for the cable car towers. Monopiles are often used in water depths between 10 m to 25 m which is much deeper than for the cable car. The diameter of monopiles is usually between 3 m and 6 m, which could lead to heavy soil displacement that should be avoided.

6.5 Further Studies

Further studies on this project could be conducted to make the results more accurate and take new aspects into consideration. One of these are to create a model of the stratigraphy and foundation in a software that uses more advanced computational models such as finite element method. These software could also calculate phenomenons such as settlement and slope stability, which has not been considered in this Thesis. Software would also be a way to verify the results in this Thesis in a more practical environment.

Another way to further develop this Thesis is to consider pile groups when designing the foundation. Pile group design is used with the main purpose to assure that any major displacements does not occur for the foundation. Also, settlement calculations could be executed to predict how the foundation, and therefore the structure, will move and settle over time.

7 Conclusion

A cable car system across the Göta River is a planned solution to prevent a public transit system as the city of Gothenburg is expanding. Two of the cable car towers was to be placed on Järntorget and Lindholmen, both located on deep deposits of soft clay. The towers will be tall and heavy constructions, which together with the ground conditions poses a great geotechnical challenge. By combining the information gathered from literature and the calculated results, a suitable and stable foundation for the cable car towers was found. Vertical and horizontal loads, as well as the overturning moment, are studied to make sure that the foundations will not collapse. Calculations on geotechnical and structural capacity are made for the foundation to function in deep deposits of soft clay. The geotechnical capacity calculations are done with the beta- and alpha-method. Environmental sustainability is also taken into account in the assessment on which foundation is the most suitable by striving for a low concrete volume.

A simplification of the geometry of the footings are made to get an even distribution of the loads. The deep foundation method was considered most suitable, since the towers are much taller than they are wide and the loads are large. The displacement pile method is found suitable, since the placement of the towers allows the soil to move radially. Concrete piles are chosen partly because they can be manufactured in Sweden, which is favourable from a sustainability perspective, and their proven function in clay. Other more environmentally friendly materials does not provide the same construction abilities as concrete and are hence not chosen. Comparisons with similar projects are made to get a better understanding on how others have tackled foundation solutions for large or challenging constructions. Lower volumes of concrete is sought for the design since it leads to a smaller ecological footprint and, therefore, plays a major role when choosing the pile dimensions.

The study shows that concrete piles are a suitable option for the foundations of the two towers. The towers are not placed in a densely built area, which makes the use of displacement piles suitable. The results shows that longer piles gives a lower total volume of concrete of the foundation, compared to shorter piles. The results also shows that the use of longer piles will reduce the amount of piles needed to obtain the required bearing capacity. This Thesis concludes that the most suitable foundation option fulfilling the aims of both a capable and material efficient foundation for tower A is 66 square-sectioned displacement jointed pre-cast concrete piles with a width of 350 mm and length of 60 m. The total concrete volume for the foundation is 2 360 m^3, where 485 m^3 are generated by the piles. For tower B the most suitable foundation is 100 square-sectioned displacement jointed pre-cast concrete piles with a width of 350 mm and length of 55 m. The total concrete volume for the foundation is 3 603 m^3, where 663 m^3 are generated by the piles.

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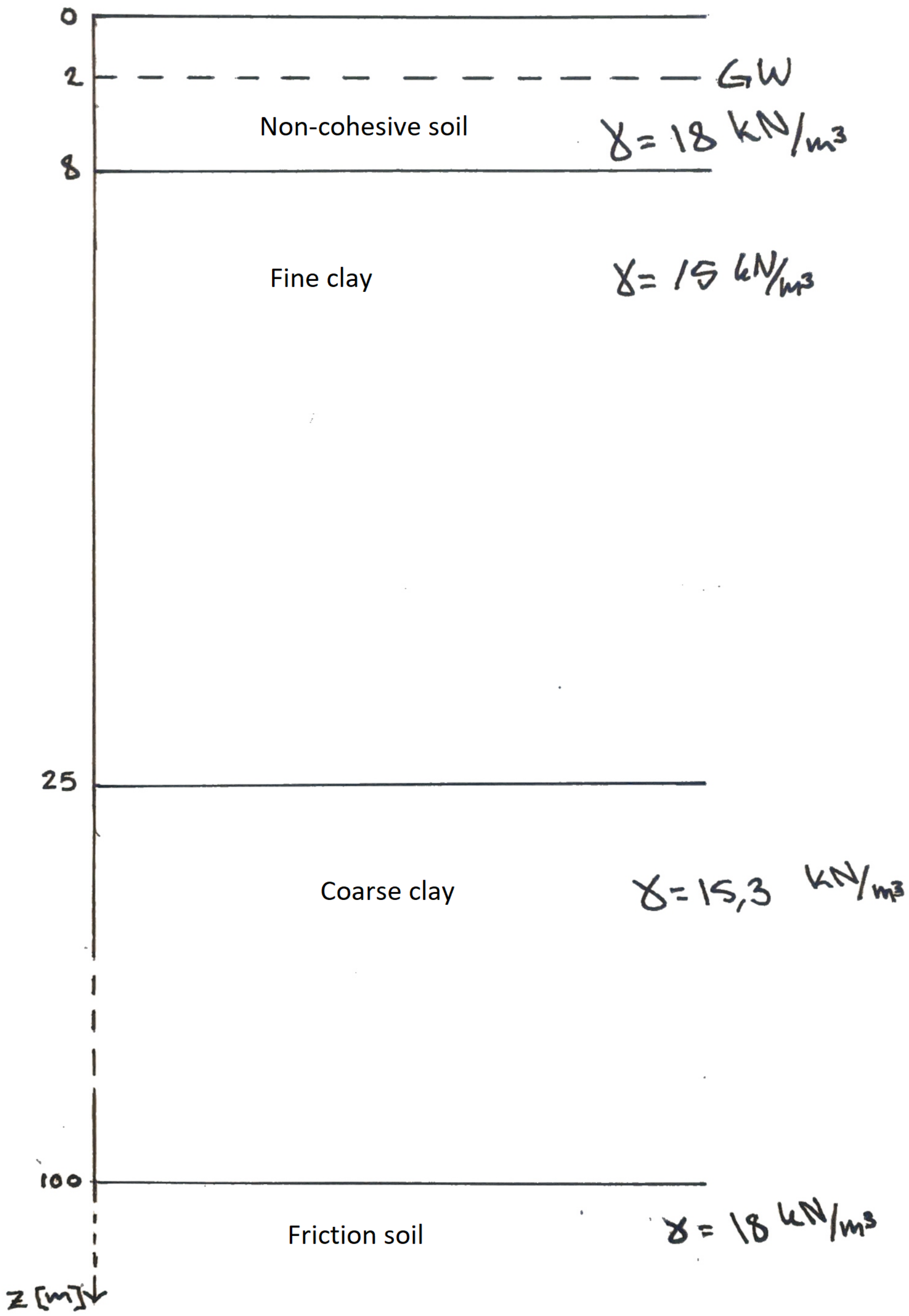
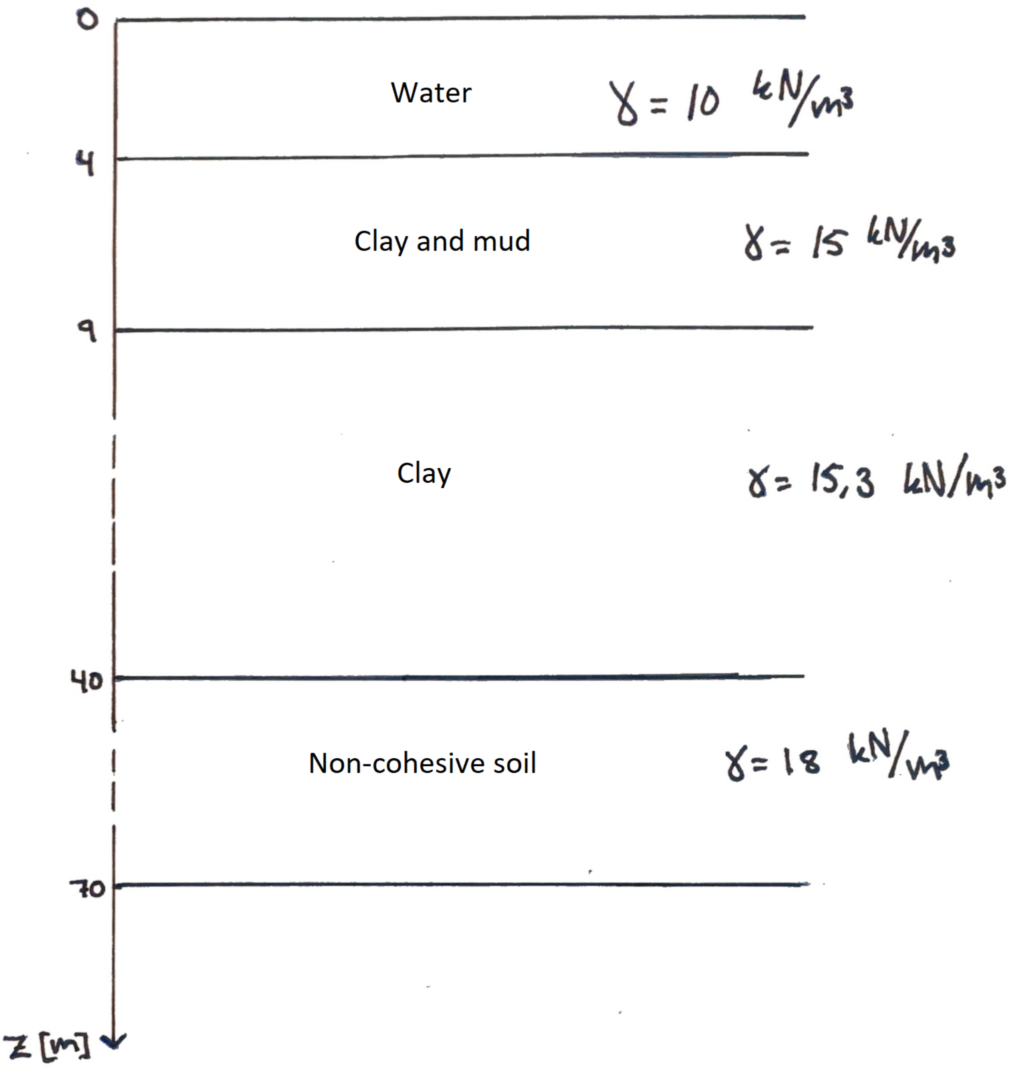
Appendices

A - Stratigraphy for Tower A



(Pedersen, 2019b)

B - Stratigraphy for Tower B



(Pedersen, 2019d)