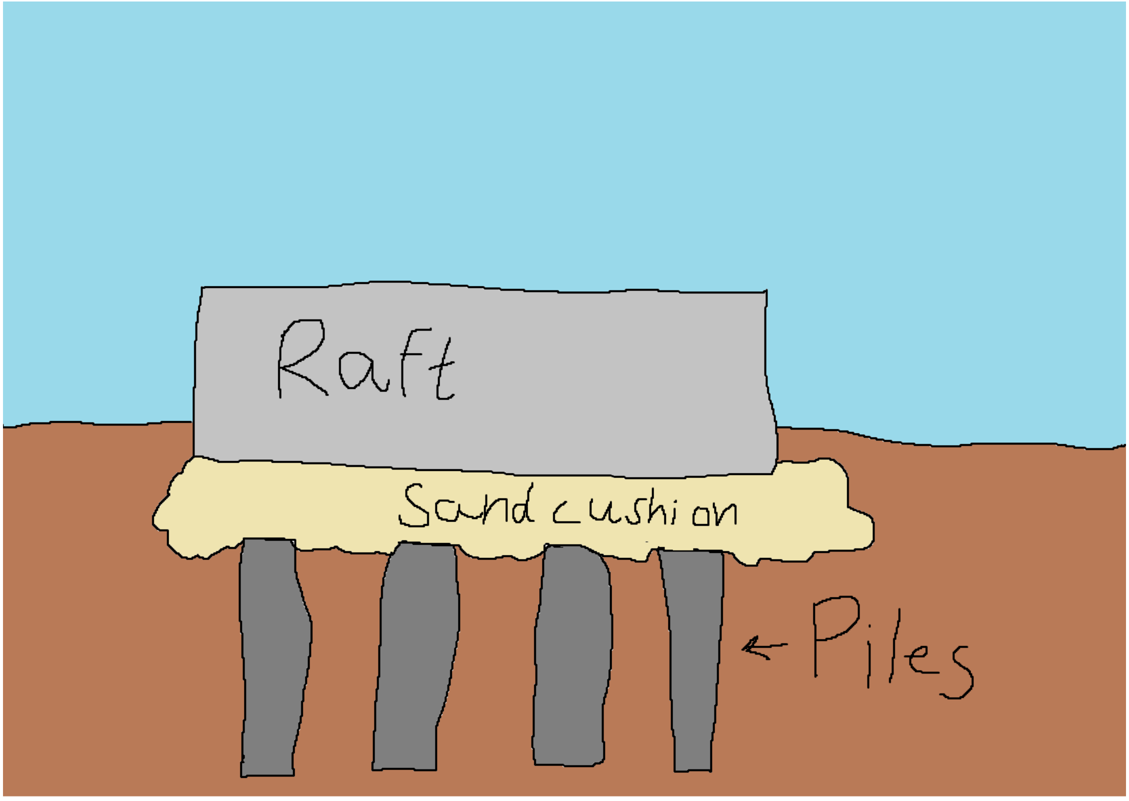

Disconnected piled raft in Gothenburg clay

A feasibility study of disconnected piled raft in large depth of clay

ACEX30

FREDRIK NORÉN

DEPARTMENT OF ARCHITECTURE AND CIVIL ENGINEERING
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2022
www.chalmers.se

Master's thesis 2022

Disconnected piled raft in Gothenburg clay

A feasibility study of disconnected piled raft in large depth of clay

FREDRIK NORÉN

Department of Architecture and Civil Engineering
Division of Infrastructure and Environmental Engineering
Chalmers University of Technology
Gothenburg, Sweden 2022

Disconnected piled raft in Gothenburg clay
A feasibility study of disconnected piled raft in large depth of clay
FREDRIK NORÉN

Supervisor: Jelke Dijkstra, Division of Geology and Geotechnics
Co-supervisor: Viviana Mangraviti, Division of Geology and Geotechnics
Examiner: Jelke Dijkstra, Division of Geology and Geotechnics

Master's Thesis 2022
Department of Architecture and Civil Engineering
Division of Infrastructure and Environmental Engineering

Chalmers University of Technology
SE-412 96 Gothenburg
Telephone +46 31 772 1000

Cover: Describing art of the disconnected piled raft foundation type.

Typeset in LaTeX
Printed by Chalmers Reproservice
Gothenburg, Sweden 2022

Disconnected pile raft in Gothenburg clay
A feasibility study of disconnected pile raft in large depth of clay
FREDRIK NORÉN
Department of Architecture and Civil Engineering
Chalmers University of Technology

Abstract

Disconnected piled raft is a rather new foundation method, where piles work as an soil reinforcement instead of supporting the raft directly. The benefit of this method is that horizontal forces subjecting the soil, will not break or buckle the piles. The disconnected piled raft method has been performed on large scale projects and this thesis is done to test the feasibility in Gothenburg clay conditions. A numerical model in the software PLAXIS were made where different heights of the cushion were tested along with different parameters for the materials. In the results it showed that a cushion thickness the same height as the width of the pile were superior in terms of displacements. Determination of the spacing were also done with previously mentioned cushion thickness as well as the time depending consolidation analysis. A sensitivity analysis of the material were made to investigate which of the parameters did affect the displacements the most. Conclusion of this thesis were that the disconnected piled raft method is feasible for the Gothenburg clay conditions if certain criterion is meet.

Keywords: Disconnected piled raft, PLAXIS, numerical model, displacement, cushion, clay.

Acknowledgements

This thesis would not have been possible without the support from my supervisors Viviana Mangraviti and Jelke Dijkstra. They helped me with completing the numerical model and structure of the thesis. I thank them for guiding me throughout the theory and useful discussions. Also, thank to my managers and colleges at Serneke for their patience to complete this thesis.

Fredrik Norén, Gothenburg, June 2022

List of Acronyms

Below is the list of acronyms that have been used throughout this thesis listed in alphabetical order:

DPR	Disconnected piled raft
OCR	Over consolidation ratio
POP	Pre overburden pressure
PR	Piled raft
UP	Unpiled raft

Nomenclature

Below is the nomenclature of indices, sets, parameters, and variables that have been used throughout this thesis.

Parameters

σ'_v	Vertical effective stress
σ'_c	Preconsolidation pressure
OCR	Over consolidation ratio
M_C	Critical state stress ratio
ϕ'_{cv}	Friction angle in critical state
K_0^{NC}	Coefficient of lateral earth pressure at rest for normally consolidated soil
$K_{0,xy}$	Coefficient of a ratio of horizontal and vertical stress
C_c	Compression index
C_s	Swelling index
e	Void ratio
e_{init}	Initial void ratio
$\lambda*$	Modified compression index
$\kappa*$	Modified swelling index
v	Poisson ratio
η	Settlement efficiency ratio
u_{yUR}	Settlement unpiled raft
u_{yDPR}	Settlement disconnected piled raft
u	Hydrostatic water pressure
γ	Unit weight
A_c	Arcing coefficient
σ_p	Pressure on pile head
d	Width of pile

h	Height of cushion
p	Surface load
$p'r$	Pressure on underlying soil
$p'c$	Vertical stress on pile cap
X	Grouped variable for spacing
B_{full}	Load part B full arcing
$B_{partial}$	Load part B partial arcing
s	Spacing of arcing
E_p	Pile efficiency
w	Total load

Contents

List of Figures

List of Tables

1

Introduction

To this date expanding cities and urbanization is on the rise, especially in densely populated cities such as Gothenburg. The location of the city is challenging for constructing structures. Except for the logistic part of the production phase, the main reason is the thick stratigraphy of soft soil that mostly consists of different clay layers contributing to extensive consolidation settlements (Olsson, 2013). Adding to that problem the region undergoes the largest development in the building and infrastructure sector in the last 50 years (Scheller and Thörn, 2018), celebrating its 400 years jubilee. Furthermore, the construction of more large-scale projects that needs stable and more environmentally friendly foundations are of interest to most contractors, they will in turn increase job opportunities and therefore increase the living standard and help in developing the future cities.

1.1 Background

When designing a load-bearing foundation for a structure there are different means of approach. A common type for small structures is placing a raft direct upon the soil seen in figure 1.1 a, referred to as an unpiled raft (UP). Adding a cushion layer under the raft, figure 1.1 b could redistribute loads and decrease settlements. But lacking the piles makes them not suitable for large structures. The conventional way to achieve a load-bearing foundation for larger structures is to use the method where piles are attached to the bottom of the raft, reefed as a piled raft (PR), figure 1.1 c. The load from the structure is directly transferred from the raft to the piles and surrounding soil. This is done either by end-bearing piles, where the piles are drilled into a rock bottom or, by cohesion piles where the friction between the soil and pile acts as an uplifting force. In recent years, a new design called disconnected piled raft (DPR) figure 1.1 d, has been researched and put to practical use. The design addresses the load-bearing problem in another way, by increasing the global bearing capacity of the soil (Halder and Manna, 2021). Compared to an PR it has different positive and negative influences on the foundation. Studies have been performed on buildings with high horizontal loads on the foundation, due to wind or geotechnical conditions. As the displacement of soils occurs either by earthquakes or other foundations, the latter as in the case of Gothenburg city center. In these studies, the benefit of a DPR is that the axial load from either the wind that affects the building or the geotechnical conditions affecting the pile will not conflict with each other (Zhu et al, 2018).

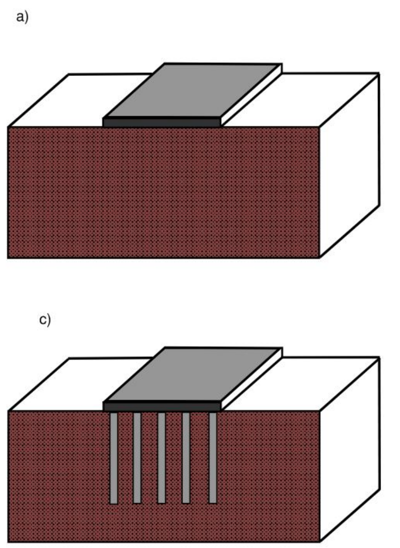

Figure 1.1: Different foundation methods

The pile heads in a PR foundation may be subjected to a high overturning moment in case of cyclic and horizontal forces (Zhu, 2017). In the PR foundation, the heads are exposed to the highest axial force as they connect to the raft and transmit the full load of the structure.
In conventional piled raft methods the spacing of the piles will affect the axial load on the pile itself. The further the distance between each pile will increase the load until the distance is far enough to inflict structural failure on the pile (Tarenia and Patra, 2019). A hand full of studies has been investigating the performance and properties regarding the cushion to prevent the high axial load on the pile head (Zhu, 2017). The granular cushion is an important part of the disconnected pile method and the cushion height along with the material has to be modified for the best results (Arun and Basheer, 2021). For instance, Halder and Manna (2021) found out that the most effective height is twice the height of the piles width, reducing the settlements by 35 %. They also found out that the cushion layer redistributes the axial loads so the loads on the piles are even distributed regarding on position under the raft. A similar conclusion was made that the settlements decreased with the pile diameter due to more area of the pile subjected to uplifting friction force (Zhu, 2017). The test concluded that the settlements increased with the thickness of the cushion and the ratio. In the findings, they found out that a cone-shaped displacement field appeared around the top of the pile and a fan-shaped appeared downwards from the cushion.

1.2 Problem

The problem in this thesis is to test the DPR over Gothenburg's soft soil conditions. To compare the DPR with the PR and UP methods and obtain the differences between the methods. The filling soil of the cushion will have a large influence, especially the friction angle of the sand, and the height of the cushion needs to be studied. Finding a working numerical model that can support the different parameters without failing and produce acceptable results. Finding a geometry that can work for the Gothenburg clay and run time depending on analysis as well as plastic analysis within the model.

1.3 Aim

The study aims to explore the feasibility of disconnected pile raft foundations in a typical profile of Gothenburg clay, to understand if the method is plausible for future projects in the area. Comparing the results to traditional designs like PR for deep foundations in terms of material use and what parameters to utilize. Identify a potential use case for these types of foundations and investigate the uncertainty of the cushion layers material. To meet these requirements, the disconnected pile raft foundations must:

- be able to withstand the vertical and horizontal loads
- function in deep layers of Gothenburg soil parameters.
- have as low environmental and economical impact as possible
- not have negative social and ethical aspects for the surrounding environment.

1.4 Limitations

The lifetime of concrete in a foundation is expected to be a minimum of 50 years expressed in Swedish law. But from an economic perspective at least 100 years could be assessed if the numerical model approves of the calculations (Svensk Betong, 2022). Therefore the consolidation of the piles and raft will have the same time limit. The limitation of a numerical analysis will be applied, where guesses at the solution are done until the problem is solved well enough. A limitation of spatial discretization needs to be present due to computational power. In-situ test of the DPR method will not be taken into consideration, since the location of foundations will vary and the report will have a more comprehensive nature.

1.5 The structure of the Thesis

This Thesis is structuered as follows:

- **Chapter 1** has described the background, what problem and aim the thesis is subjected to.
- **Chapter 2** This chapter will consist of the necessary theory to understand what a DPR is and how it works. Comparing different projects and describing how the foundation type impacts the environment. Different loads and the negative skin friction affecting the foundation along with the neutral plane will also be described.
- **Chapter 3** Describes the method used for the numerical model, how the model is constructed, and in what stages. To connect with the aim of the thesis,

an identification of Gothenburg Clay has to be analyzed. The parameters from the identification will later be used for a numerical analysis of chosen foundation solution and compared with a more conventional design type. Also, the material analysis of the cushion layer will be investigated. Locating what parameters affect the load-bearing capacity.
- **Chapter 4** The results from the previous method chapter are presented here. The parameters of each material and the geometry is concluded. Furthermore, the result of a sensitivity analysis that describes the uncertainty of the parameters is addressed.
- **Chapter 5** Where the results and comparisons of parameters are discussed.
- **Chapter 6** Concludes the Thesis.

2

Theory

2.1 Similar projects and tests

Disconnected piled raft is, as mentioned, a relatively new foundation type with not as many reference projects as for instance the conventional piled raft foundation type. Two projects located in the Mediterranean that uses the DPR method will be introduced, also a common way to test the method on small scale will be presented.

In 2004 the Rion Antrion Bridge where completed, located in Greece over the strait of Corinth (Biesiadecki et al, 2004) seen in figure 2.1. The requirements for the bridge were specific since it is located in an area where there is large tectonic activity, more specific the Eurasian plate slides along the African plate (King, 2005), where movements up to 2 meters could occur (Biesiadecki et al, 2004). The depth of bedrock is far deeper than the depth of end-bearing piles reach, so the only solution would be to use cohesion piles. The bridge itself is 2.9 kilometers long and has two lanes in each direction, with a width of 27.2 meters. First, a highly technical solution with reinforcing the underlying seabed with 2000 mm steel inclusions, and shock absorption at critical locations along with cables and bearings to mitigate the horizontal forces. This solution was found to be too risky and financiers agreed to develop another method. After the soil analyses were done the team found out that it was sufficient to stabilize the top soil layer down to 30 meters, where the shear strength was high enough to withstand the horizontal seismic forces. The gravel base was also implemented to grant plastic deformations a free space without the risk of rotation of the inclusions. Not only that the gravel also helped the axial forces to be transmitted through the inclusions, acting as a path to deeper soils where the soil could resist larger loads. The steel inclusions were saved since they were effective at increasing the shear resistance in the soil. Spacing of the inclusions was done by using numerical modeling. The calculation showed an increase in the spacing of almost 100 percent, decreasing the number of inclusions by half the original amount.
Another project that uses the DPR is the MOSE “Modulo sperimentale elettromeccanico” project in Venice, where large flood gates are installed in the bay to block out rising sea levels and protect the city from flooding (Fioravante and Giretti, 2010). The project started in 2003 and where to be finished in 2014, but had to be halted and will be fully operational in 2023 (Water Technology, 2022). The system is installed as whole concrete elements that are built on land and transported out to sea where its submerged (Fioravante and Giretti, 2010). Under the element a foundation that consists of a granular layer of 1 meter was constructed, as can be seen

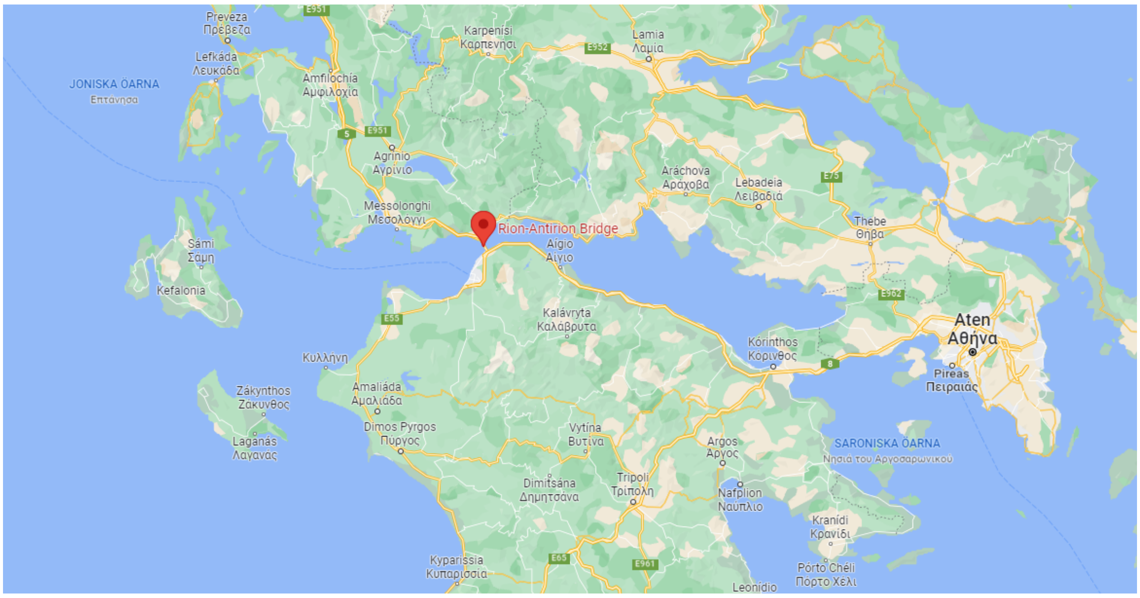

Figure 2.1: Location of the Rion Antrion Bridge

in fig 2.2. Beneath the granular layer, piles with dimensions of 500mm for each side were driven down to a depth of 19 meters. The granular layer between the concrete box and the piles acts to reduce single-point pressures and prevent failures. The pile itself acts therefore as soil reinforcement, and since the placing of the element is hard to monitor underwater while submerging it, the granular layer spreads out the differential settlement that could occur due to the soil being non-homogeneous.

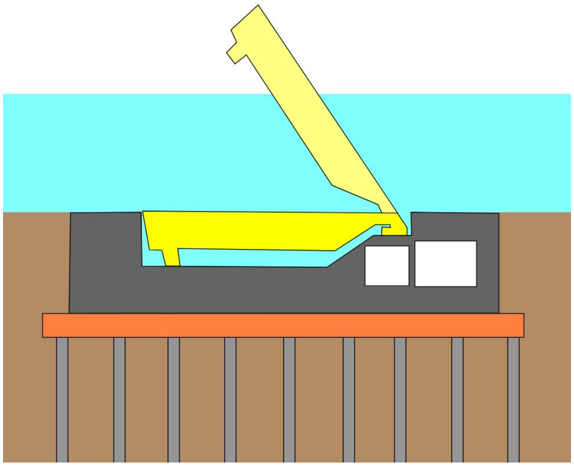

Figure 2.2: Foundation method MOSE

Both of the previously described projects are located underwater and close to areas with large impacts from the natural forces. They also are big infrastructure projects that are associated with large economic investments and benefits, thus making them hard to test out. A minor scale project implemented by a number of researchers is to use a small test tank as Arun and Basheer (2021) did while testing the settlement behavior with different vertical loading conditions. Zhu (2017) did a similar test where the load sharing behavior was analyzed in a similar tank. The idea is to fill a tank with fine grain sand packing it in layers to simulate stratigraphy of real soil conditions seen in figure 2.3. A rod either of plastic or aluminum is then installed in the middle of the tank and a cushion layer is placed upon the sand. A small raft with a hydraulic jack pressing down on it is located on the cushion, inflicting a vertical downward force. To get results, sensors are placed along the rod, and measurements are taken after each loading step. This testing method is a good compliment but the small scale makes it hard to accurate for large projects with more uncertainty.

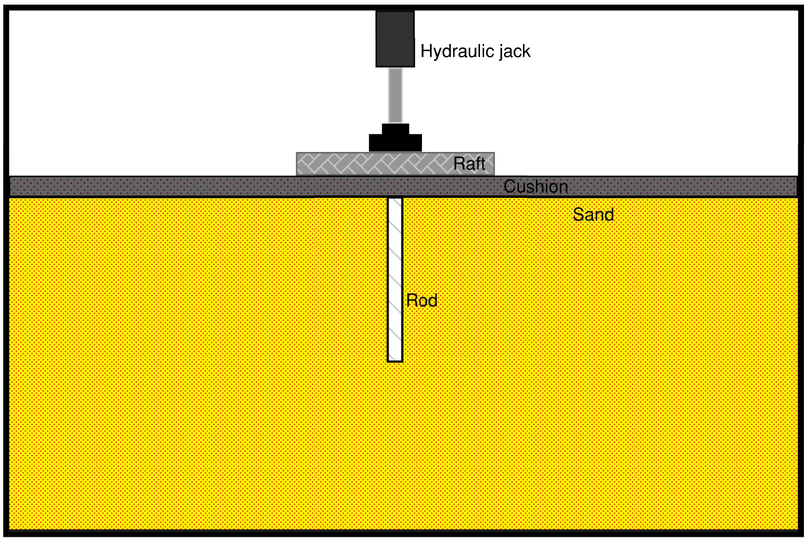

Figure 2.3: Testing tank method

2.2 Sustainable Development

As for now, concrete stands for 8-9 percent of anthropogenic greenhouse gas emissions (Miller, 2018), by hopefully reducing the amount of concrete needed for a foundation the environmental impact done by the concrete will therefore be reduced. While the emissions will be decreased due to the usage of less material for the case of a DPR foundation, this is not absolutely true since more machinery is needed to dig out the cushion. After that, the cushion material more than often is sand needs to be mined and transported to the site. Even if the sand generates less CO2-eq emissions than concrete, the amount of sand needed for a DPR exceeds for instance the Portland cement needed for PR. This is hard to investigate since

it depends on how large the load of the structure is compared with how thick the cushion is, settlement requirements the scarcity of sand in the surrounding area, and more.
The same goes for the economical part. Analysis can be done with similar values and is more project-based than regional. One could for example choose a project where the contractor has their own machines for digging the cushion or needs to hire a subcontractor for the piling.

2.3 Mechanical behaviour of pile foundations

All foundations are subjected to different kinds of loads. The most obvious one is the vertical load from the structure above the raft. Point loads could be used to simulate the structure if the location of the load is in the same vertical line as the pile. In that case, no bending moment is occurring in the raft and transferred down to the pile. Since the raft often is made of concrete and is non-elastic the load will be transferred vertically down. In a DPR model, the pile is not connected with the raft, making the pile move sideways if under the influence of a horizontal force. No horizontal loads will be taken into consideration since they will not impact the bending moment on the pile in the case of a DPR model.
Piles come in different dimensions and lengths. But all piles need to satisfy the criteria of the single pile equation 2.1. Where the total load of the foundation on the single pile is lower than the resistance of the pile.

$$Q_{tot} < R_{pile} \tag{2.1}$$

Where the former equation is a simplification. In more common practice there is a down drag effect, weight from the pile, and negative skin friction (NSF). End-bearing toe resistance and skin resistance, while the level of the water table also impacts the bearing capacity.
The length of the pile is determined by the underlying and surrounding soil. The geotechnical strength of the different soils in the stratigraphy varies from different locations. Thus, a static analysis of the strength can be made to meet the design values. With that set, parameters such as length, diameter, and cost can be evaluated.
The diameter of the pile is also of importance since the sides of the pile create an interface that acts with friction to the soil and creates an uplifting force. The pile joints have different characteristics from the concrete pile but will not be taken into consideration. Therefore, the pile will have a homogeneous concrete mix with no joints. The design of the pile can be done with the alpha-method which is a common use for soils such as clays. Where adhesion factor, the undrained shear strength, area of the pile surface, and design values factors are considered (Sällfors, 2013). If piles are installed in soil that is consolidating due to increased loads, NSF occurs along the sides of the pile seen in figure 2.4. This is due to the downward movement of the consolidating soil being higher than the movement of the pile. Making the friction along the sides of the pile counter-act the purpose of the pile. The consolidation of clay increases the effective stress and will in turn increase the friction between the

pile and the clay (Fellenius, 2006).

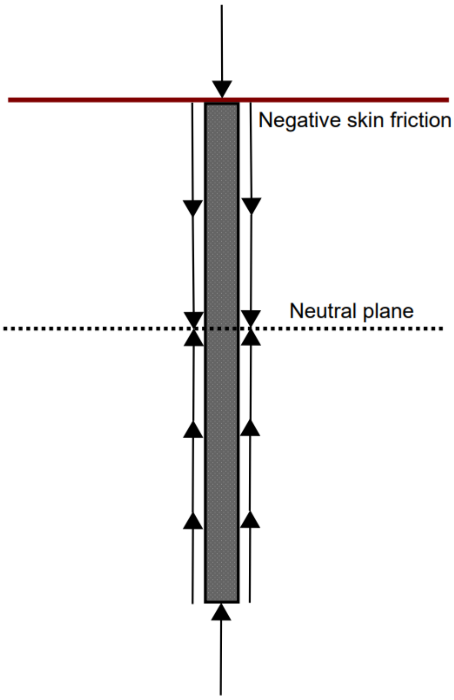

Figure 2.4: Concept of negative skin friction

In a DPR model, this is more notable because the cushion layer displaces less over the pile than the clay. The way the cushion layer work is to distribute the loads more evenly over the same area, resulting in the supporting forces of the subsoil being lesser than the supporting forces of the pile. The significance of the phenomena depends entirely on the consolidation rate and the elastic compression of the material used in the pile. The NSF decreases with depth until the friction becomes zero and transforms into a load-bearing friction force. At the depth where the positive and negative skin friction is at equilibrium is the location of the neutral plane. At this plane, the pile is exposed to the maximal compression load. This does not occur if the piles are not disconnected or end-bearing. Tests conducted on the group effect of NSF concluded that the NSF is higher on single and corner piles than those surrounded by other (Huang et al, 2015). The same tests also stated that if the spacing between the piles is further than five times the dimension of the pile, the group effect does not impact the NSF or neutral plane. Where the effective stresses are higher for a single pile than in a group, resulting in the drag load being higher but the neutral plane does not change.

3

Methods and numerical model

3.1 Computing software

To decrease the calculation process the computing program PLAXIS 2D was used. It is software that calculates the finite element in two-dimensions (Brinkgreve et al, 2012). It consists of analysis for deformation, soil stability, and groundwater flow. The intention of the program is to aid geotechnical engineers as a practical tool for numerical modeling.
The usage of the program consists of different phases. In the first stage, the soil parameters are specified and different materials are added to the model. Those materials can be evaluated with different material models, the most common ones being Mohr-Colomub, hardening soil, and soft soil models.
After the initial step, the geometry of the raft and piles is determined as well as the stratigraphy of the soil. The model also requires to have a mesh with connecting nodes, which are used for calculating the displacement. The program also has the option to implement groundwater flow and level. The final phase is where staged construction is introduced. In this phase displacements over time are calculated where both direct displacements and consolidation displacements can be analyzed. In the staged construction phase the model calculation path is as follows:

① Initial phase
② Construction of the pile
③ Activating the interface
④ Building up the cushion
⑤ Applying the plate and the load

3.2 Geometry

When constructing a geometry to work with in PLAXIS, it is important that it could show the difference between a UP, DPR, and PR. The geometry is based on a 2-D version of Ata et al (2015) numerical analysis of unconnected piled raft with cushion report. To determine the geometry some assumptions have been done. In PLAXIS there is an option to either work with plain strain or an axisymmetric model (Bentley, 2020). The plane strain model is used for cross-sections that are constant and displacements in the z-axis are zero, labeled an in fig 3.1. The axisymmetric model is different because it rotates around a central y-axis, labeled b in fig 3.1. The x-axis represents a radius and deformation along with the stress state is equal around the central axis. The x-axis can thus not be negative. The axisymmetric conditions are considered representative for modeling the mechanical behavior of a single pile. The raft was replaced in PLAXIS with an elastic plate seen above the cushion in figure 3.2. This is done to mitigate some problems with mesh generation and results depending on the parameters of the raft instead of focusing on the cushion material and clay. The plate had a large value of EI to resist the bending deformation and could distribute the loads correctly without any deformations in the plate. In the model, there were no horizontal forces in any phase, but for the phase where there is no cushion, an overturning moment would occur from the center between the piles making them subject to tensile and compression forces, this is not corrected for in that phase. This is done to test only the stresses and displacement affecting the piles not depending on the structure above.

The cushion is located directly under the steel plate, and different values of cushion height were considered, a cui of the results are discussed in § 3.3. The height is also discussed in the same section. Under the cushion, piles are running vertically down to 10 meters. The width of the pile is 500 mm.

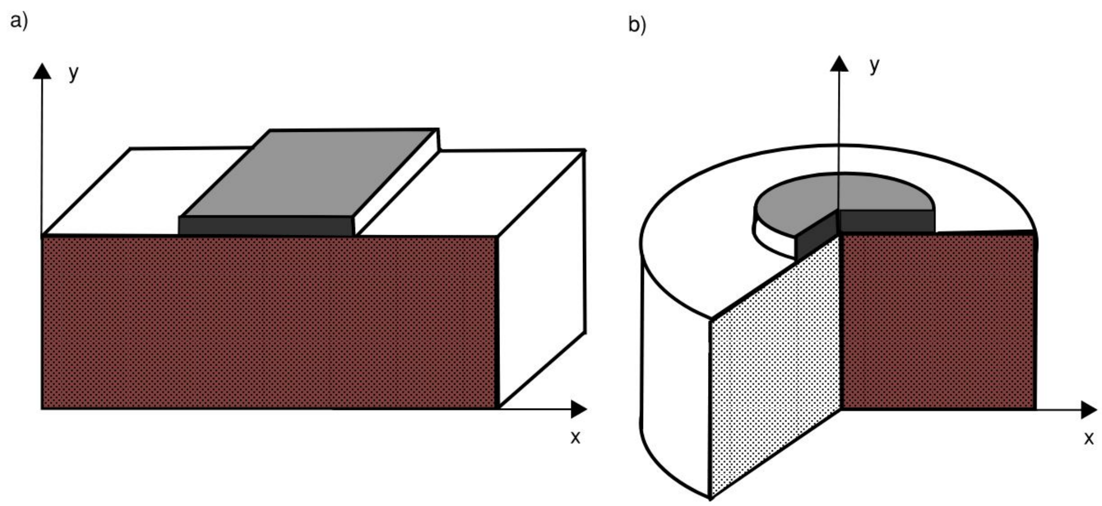

Figure 3.1: a) Plane strain model b) Axisymmetric model

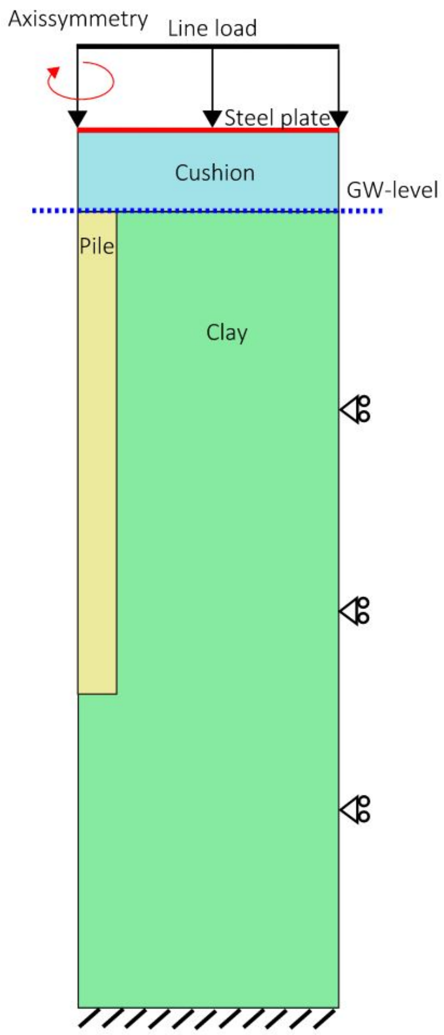

Figure 3.2: Model used in PLAXIS, with material and boundary conditions

The cushion is modeled in different phases to determine the most efficient height regarding the downward movement with the forces occurring on the pile and the cushion itself. The phases will be done in stages one after another with resetting the displacements after each step seen in figure 3.3. Then building the cushion up rather than excavating the clay, since the study focuses on the behavior of DPR after loading, the effect of the cushion height, and the mechanical behavior of the foundation method. This method saves calculation time and fewer phases can be done since the effects of both excavation and construction of the pile are disregarded. The thickness of the cushion layer is the most important and can be explained as a ratio between the thickness (h) and pile diameter (d). The different h/d ratios that will be considered are 1, 2, and 3. A phase without any cushion will also be considered to evaluate the difference. An interface between the clay and the pile has to be defined for the model to work more correctly. In PLAXIS the interface has zero thickness and is to describe the behavior of different materials coming in contact with each other by default PLAXIS uses a value of the reduction factor R_{inter} to define the values of the parameters of the interface. The values used is presented in table 3.1.

Table 3.1: Strength/stiffnes reduction factor

Parameter	Value
Cohesion, c_i	1.0
Friction angle, φ_i	44.0
Shear modulus G_i	1.92
Oedometer modulus $E_{oed,i}$	21.1

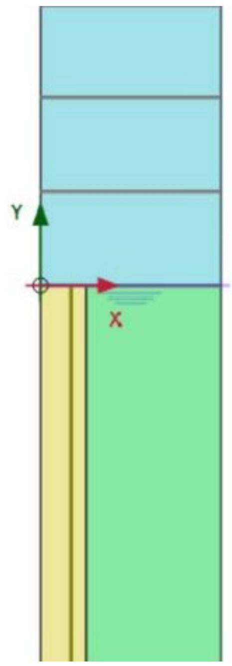

Figure 3.3: Different heights in different phases

To be able to calculate the stresses and use the core of the finite element method, a mesh is generated to split the geometry into smaller elements that are connected to each other by a number of nodes. This generation is named discretization and together with all the nodes and elements, it creates a mesh. By using this method, requirements can be calculated at the elements and not along the whole surface. Since this is a two-dimensional calculation in axis symmetry, surface elements like the triangular element are generated. To get a more correct and precise model the mesh can be refined at certain key points and lines, this way the nodes come closer to each other and generate a mesh with more detail in specific parts. For this model, the key points are at the top of the pile head and along the x-axis seen in fig 3.4. When the mesh is generated the stress analysis calculates the displacement of each node. If the displacement is known the secondary outputs of strain or stresses can be evaluated. The number of nodes generated for this model is 22 703.

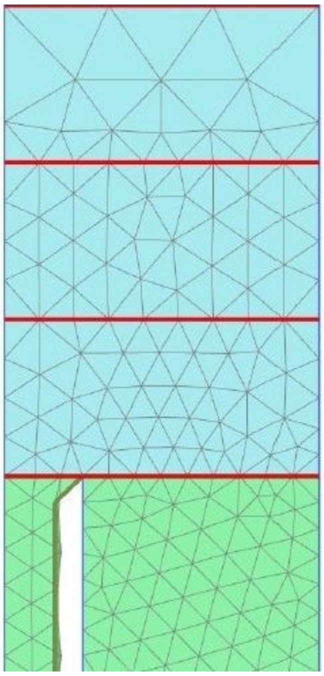

Figure 3.4: Generated mesh with denser triangular elements along the x-axis

The difference between the option of choosing 6 or 15 noded triangular elements in PLAXIS is mainly the accuracy of the calculation. The 15-noded option uses a higher order of integration and is superior to capture the failure conditions. That is also true if one would refine the 6-noded option to have the same amount of nodes as the 15-noded element. Geotechnical models often use the 15 noded element option since it generates a more solid model.

3.3 Materials

The soft soil model origins form a modified Cam-Clay model but unlike the Cam-Clay model, it is not regarded as a critical state model (Karstunen and Amavasai, 2017). Clay usually consists of deposits from fine grain particles that have been sediment at the bottom of oceans or lakes at a low velocity. If the clay has been confirmed in the ocean it has a more open structure, due to the salt content in the ocean water, and thus has a higher ability to compress than clay conformed in water with low salt content (Sällfors, 2013). The ability to compress is directly linked to the loading of the soil. Properties of Gothenburg clay originate from tests made in Utby just outside of the city, seen in figure 3.5. The stiffness properties are evaluated from the CRS tests performed on samples from the site. The Oedometer test yields the in situ vertical effective stress σ'_v and σ'_c preconsolidation pressure. Choosing to use pre-overburden pressure POP or overconsolidation ratio OCR depends on the geotechnical history of the site (Karstunen and Amavasai, 2017).

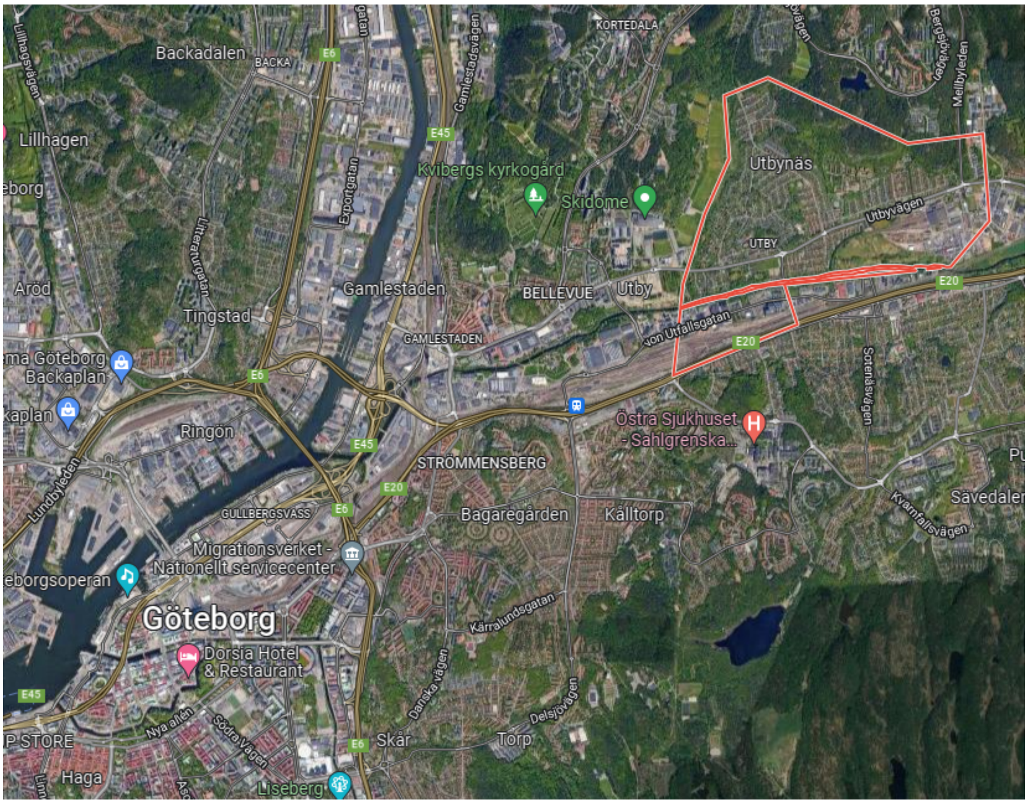

Figure 3.5: Location of Utby

From a triaxial test made by Karstunen and Amavasai (2017), the friction angle can be derived by using the stress ratio of the critical state, also called M_C using equation 3.1

$$sin\varphi'_{cv} = 3 \cdot M_C/(6 + M_C) \tag{3.1}$$

When the friction angle in the critical state is determined, Jaky's formula can be used to calculate the coefficient for the lateral earth pressure K_0^{NC}, described in equation 3.2.

$$K_0^{NC} = 1 - sin\varphi'_{cv} \tag{3.2}$$

Furthermore the consideration of the OCR a ratio between the vertical and horizontal stress is calculated with a modulation of Jaky's formula in equation 3.3.

$$K_{0,x} = K_{0,z} = 1 - sin\varphi'_{cv} \cdot \sqrt{OCR} \tag{3.3}$$

The main difference between parameters in the soft soil model and Mohr-Coulomb model is the modified compression and swelling indexes $\lambda*$ and $\kappa*$. As they are non-linear elastic compared to the linear elasticity in the Mohr-Coulomb model. Both values relate to the compression index C_c and swelling index C_s shown in figure 3.6. Where it can be noticed that the void ratio is plotted with the vertical stress on a logarithmic scale. The steepest part of the curve resembles the compression index, and the unloading curves the swelling index. Where unloading to reloading part is not possible, the original loading part can be used.

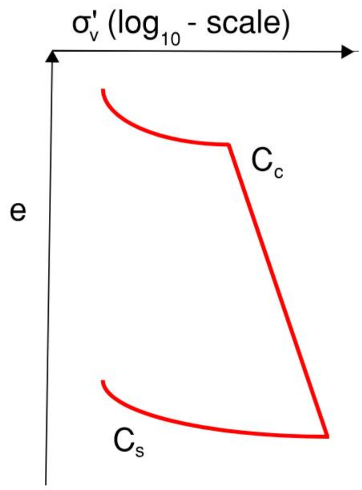

Figure 3.6: Compression and swelling index

$$\lambda* = C_c/2.3(1+e) \qquad (3.4) \qquad\qquad \kappa* = C_s/(1+e) \qquad (3.5)$$

The void ratio e is needed for evaluating the compression and swelling index but is also used for hydraulic conductivity k to calculate the permeability of the soil. The poisson number is a ratio between the axial and transversal strain in a soil, working in the perpendicular direction of the forces enforced to the soil (Sas et al, 2013). In soft soil modeling the poisson's ratio for unloading and reloading is required, not to be compared to the same poisson ratio in the Mohr-Coulomb model. In the Mohr-Coulomb model, it is elastic until failure unlike in the case of the soft soil model (Karstunen and Amavasai, 2017). The poisson ratio is often assumed between 0.1 and 0.2. While this study assumes a value of 0.2 further investigations will be addressed with a sensitivity analysis.
Studies have proven that the cushion material has a large impact on the settlement and negative skin friction of the piles (Halder and Manna, 2021). Where the properties of particle size, density, and friction angle have the largest influence as well as the geometry. The particle size and friction angle influences each other due to interlocking settlements between the grains in the cushion layer (Vangla and Latha, 2015). The density impacts the vertical load on the piles, where increased grain density increases the load since is less void between each grain. The different material parameters that are used are presented in table 3.3. Both the density and the friction angle depend on the grain size and thus the grain size can be neglected as it is already calculated for in those parameters. A minor difference between sandy materials does occur due to the shape of the grains.
By following equation 3.1, 3.2, 3.3, 3.4 and 3.5, the parameter values used in the model is presented in table 3.2. ψ and k_{xy} is set to low numbers for calculation reasons in PLAXIS. The OCR value of 1.45 show signs of over consolidated clays that are representative for the Gothenburg region Olsson (2010). The material of

the clay is set as undrained, since it is below the water table.

Table 3.2: Utby clay: model parameters for Soft Soil

Parameter	Value
λ^*	0.296
κ^*	0.020
ν_{ur}	0.2
e_{init}	2
φ'_{cv}	38.3
ψ	0.001
K_0^{nc}	0.38
$K_{0,x} = K_{0,z}$	0.2537
k_{xy}	0.00001
OCR	1.45

The standard fill material properties are presented in table 3.3. In this case, the low number for c'_{ref} is for calculation reasons inside the software. The material is set as drained above the water table.

Table 3.3: Cushion properties

Input	Sand
$\gamma_{saturated}(kN/m^3)$	18
$\gamma_{unsaturated}(kN/m^3)$	19
$e_{init}(kN/m^3)$	0.5
E (kN/m^2)	40.00E3
ν $(-)$	0.3
$c'_{ref}(kN/m^2)$	0.001
Friction angle $\varphi(°)$	38
Dilatancy angle $\psi(°)$	0
$k_x = k_y$	1

Piles used for DPR foundations are standard cohesion piles made of concrete. The material properties of concrete are well known and are presented in table 3.4 (Tradigo et al, 2014), with the value of $k_{x,y}$ set at zero means that the material is impermeable and no drainage type is needed.

Table 3.4: Pile properties

Parameter	Pile
γ (kN/m^3)	25
E (kN/m^2)	36.00E6
ν $(-)$	0.2
$k_{x,y}(m/day)$	0

3.4 Boundary conditions

In a lake where the water is stationary there is a balance of hydro static water pressure where the pressure from the surface can be calculated with 3.6. The same goes for soils where the water is in hydro static equilibrium, and can thus be calculated with the same equation (Sällfors, 2013).

$$u = \gamma_W \cdot z \tag{3.6}$$

Where γ_W is the density of water and z is the depth from the groundwater table. This can in turn calculate the total stresses by subtracting the pore pressure from the effective stresses. In Gothenburg the groundwater table fluctuates between 1.5 meters and 0.8, depending on the seasons. But since the cushion material is drained and not filled in when excavating the water table for the model was at ground level 0 m seen in figure 3.2 beneath the cushion. No drainage or pumping is assumed therefore there is no hydrodynamic state for the water.
Beneath the clay solid impermeable rock is the boundary condition seen in figure 3.2, the boundary radiated from the central axis is only subjected to vertical forces.

3.5 Sensitivity analysis

Even if comprehensive testing is done on each material, there will always be uncertainty in the variables due to the soil not being perfectly homogeneous. The parameters of the filling material will impact the displacements in the model. In the sensitivity analysis and parameter variation tool made in PLAXIS the key parameters can be evaluated. The tool calculates how different variables uncertainty adds to the models comprehensive uncertainty (Witasse, 2021). It works with every material, and each variable needs to fill the criterion for a successful model. For instance, a variable that makes the model fail will not be included. A criterion for the model needs to be determined for the analysis to work. The criterion needs to be set out in which phase it shall operate, in this model displacement in the vertical axis is used in a specific node. In the end, a sensitivity score is obtained and the variable with the highest score impacts the criterion for displacement the most. When the score is calculated a parameter variation tool helps with isolating the parameters that obtained the highest score. The isolation is done to reduce calculation time because the number of variables from the sensitivity analysis is twice as many in the parameter variation tool. From there a maximum and minimum project with the highest and lowest boundaries can be viewed and evaluated.

4

Results

4.1 Cushion geometry

A cross-section along the bottom of the plate in different phases was analyzed. The result from the vertical displacement in that section seen in fig 4.1, shows that a higher h/d ratio and thus a higher cushion layer results in an increased vertical displacement for ratios. The phase without the cushion had a lower displacement than all others. Also notable in the figure is that the displacement over the pile head is almost the same as over the clay layer. In the phase with a h/d ratio of one, there was a small difference in displacement from over the pile head and the clay, with the latter being larger. This did not occur for the other phases. The optimal load-bearing height can not only be determined from the results of the displacement, since the height of the cushion also impacts the arching in the cushion material later described in section 4.4. But for settlement purposes on a single pile, the h/d ratio of 1 performed the best result of the phases with a cushion installed.

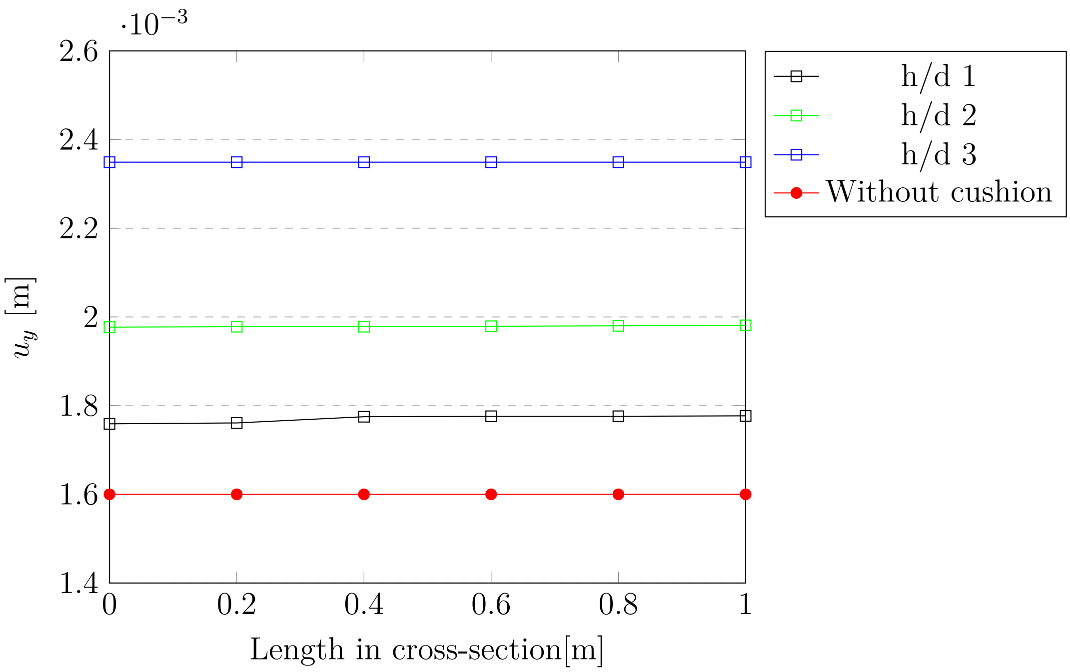

Figure 4.1: Vertical displacement under the steal plate for each h/d ratio

In figure 4.2 a comparison of the displacement for the phase with a h/d ratio of 1 and without cushion is done with the same phases in a UP model. The results show that a larger displacement is occurring than in the DPR case. This is expected since the underlying pile supporting the upwards forces from the skin friction along the shaft and the toe resistance is missing. In the figure, it is also notable that the linear form of the UP phases behaves the same, as if the model did not have any cushion layer at all.

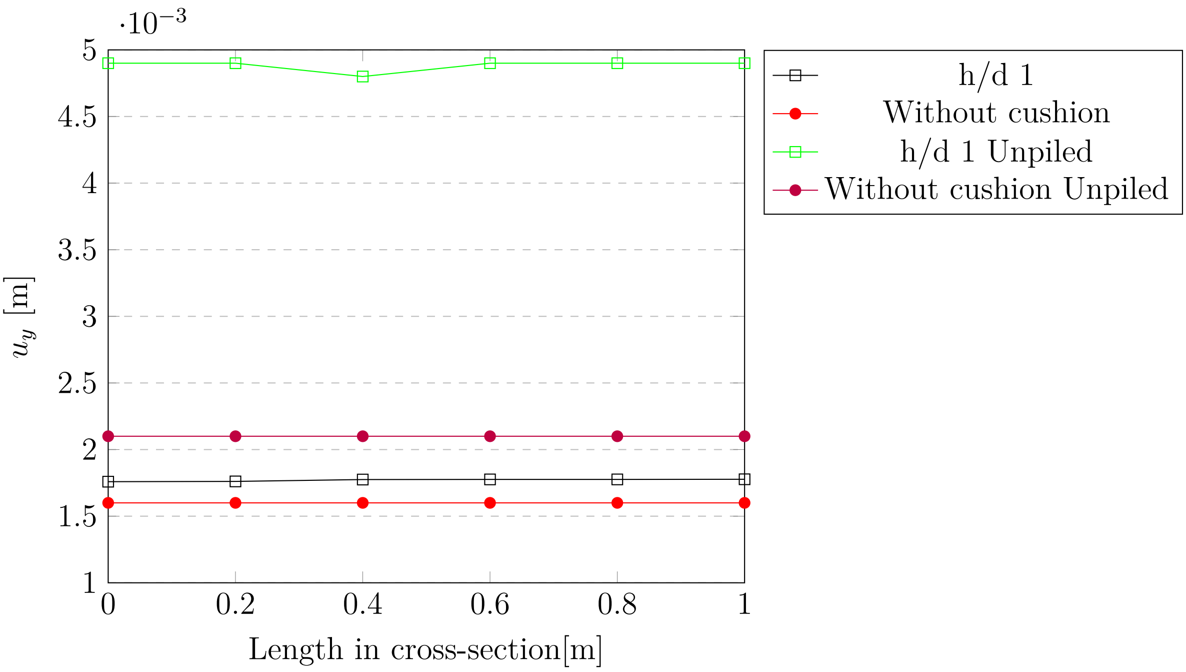

Figure 4.2: Vertical displacements comparison between an UP, PR and DPR model.

The vertical cartesian stresses evaluation from each phase can be seen in figure 4.3 from PLAXIS software. The stresses increases as expected when the h/d ratio increases, since more material is added and thus more weight over the clay. The stresses for each phase are larger over the pile and a large decrease can be seen over the clay.

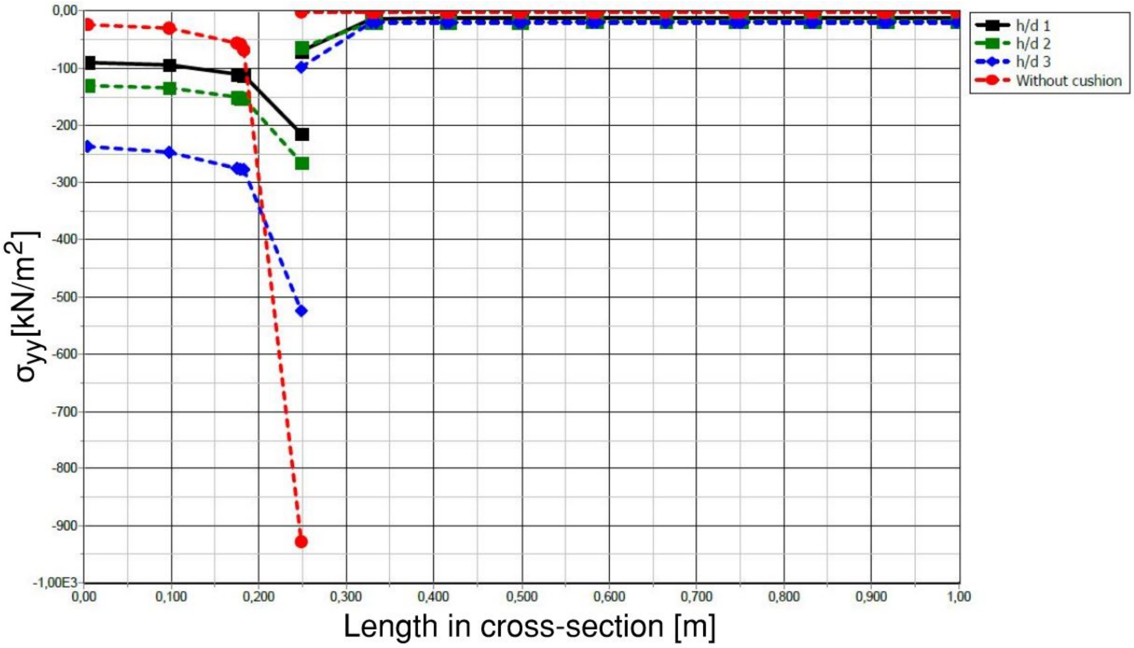

Figure 4.3: Vertical cartesian stresses

The average vertical displacements result from the respective cross-sections from figure 4.1 are plotted in figure 4.4, and show an increase of displacements for a higher h/d ratio. For a h/d ratio of 3 it is $2.35mm$ and for the phase, without any cushion, it is $1.76mm$. From figure 4.5 it can be noted that the displacements follow the same curve as the average vertical cartesian stresses. The stresses all increase with the cushion layers thickness for the same depth as the displacements.

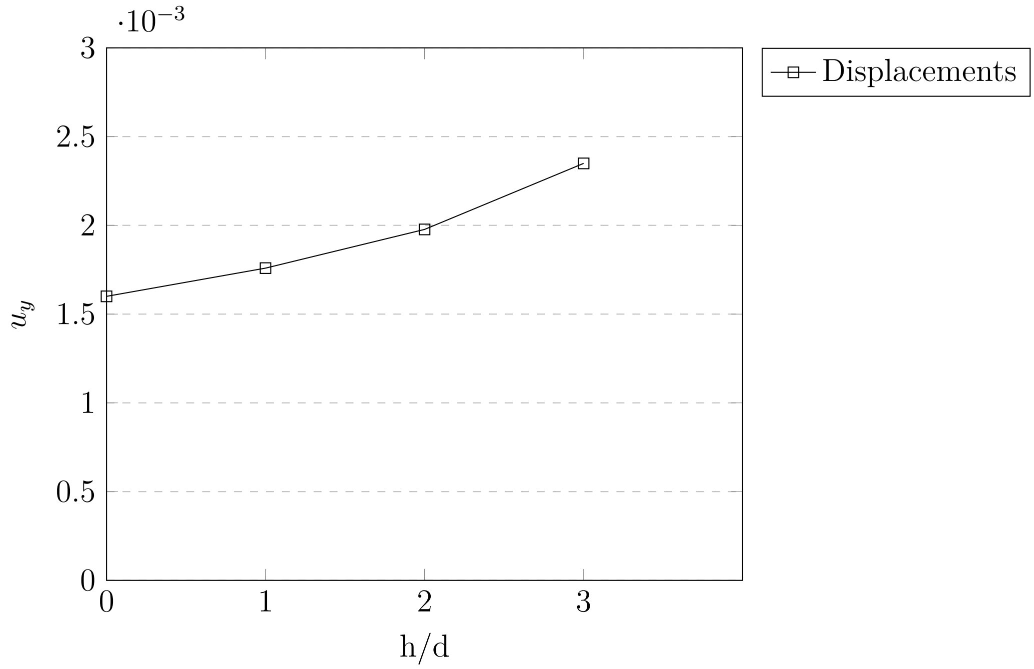

Figure 4.4: Vertical displacement for different h/d ratios in a cross-section under the cushion

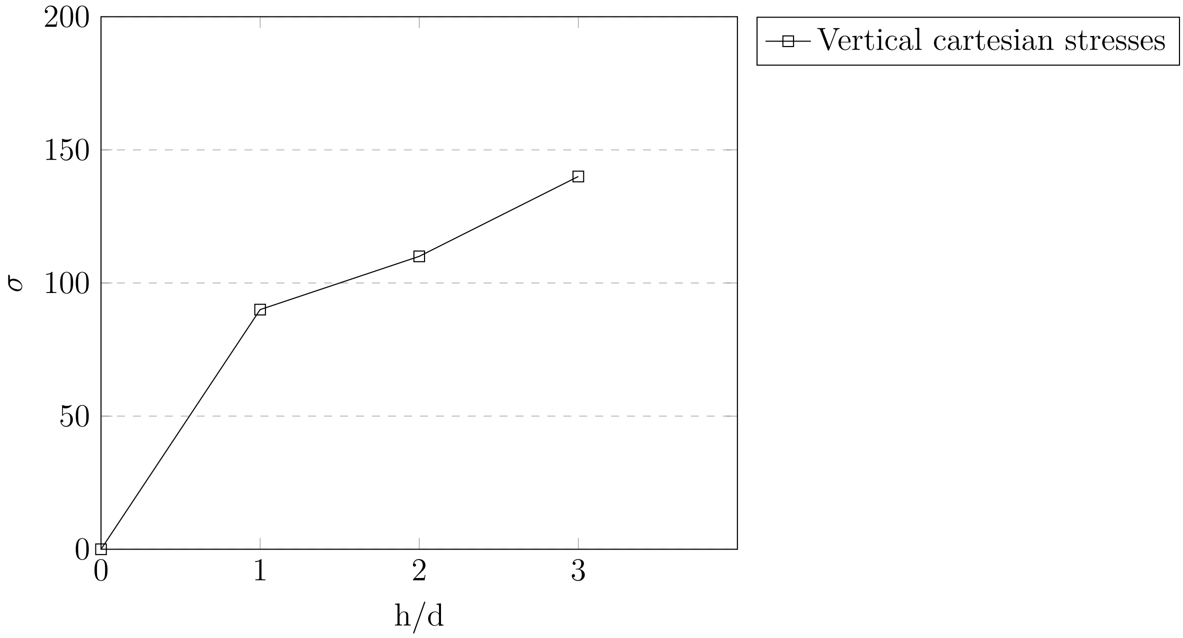

Figure 4.5: Vertical cartesian stresses for different h/d ratios in a cross-section under the cushion

To do a qualitative assessment of the impact on the settlements from the cushion layer it can be expressed in equation 4.1

$$\eta = (u_{yUR} - u_{yDPR})/u_{yUR} \tag{4.1}$$

Where η is the settlement efficiency ratio and u_{yUR} and u_{yDPR} are settlement for the UP- and DPR-model. η must belong to the span of $0 \leq \eta \leq 1$, where a larger number resembles higher efficiency. The efficiency factor η is plotted with each h/d ratio phase and shows a decrease in efficiency as the h/d ratio increases. Making the h/d ratio of 1 the best option with a η of 49.7%.

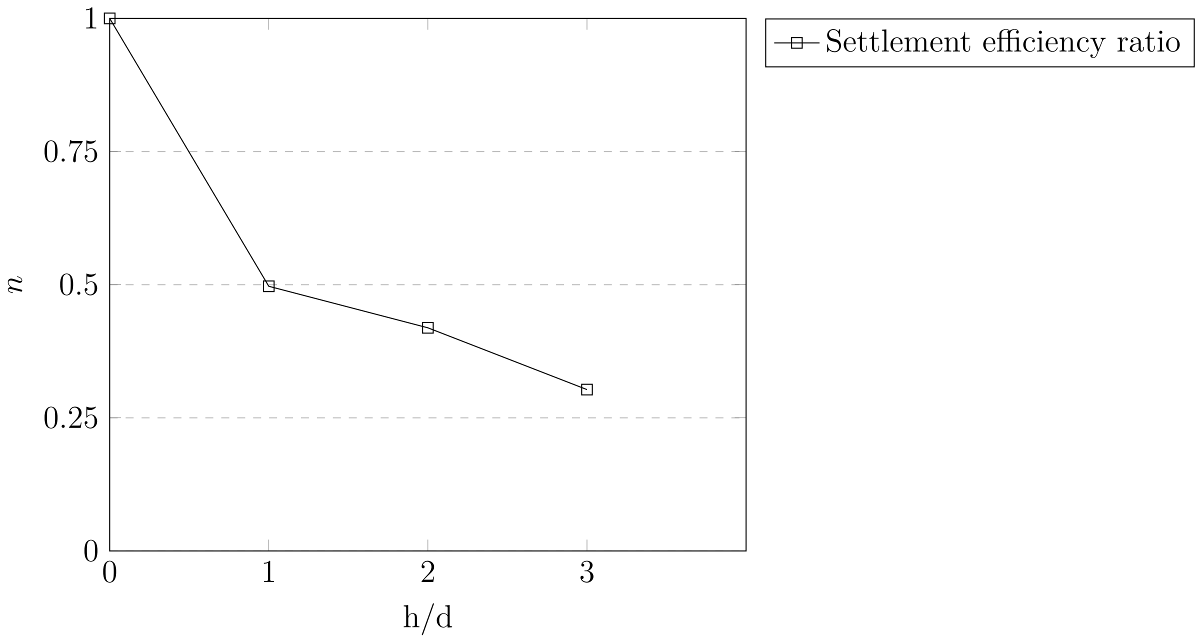

Figure 4.6: Settlement efficiency ratio with in different h/d ratio phases

4.2 Consolidation

An analysis with the calculation type of consolidation where made for a period of 100 years, after the load on the cushion was activated. The main purpose is to dispel the extra pore pressure and to analyze how the conductivity and permeabilities of the materials behave over a longer period. In figure 4.7 results from the consolidation calculation type are compared with the plastic result. In the undrained plastic phases without any cushion and a h/d ratio of 1 the results were similar. But for the consolidation calculation type, the h/d ratio of 1 was larger than the phase without any cushion.

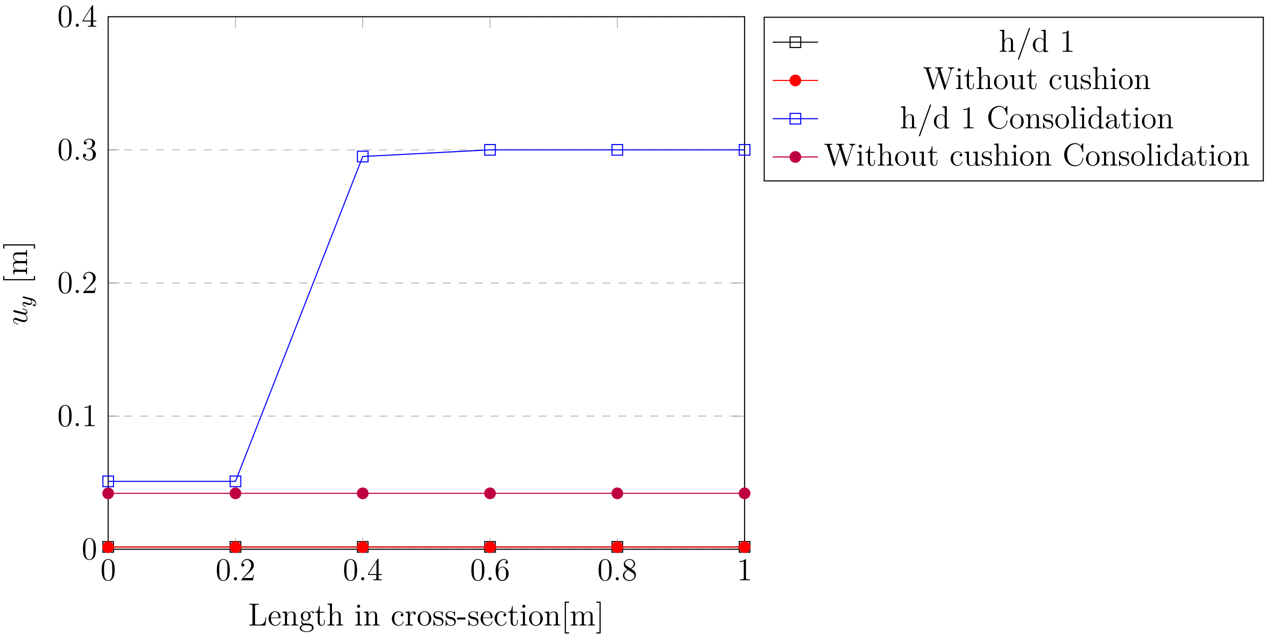

Figure 4.7: Comparison of plastic and consolidation calculation type on displacement.

If plotting the shear stresses from the same phases, it is visible in figure 4.8 from PLAXIS, that the phases without any cushion did not contribute to the NSF, because the is no material from the cushion to be vertically displaced more then the pile itself. Both the plastic and consolidation calculation types for the h/d ratio of 1 did have negative stresses. It proves the concept of NSF where the tangential stresses are 0 the neutral plan exists. For the plastic calculation type, the neutral plane exists at 2m depth, whereas in the consolidation it exists at a depth of 5m.

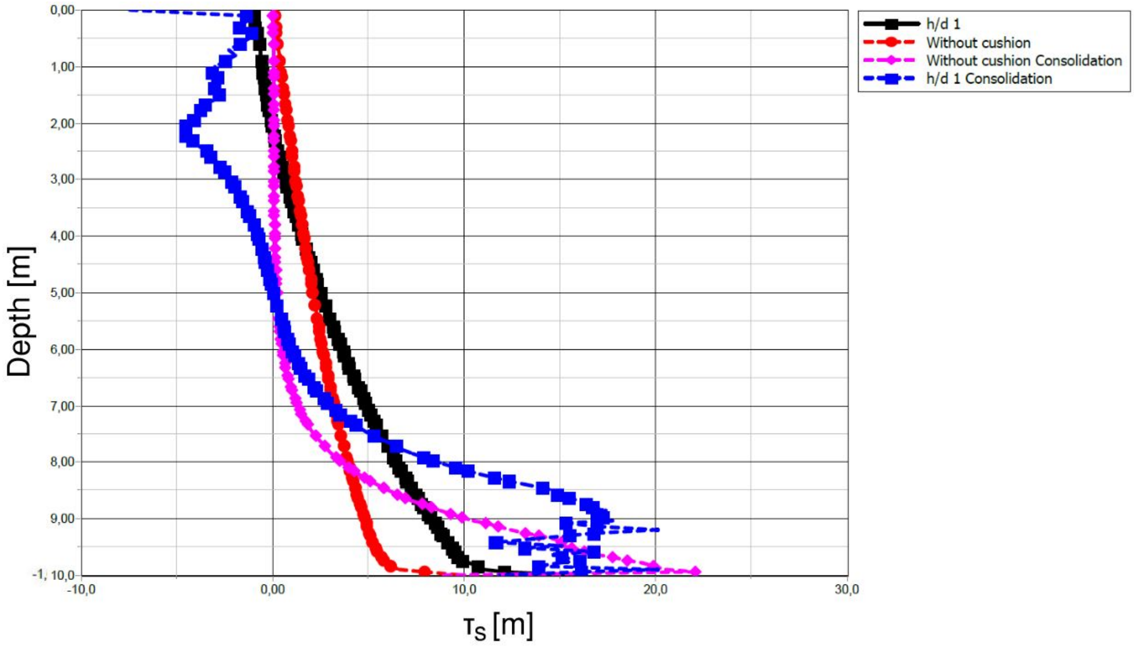

Figure 4.8: Sher stresses at the interphase between the pile and soil

4.3 Spacing in terms of arching

When installing a cushion layer some kind of geo-fabric or geotextile needs to separate the grain material from the soft soil. When the separation material is installed spacing between piles can be designed by following four steps from the British Standard BS8006 (Eekelen et al, 2011). The method divides the different loads affecting the pile into A, B, and C parts. A transmits directly into the pile, B transmits through the fill between the piles and is crucial for the arcing phenomena. C is transmitted directly into the subsoil since the geo-textile separates it from the overlaying cushion material. The model is in axisymmetry and therefore can equations for 3D be used in a 2D model (Jones et al, 1990). The arcing coefficient A_c for friction piles is described in equation 4.2. To determine the spacing and evaluate the efficiency of the pile, load part B is essential since it decides how much of the load is between the piles that are transmitted to the supporting pile.

$$A_c = 1.5 \cdot h/d - 0.07 \tag{4.2}$$

Where h is the height of the fill and d is the width of the pile. The pressure on the pile head σ_p can be calculated in the 2D case by using the arcing coefficient A_c and rewriting equation 4.3 to 4.4.

$$\sigma_p/(\gamma \cdot h) = A_c \cdot d/h \tag{4.3}$$

$$\sigma_p = A_c \cdot d \cdot \gamma \tag{4.4}$$

The pressure on the underlying soil can be calculated with the load on the surface p, in equation 4.5.

$$p'r = (\gamma \cdot h + p)X \tag{4.5}$$

Including the vertical stress on the pile cap $p'c$ in the grouped variable X is:

$$X = (s^2 - d^2 \cdot p'c/(\gamma \cdot h + p))/(s^2 - d^2) \tag{4.6}$$

Depending on the height of the fill, full or partial arcing should be assumed. For full arcing the statement $h > 1.4(s - d)$ needs to be fully filled. If the statement is not satisfied partial arcing needs to be assumed. The load part B can therefore be calculated with equation 4.7 or 4.8.

$$B_{full} = 2.8 \cdot s\gamma(s - d)^2 X \tag{4.7}$$

$$B_{partial} = (\gamma h + p)(s^2 - d^2)X \tag{4.8}$$

The pile efficiency depending on the spacing can then be calculated with equation 4.9 for full arcing and 4.10 for partial arcing. w is the total load from the overlying forces.

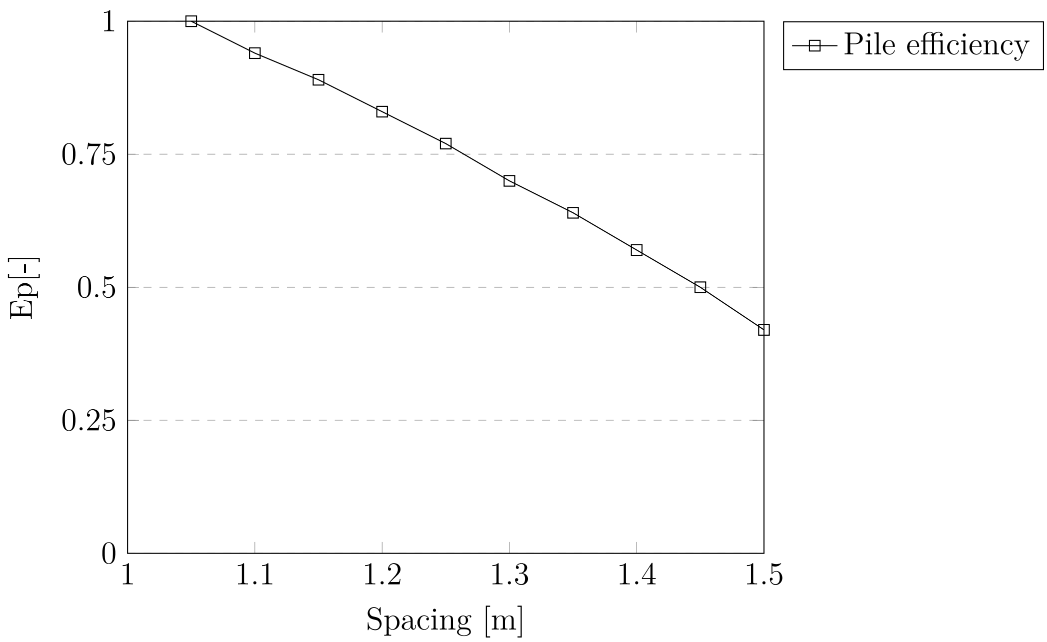

Figure 4.9: Pile efficiency depending on the spacing between the piles

$$E_p = 1 - B_{full}/w_{tot} \quad (4.9) \qquad E_p = 1 - B_{partial}/w_{tot} \quad (4.10)$$

E_p needs to fulfill $0 \leq E_p \leq 1$ with an value of 1 means perfect efficiency. Spacing for the piles is done with the goal to maximize the E_p. By plotting the efficiency with the spacing it is clear from figure 4.9 that efficiency decreases as the spacing are increased. With the height of the cushion being 0.5 meters and the statement for full arcing is not fulfilled by the equation $h > 1.4(s - d)$. In the case of this model equation 4.10 for partial arcing is used to obtain the optimal efficiency. The result showed that a spacing between the piles should be 1.05 meters to generate an E_p value of 1, thus being the optimal spacing for the arcing phenomena to occur. If taking the output from PLAXIS and calculating the same way in equation 4.11 it gains a result of 39.9% for a h/d ratio of 1.

$$E_{p,plaxis} = 1 - B_{p,plaxis}/w_{tot} \tag{4.11}$$

4.4 Sensitivity and uncertainty of parameters

Conducting the sensitivity analysis with the tool in PLAXIS for the model in the phase with a h/d ratio of 1 at node 918, located where the cushion meets the pile and the clay, with the value type set on the vertical displacement. The parameters that were examined was ϕ', γ, E' and v'. The SensiScore shown in figure 4.10 indicates that the most uncertainty of the material is in ϕ' and γ, having a score of 45 and 37. Whereas the E' and v' only have a score of 5 and 13.

Type	Material	Parameter	Min	Ref	Max	SensiScore	
Soil	Fill	φ' (phi)	34,00	38,00	42,00		45
Soil	Fill	γ_{unsat}	16,00	17,00	19,00		37
Soil	Fill	E'	35,00E3	40,00E3	45,00E3		5
Soil	Fill	v' (nu)	0,1000	0,3000	0,3000		13

Figure 4.10: Sensitivity analysis tool in PLAXIS

Continuing with the parameter variation the E' and v' parameters are neglected since they do not contribute notably to the uncertainty as seen in figure 4.11. A max and min project can be evaluated on the boundaries of the parameters with the highest scores.

	Type	Material	Parameter	Min	Ref	Max	SensiScore	
☑	Soil	Fill	φ' (phi)	34,00	38,00	42,00		45
☑	Soil	Fill	γ_{unsat}	16,00	17,00	19,00		37
☐	Soil	Fill	E'	35,00E3	40,00E3	45,00E3		5
☐	Soil	Fill	v' (nu)	0,1000	0,3000	0,3000		13

Figure 4.11: Parameter varation tool in PLAXIS

In table 4.1 where the parameter variation tool creates a maximum and minimum model of each parameter value, the displacement is decreasing as the friction angle ϕ' and density γ is increasing. Even if the clay is consolidated after the time frame of 100 years, the displacement is lower if the maximum values are used.

Table 4.1: Displacement at maximum and minimum project from the parameter variation tool in PLAXIS.

Undrained	ϕ'	γ_{unsat}	$u_{y,Undrained}$	$u_{y,Consolidation}$
Min	34°	16	0.260	0.399
Original	38°	17	0.254	0.389
Max	42°	19	0.238	0.297

5
Discussion

From the literature study, it is obvious that the DPR method has been tested for both numerical modeling and also put into practical use. The literature study was lacking examples of smaller projects, and more than often the DPR method may be too technical or cumbersome to implement on those kinds of projects. Even if there have been tests in geotechnical laboratories to find out parameter settings and geometry, it would be hard to do similar real-scale tests in-situ. Mostly due to the fact that contractors do not have the time or are willing to pay the cost for it.
The behavior of the material was set to undrained. Having the undrained behavior on the cushion material is only important if the material is saturated. In this model, the cushion material starts above but parts of the material will be below after the phase is completed. In that case, the permeabilities will affect the evolution of displacement. When calculating the $K0_{x,y}$ with the modified jaky's formula in equation 3.3 the value of 0.256 [-] seems a bit low and if increasing the value to the more reasonable 0.5 [-], the displacement increased.
Time-depending calculation with consolidation showed that after a significant time the displacements will increase due to the parameters of the clay, mostly depending on the excess pore pressure dissipation and hydraulic conductivity of the clay. But also if the clay is over or under consolidated from previous loads from the large ice layer during the last ice age. For a project that is supposed to last a long time, displacements happening from consolidation needs to be addressed. For minor scale projects, the loads are smaller and thus the consolidation settlements are decreased for the time span. Making the plastic calculation type more feasible, but still depending on the clay parameters. The time frame of one hundred years is not an option for smaller projects, and consolidation settlements would be smaller for a shorter time.
The height of the cushion layer from figure 4.4 shows a similar result as Halder and Manna (2021) found in their study, where the h/d ratio of 1 did have a η of 45 and the result from this thesis concluded a result of 50. Where the settlement efficiency results correspond to the results from the thesis, further solidating the outcome of the numerical modeling being somewhat accurate to a 1g model. The difference is that they concluded that the optimal h/d ratio would be 2, and in this thesis, the results concluded that a h/d ratio of 1 is a better choice, this is because of the different parameters in the cushion material, the material they used for the cushion did have a higher friction angle of 47 to 56. Also, some numerical differences could have occurred since they did not perform a FEM analysis, and they did perform the 1g model test for a pile group instead of a single pile. As seen in figure 4.6 the efficiency ratio did decrease with the h/d ratio increased. This is due to the

settlements in the previous phase being smaller.
The British Standard for pile spacing considers the arching phenomena, and therefore must consider the height of the soil or cushion layer to be able to work, if there is no material for the arching to take place in, it will not occur. A common practice used in the field is to use a pile spacing of three times the width of the pile. For this model that would yield a spacing between piles of 1.5 meters, from figure 4.9 it can be noted that the pile efficiency from arcing would be 42%, which is a good value for industry standards since 100% is almost impossible to obtain. Comparing the hand calculation with the output from PLAXIS the difference was only 2.1%. The difference can be explained by numerical error or by the fact that it's an average of the output from PLAXIS. To further investigate this, spacing can be calculated with higher h/d ratios, If changing the height of the cushion one must consider if the partial or full arching calculation should be used.
When modeling complex structures using PLAXIS, the time it takes to calculate each phase differs from how many nodes are present in the mesh. But also how many steps each phase should take to reach a result. In the phase where an h/d ratio of 3 would be obtained PLAXIS did not meet the accuracy needed to achieve a result. In that case, the maximum steps and iterations were increased as well as the accuracy requirements. This did not impact the results but did manage to get the model to work but with a longer calculation time. To decrease the calculation time even further embedded piles could be implemented. An embedded pile element is a 1D overlay to a 3D model, as the embedded pile is not physically in the model it is implemented after generating the mesh (Tradigo et al, 2015). The interfaces between the embedded pile and the soil are of the most importance.
The results of the max and min projects in the parameter variation tool described in table 4.1 showed decreasing displacement when increasing the γ, but this is not true. The way the parameter variation tool works is that it takes all the minimum values and creates a project model and then the same for the maximum values. In this case, the friction angle of the cushion material did impact the model more than the density. As could be noted in the Sensiscore from figure 4.10, the uncertainty is higher for the friction angle than the density, further increasing the importance of using a material with a higher friction angle. The sensitivity analysis could be developed more by adding different materials for the concrete or clay, but since the thesis is concentrated around Gothenburg clay there was no reason to change those parameters.

5.1 Conclusion

This study concluded that it is feasible to use DPR in Gothenburg clay. The piles working as soil reinforcement under the cushion layer had a large impact on the vertical displacements. But if not subjected to horizontal forces that could buckle or crack the piles the PR might be a better solution with Gothenburg clay parameters, depending on the situation and project in mind. To summarize this thesis and to give an answer to the problem of a project should use the DPR method instead of the PR method some vital key questions should be taken into account.

- The foundation should be subject to horizontal forces to be able to use the

DPR method to its full capacity.
- Choosing a cushion fill material where the friction angle should be as large as possible, to reduce the vertical displacements. The density of the material also had a large impact on the vertical displacements.
- The optimal height of the cushion layer is depending on the spacing between the piles and the arching phenomena. But results showed that a height lower than a h/d ratio of 1 did not affect the displacement, making the arching to be only partial. If the model would have an increased cushion height, full arching might need to be considered.
- The conditions of the stratigraphy and the soil parameters should be carefully investigated since they will impact the displacement notably if the subsoil is not strong enough.
- Consolidation analysis inflicted larger displacements than undrained. Making it more crucial to investigate if the structure should be operational for a longer period.
- NSF did not occur for the models without any cushion.

5.2 Further studies

Further studies in this numerical model could be done to achieve more accurate results. Elaborating with different heights and loads on the foundation. The model could also be done with a pile group to better understand how displacements behave if the soils load-bearing capability is shared by more piles. The model could also be done with another 2D numerical model software like MIDAS, FLAC, or ABAQUS. If done correctly the software should have the same outcome. An optimization of combining the pile spacing from the British standard and cushion height would be an interesting study. If contractors are willing to pay the costs, in-situ tests can also be beneficial to further understand if the DPR method would be a good choice of foundation.

References

Arun and Basheer. (2021). *Settlement behaviour of disconnected piled raft foundation under vertical loading conditions.* Retrieved from https://www.irjet.net/archives/V8/i5/IRJET-V8I5148.pdf

Ata et al. (2015). *Numerical analysis of unconnected piled raft with cushion.* Retrieved from https://doi.org/10.1016/j.asej.2014.11.002

Bentley. (2020). *Plaxis 2d-reference manual.* Retrieved from https://communities.bentley.com/cfs-file/__key/communityserver-wikis-components-files/00-00-00-05-58/3113.PLAXIS2DCE_2D00_V20.02_2D00_2_2D00_Reference.pdf

Biesiadecki et al. (2004). *Rion – antirion bridge foundations: A blend of design and construction innovation.* Retrieved from https://scholarsmine.mst.edu/cgi/viewcontent.cgi?article=2623&context=icchge

Brinkgreve et al. (2012). *Plaxis 2d 2012.* Retrieved from https://d3pcsg2wjq9izr.cloudfront.net/files/3873/download/370462/2D2012-0-Gen-Info.pdf

Eekelen et al. (2011). *Analysis and modification of the british standard bs8006 for the design of piled embankments.* Retrieved from doi:10.1016/j.geotexmem.2011.02.001

Fellenius. (2006). *Results from long-term measurement in piles of drag load and downdrag.* Retrieved from https://DOI:10.1139/T06-009

Fioravante and Giretti. (2010). *Contact versus noncontact piled raft foundations.* Retrieved from https://www.water-technology.net/projects/mose-project/

Halder and Manna. (2021). *Large scale model testing to investigate the influence of granular cushion layer on the performance of disconnected piled raft system.* Retrieved from https://doi.org/10.1007/s11440-020-01121-5

Huang et al. (2015). *The group effect on negative skin friction on piles.* Retrieved from https://doi.org/10.1016/j.proeng.2015.08.367

Jones et al. (1990). *Geotextile reinforced piled embankments. in: Den hoedt (ed.), geotextiles, geomembranes and related products.* Retrieved from https://webapps.unitn.it/Biblioteca/it/Web/EngibankFile/1062737.pdf

Karstunen and Amavasai. (2017). *Best soil: Soft soil modelling and parameter determination.* Retrieved from https://research.chalmers.se/publication/522789/file/522789_Fulltext.pdf

King. (2005). *Plate tectonics map - plate boundary map.* Retrieved from https://geology.com/plate-tectonics.shtml

Miller. (2018). *Supplementary cementitious materials to mitigate greenhouse gas* *emissions from concrete: can there be too much of a good thing.* Retrieved from https://doi.org/10.1016/j.jclepro.2018.01.008

Olsson. (2010). *Calculating long-term settlement in soft clays – with special focus on the gothenburg region.* Retrieved from https://www.sgi.se/globalassets/publikationer/rapporter/pdf/sgi-r74.pdf

Olsson. (2013). *On rate-dependency of gothenburg clay.* Retrieved from https://www.researchgate.net/profile/Mats-Karlsson/publication/292139966_On_Rate-Dependency_of_Gothenburg_Clay/links/56a9e4f608ae2df82165d7e9/On-Rate-Dependency-of-Gothenburg-Clay.pdf

Sas et al. (2013). *Determination of poisson's ratio by means of resonant column tests.* Retrieved from http://www.ejpau.media.pl/volume16/issue3/art-03.html

Scheller and Thörn. (2018). *Governing 'sustainable urban development' through self-build groups and co-housing: The cases of hamburg and gothenburg.* Retrieved from https://doi.org/10.1111/1468-2427.12652

Svensk Betong. (2022). *Livslängd för byggnader.* Retrieved from https://www.svenskbetong.se/bygga-med-betong/bygga-med-prefab/miljo-och-hallbarhet/livslangd-for-byggnader

Sällfors. (2013). *Geoteknik jordmateriallära jordmekanik.* Cremona at Chalmers University of Technology.

Tarenia and Patra. (2019). *Behaviour of disconnected and connected piled raft foundation subjected to compressive load.* Retrieved from DOI:10.11159/icgre19.180

Tradigo et al. (2014). *Non-linear soil-structure interaction in disconnected piled raft foundations.* Retrieved from https://dx.doi.org/10.1016/j.compgeo.2014.08.014

Tradigo et al. (2015). *On the use of embedded pile elements for the numerical analysis of disconnected piled raft.* Retrieved from https://dx.doi.org/10.1016/j.compgeo.2015.11.005

Vangla and Latha. (2015). *Influence of particle size on the friction and interfacial shear strength of sands of similar morphology.* Retrieved from https://DOI10.1007/s40891-014-0008-9

Water Technology. (2022). *Mose project, venice, venetian lagoon.* Retrieved from https://www.water-technology.net/projects/mose-project/

Witasse. (2021). *Parameters variation: Model customization and sensitivity analyses.* Retrieved from https://blog.virtuosity.com/parameters-variation-model-customization-and-sensitivity-analyses

Zhu. (2017). *Analysis of the load sharing behaviour and cushion failure mode for a disconnected piled raft.* Retrieved from https://doi.org/10.1155/2017/3856864

Zhu et al. (2018). *Horizontal loading tests on disconnected piled rafts and a simplified method to evaluate the horizontal bearing capacity.* Retrieved from https://doi.org/10.1155/2018/3956509

DEPARTMENT OF ARCHITECTURE AND CIVIL ENGINEERING
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden
www.chalmers.se

CHALMERS
UNIVERSITY OF TECHNOLOGY