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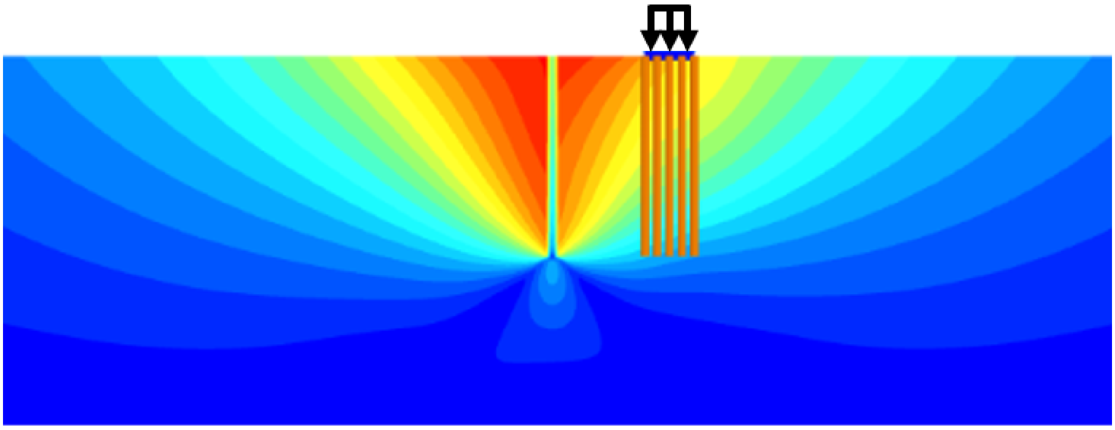

Interaction between new and existing foundations during pile installation

A parameter study based on numerical modelling

Master's Thesis in Infrastructure and Environmental Engineering

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Cover: Vertical movements from pile installation with an adjacent piled raft affecting the displacement field.

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Abstract

Dense urban areas are becoming a challenge for many large growing cities due to the urbanisation. Gothenburg in Sweden is one of many examples of a city facing this challenge while also being located in an area with challenging soil conditions, constituting of deep deposits of soft clay. This needs to be considered during the design phase of large constructions, in which often requires deep foundations that can affect surrounding structures due to the mass displacements originating from the pile installation. This Thesis is an investigation of mass displacement due to pile installation in soft soil. The magnitude and extent of the soil movements will be investigated and the impact of existing structures quantified. The analysis was performed with numerical modelling in the geotechnical program Plaxis, where a parameter study was performed. Parameters such as pile length, width of raft, load on structure, soil stiffness, among other parameters, were varied to study the influence on the soil movement and the existing adjacent structure. The results are discussed in relation to analytical calculation methods and field data from similar conditions. The result shows a redistribution of heave and horizontal displacements from pile installation, caused by the interference of an existing piled foundation. The piles in the existing structure redistributed the soil movements while the load had little to no impact. The compressive loads in the existing piles reduced significantly due to nearby pile installation, with a risk of reducing further, leading to tensile loads. The displacements from pile installation acts similar as downdrag but in reverse on the existing piles. In addition to tension, the piles also experience increased bending moment, especially near the pile head, at the perimeter of the raft.

Keywords: Geotechnics, geology, pile installation, mass displacement, soil movement, deep foundations, numerical modelling, Plaxis, parameter study.

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Kajsa Alte, Niklas Björn, Gothenburg, June 2023

List of Acronyms

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

ESP	Effective stress path
CEM	Cavity expansion method
FEM	Finite element method
SPM	Strain path method
SSPM	Shallow strain path method
PLD	Prescribed line displacement
TSP	Total stress path
OCR	Over consolidation ratio
VS	Volumetric strain

Nomenclature

Below is the nomenclature of the parameter that have been used throughout this Thesis.

γ	Unit weight $[kN/m^3]$
ϵ	Strain [-]
θ	Water content [%]
ν	Poisson's ratio [-]
ν'	Effective Poisson's ratio [-]
ϕ	Friction angle [deg]
ϕ'	Effective friction angle [°]
ψ	Dilatancy angle [deg]
ψ'	Effective dilatancy [deg]
D	Diameter of existing pile [m]
E	Young's modulus $[kN/m^2]$
E'	Effective Young's modulus $[kN/m^2]$
G	Shear modulus [GPa]
K	Bulk modulus [GPa]
L_{exist}	Length of existing pile [m]
L_{inst}	Length of installed pile [m]
L_p	Pile length [m]
$L_{spacing}$	Centre to centre distance of piles [m]
S_t	Sensitivity [-]
b	Width of footing [m]
b_{raft}	Width of raft [m]
$b_{superpile}$	Width of footing [m]
d	Distance between installed pile and existing raft [m]
c	Cohesion [-]
c'	Effective cohesion [-]

c_u	Undrained shear strength [kPa]
k	Permeability [m/s]
q	Building load [kN/m]
w	Width of superpile/imposed displacement[m]

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1
Introduction

Gothenburg is the second largest city in Sweden with a lot of plans for development. An expected increase in population with 150 000 people until year 2035 puts pressure on development of housing and infrastructure in an already dense city (Göteborgs Stad, 2014). Gothenburg is situated upon deep deposit of soft clay which needs to be considered during design and construction due to its low bearing capacities and susceptibility for long-term settlements. The clay layer in Gothenburg can reach a depth of more than 100 metre, which can be seen in Figure 1.1.

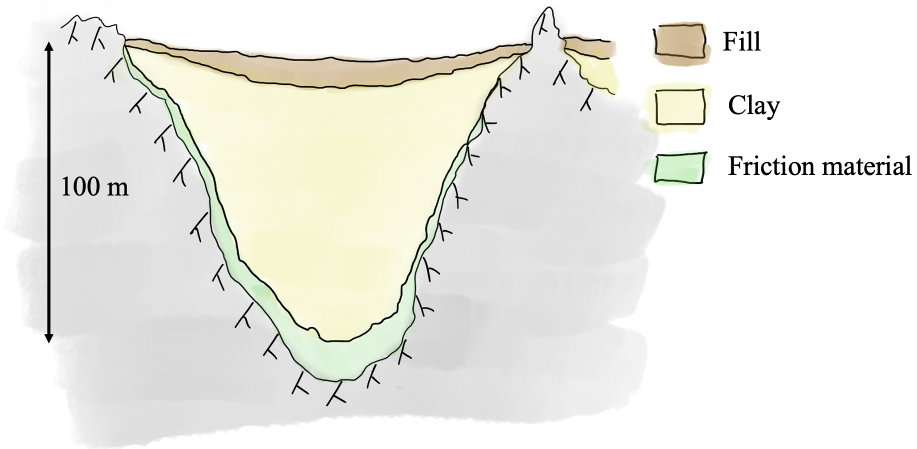


Figure 1.1: Principal section of deep clay layer in Gothenburg.

A typical design solution is deep foundations with piles to transfer structural loads to more stable depths and mitigate the settlements. The design of the pile foundation (pile length, type and amount) is largely based on the height and consequently weight of the overlaying construction. The installation of a pile will disturb and remould the soil in its proximity. Furthermore, the installation of piles will lead to movements in the surrounding soil. The magnitude of these movements will be dependent on the pile type, installation method and characteristics of the soil. There has been substantial technical efforts and research reports dedicated to understand and simulate the resulting mass displacement from pile installation. While there has been limited research dedicated to investigating the effects of mass displacement on nearby structures and vice versa, specifically how nearby structures influence the distribution of mass displacement. Current analytical methods to estimate mass displacement of soil are optimal in free field conditions, assuming ideal conditions, meaning no adjacent piles or structures impacting the soil movement. That is rarely the case and Gothenburg shows a good example of a dense and complex urban setting with existing deep foundations in proximity to newly installed piles. These conditions creates an uncertainty in prediction of building displacements that can generate large cost in a later stage of the project which can be avoided with better knowledge about the installation effects on adjacent structures. Since pile installation generates heave and horizontal soil movement, adjacent piles can be exposed to detrimental uplifting forces and bending moments. It is therefore of interest to investigate how the existing piles are affected by mass displacement, as well as provide more knowledge how soil moves in a complex urban setting during installation of piles.

1.1 Aim

The aim of this Thesis is to investigate the interaction between new and existing foundations during and after pile installation, i.e. the study will investigate how an existing foundation is affected by the displacement from the installation of adjacent piles, as well as to study how a nearby existing foundation influence the distribution of mass displacement from nearby piling activities. The following objectives will be addressed.

- Create a 2D model that captures the interaction between mass displacement and structures during pile installation by calibrating it towards a real case scenario.
- Quantify horizontal and vertical movements of soil when inducing a displacement field representing the installation of a pile.
- Investigate the interaction between newly installed and existing pile groups by performing a parameter study by altering geometries, properties and type of adjacent structure as well as soil properties and magnitude of applied load.
- Examine structural forces and deflection in the existing piles of the adjacent structure arising from a displacement field representing a pile installation.
- Discuss and conclude results and risks with pile installation.

1.2 Limitations

This study is limited to mass displacement from pile installation in soft soil. The focus area is a dense urban setting with a floating pile foundation using prefabricated concrete piles. Displacements from installation will be analysed directly after installation as a short term case.

2 Theory

Foundations can be divided into shallow and deep, where shallow foundations are typically used for smaller buildings in soils with higher strength and stiffness. As the ground conditions get more challenging and the construction above is taller and heavier, the need for deep foundations, such as piling, gets larger. Piles are typically divided into end-bearing piles and cohesion piles (also referred to as floating piles). End-bearing piles transfer the load from the overlaying construction to the bedrock or more competent soil layers, whereas cohesion piles transfer the load from the overlaying construction to the surrounding soil through the interface by cohesion between the soil and pile, see illustration in Figure 2.1.

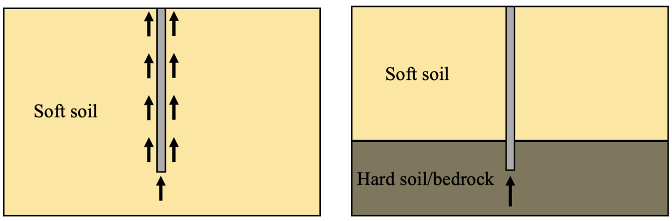


Figure 2.1: Simplified illustration of how cohesion- and end-bearing piles carry loads.

There are different installation methods for piles and driving is the most common in Sweden (Hercules Grundläggning AB, 2022). Driven piles are a so-called displacement pile, which create local disturbances by remoulding the soil closest to the pile(Fleming et al., 2008). Pile installation imposes mass displacement in which leads to an increase in pore water pressure if the soil is a cohesive with low permeability. A cohesive soil does not allow for volume change and therefore increase the pore pressure instead, called excess pore water pressure. This results in a decrease in effective stress and an increase in total stress. After installation occurs the equalisation phase and the excess pore water dissipates where the soil find a new equal state during consolidation. The capacity of the installed pile will increase with time as the soil regains its strength when the excess pore water pressure dissipates.

There are other techniques for pile installation, such as boring, which does not create the same magnitude of soil movement. However, such techniques are more expensive and takes longer time. Driven precasted concrete piles are therefore due economic advantages the preferred choice for foundations in Sweden.

The process of pile installation and its effect on adjacent soil have been investigated by several researchers. As stated before, the installation of piles both remoulds and initiate soil movements in the surroundings. It is shown that remoulding of the soil has a negative impact on the shear strength of the soil but only temporarily and within a very short distance from the pile (Roy et al., 1981; Gue, 1984; Hwang et al., 2001). More relevant to this study is the mass displacements which is significant at some distance from the installed pile. The following Chapter will describe the pre-requisites for mass displacement of soil, its behaviour during piling, different methods to estimate this mass displacement of soil and how this mass displacement is believed to affect nearby structures.

2.1 Mass displacement due to pile installation

There are a few soil properties that constitutes pre-requisites for the behaviour of mass displacement. Sensitivity of a soil have an influence as it has been observed that an insensitive soil generates more displacements compared to a more sensitive one (Hagerty & Peck, 1971; Dugan & Freed, 1984; Hintze et al., 1997). A sensitive soil is instead more susceptible to changes in shear strength and pore pressures close to the pile, which earlier have been mentioned as remoulding. The most critical condition, in regard to mass displacement, is when the soil acts in short-term as incompressible when subjected to a force. This can occur when a soil is of low permeability and highly saturated. The presence of water in the pore spaces and the limited possibility for it to dissipate creates incompressible conditions. Clay is a good example of this, since it is a very fine material with typically low permeability, which leads to slow consolidation over time when subjected to a force. The mass displacement occurs instantaneously during the pile installation, and an assumption can be made that the volume of mass displaced then equals the volume of piles installed since no compression occurs.

The incompressibility of a soil is dependent on Poisson's ratio. Poisson's ratio together with Young's modulus, E, can describe the elastic response in an isotropic material. A Poisson's ratio of 0.5 implies that the material is incompressible according to an undrained case. To better explain Poisson's ratio and incompressibility, the elasticity can be divided in to bulk modulus, K, which measures the resistance to volume change, and shear modulus, G, which measures resistance to distortion (or shear). The relation between Poisson's ratio, Young's modulus and the bulk modulus is written in equation 2.1, and which is seen $\nu = 0.5$ means $K_0 = \infty$.

$$K = \frac{E}{3(1-2\nu)} \tag{2.1}$$

The most critical case for mass displacement is when constant volume occurs (due to no compression), leading to displacements in the soil, i.e the undrained case. The relationship can be explained with the undrained total elastic response in equation

2.2.

$$\begin{bmatrix} \Delta\epsilon_p \\ \Delta\epsilon_q \end{bmatrix} = \begin{bmatrix} \frac{1}{K} & 0 \\ 0 & \frac{1}{3G} \end{bmatrix} \begin{bmatrix} \Delta p \\ \Delta q \end{bmatrix} \tag{2.2}$$

If no volume change occurs, $\Delta\epsilon_p = 0$, which implies that $\frac{\Delta p}{K} = 0$. The change in mean stress, (Δp), is dependent on the pore pressure which rapidly increases due to no drainage. To achieve strain being 0 and no compression occurring, the bulk modulus must be large (or infinite). Therefore Poisson's ratio of 0.5 creates the highest possible bulk modulus according to equation 2.1.

2.1.1 Single pile

Various research have been conducted to better understand mass displacement around one single pile which have been captured with lab tests, field measurements and various analytical and numerical methods (Hagerty & Peck, 1971; Bozozuk et al., 1978; Randolph et al., 1979; Gue, 1984; Dugan & Freed, 1984; Lehane & Gill, 2004; Ni et al., 2010; Edstam & Kullingsjö, 2010). The typical displacement field in the soil can be seen in Figure 2.2. The closest vicinity to the pile, also called the smear zone, soil moves downwards due to shaft friction towards the circular area beneath the pile, creating a bulb of pressure. Outside of this closest area around the pile, the soil instead have a radial displacements. Further away from the pile, the displacement gradually changes from radial to heaving displacements.

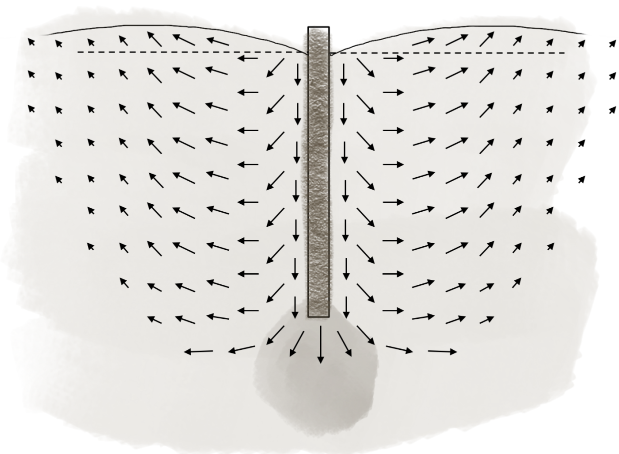


Figure 2.2: Schematic illustration of displacement field around installed displacement pile.

2.1.2 Pile groups

There are a several factors that is considered to have an impact on the displacement from installation of a pile group. Hagerty & Peck (1971) analysed different case studies that measured field movement from piling. They concluded that the pile volume appears as ground heave, where approximately half of the volume creates heave inside the piling area and the other half outside of the piling area. However, Massarsch & Wersäll (2013b) concluded that this is not true for longer piles where the heave outside the piling area is larger then 50%. They conclude that pile diameter and spacing affects the heave, while the pile length determines how far from the piling area the heave occurs.

If the piling area is located in a slope, the displacement direction is affected (Hagerty & Peck, 1971; Massarsch & Wersäll, 2013a). The resulting direction of movement would occur towards the lower elevation and the amount of change in direction is dependent on the gradient of the slope. Another factor that has been noticed to have an effect on the displacement field is the installation order of piles in a pile group. Hagerty & Peck (1971) concludes in their study that an order of installation from the outside of the foundation towards the middle, redistributes the displacement with less surface heave occurring outside of the piling area and more on the inside. Massarsch & Wersäll (2013b) agrees with this result by concluding that the most recent installed pile generates more heave in the surrounding area, compared to the previous installed.

2.2 Analytical calculation methods

Several analytical methods are available to estimate the mass displacement from installation of displacement piles. A common method in Sweden is the so-called Hellman/Rehnman method. A method based on superposition principle, where the horizontal movement as well as the heave at the ground surface is obtained (Rehnman et al., 1993). The method assumes that the soil will move the volume of piles installed, and therefore does not contain any parameters related to the soil. Only geometry of the piles and piling area and factors representing the weight of adjacent building, see Figure 2.3. The method assumes the displacement to affect a wedge shape around the piling area which reaches a distance of about one pile length on the ground surface, creating an inclination of 1:1.

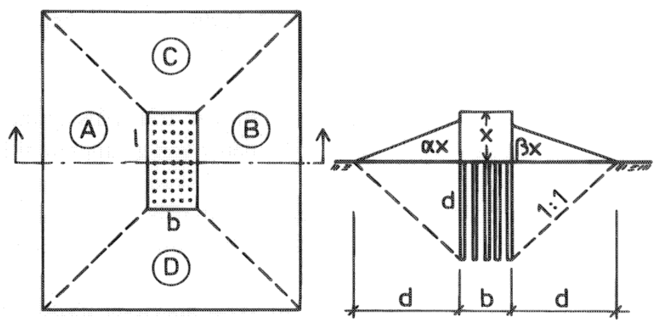


Figure 2.3: Heave at ground surface from pile installation. From Rehnman et al. (1993)

Where heave at ground surface can be calculated with equation 2.3

$$x = \frac{\eta(V_{piles} - V_{clayplugs})}{d((\alpha+\beta)(\frac{l}{2}+\frac{d}{3}) + (\gamma+\delta)(\frac{b}{2}+\frac{d}{3}) + \frac{bl}{d}} \tag{2.3}$$

Where

x - heave in piling area

η - heave factor, normally $\eta = 0.75$

V_{piles} - volume of installed piles

$V_{claypluggs}$ - volume of clay plugs

d - pile length

b - width of piling area

l - length of piling area

αx - heave of building A closest to the piling area

βx - heave of building B

γx - heave of building C

δx - heave of building D

α, β, γ and δ represent the weight of the building from 0 (heavy) to 1 (light). The heave factor, η, relates to the compressibility of the soil from 0.5 to 1.

Another method is the Strain Path Method (SPM), which is also independent from soil parameters, that provides reasonable well prediction for displacements close to the tip of the pile (Baligh, 1985). The method constitutes of integrating expanding spherical volume along the pile, assuming a friction less and incompressible soil. It is however limited in its prediction further away from the pile and closer to the surface since it does not consider a stress free ground surface. To make up for a stress free ground surface the SPM was modified to what is called the Shallow Strain Path Method (SSPM). This method, developed by Sagaseta et al. (1997), shows better agreement of soil behaviour closer to the surface, see Figure 2.4.

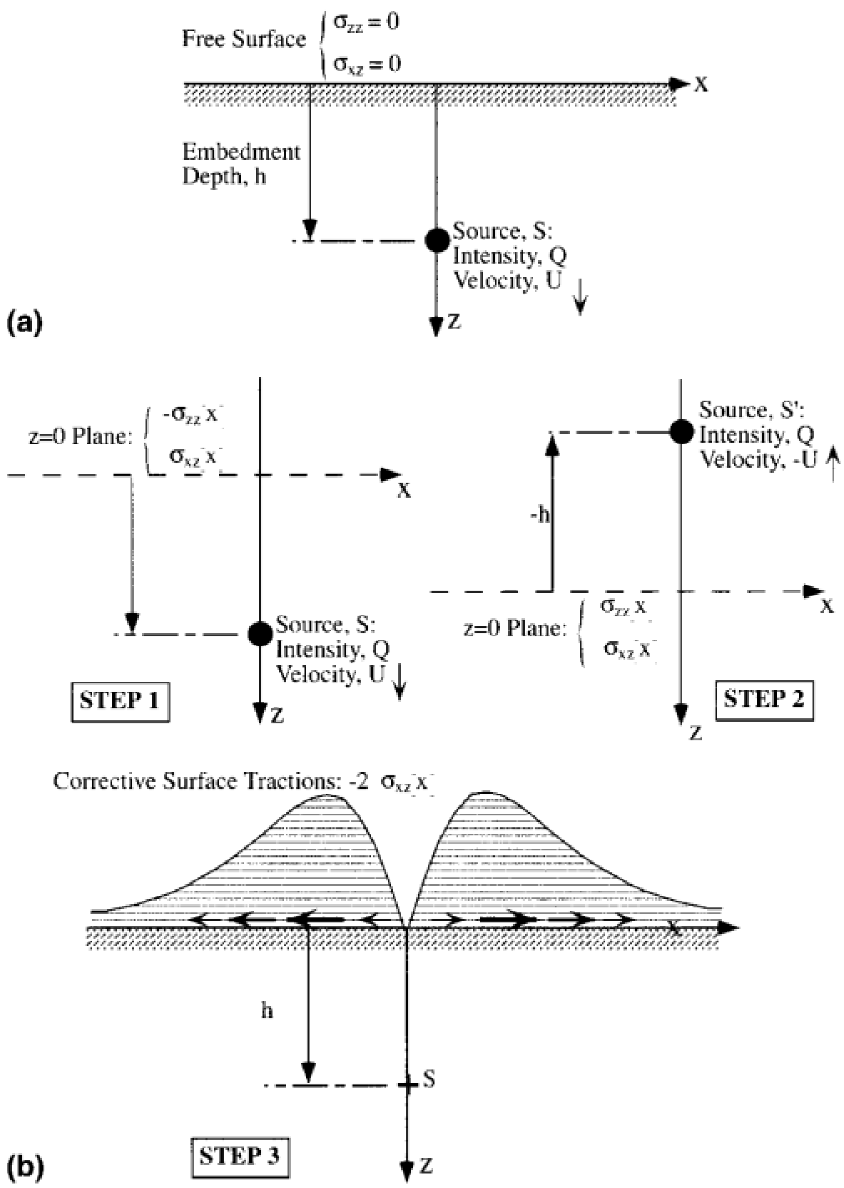


Figure 2.4: Conceptual model for Shallow strain path method a) representation of problem b) equivalent solution. From Sagaseta et al. (1997)

Horizontal displacements and heave at ground surface for a simple pile (axisymmetric) can be calculated with equation 2.4 and 2.5.

$$\delta_r = \frac{R^2}{2}\frac{L_p}{r\sqrt{r^2 + L_p^2}} \tag{2.4}$$

$$\delta_z = -\frac{R^2}{2}(\frac{1}{r} - \frac{1}{\sqrt{r^2 + L_p^2}}) \tag{2.5}$$

Horizontal displacements and heave at ground surface for a planar wall (plane strain) can be calculated with equation 2.6 and 2.7.

$$\delta_x = 2\frac{w}{\pi}tan^{-1}(\frac{L_p}{x}) \quad (2.6)$$

$$\delta_z = -\frac{w}{\pi}ln[1 + (\frac{L_p}{x})^2] \quad (2.7)$$

Where

R - Radius of pile

L_p - Length of pile

r - Horizontal distance from centre of simple pile

w - Half width of planar wall

x - Horizontal distance from centre of planar wall

Both Hellman/Rehnman and SSPM can provide good estimations for mass displacement in a free field area. However, free field is in reality rarely the case and neither of these methods includes detailed influence from already existing adjacent structures.

Another commonly used theory when modelling mass displacement is the Cavity Expansion Method (CEM) which was first introduced by Bishop et al. in 1945. The method is based on continuum mechanics with a stress-strain model of the medium (soil). By expanding a spherical or cylindrical hole in a soil creating radial stresses, the change in displacement, pore pressure and stresses can be observed. The use of CEM can be applied to capacity calculations such as piling or tunnelling, and interpretation methods for soil testing (Yu, 2000).

2.3 Numerical modelling

Numerical modelling in geotechnical engineering comes with large complexities and possibilities. Potts (2003) wrote a paper about numerical modelling and its application to geotechnical problems by reviewing the possibility to replace conventional methods with numerical. He discussed the complexity of input parameters, constitutive models and real-life cases by explaining the possibilities and limitations. Potts argues that numerical modelling is by far the best tool a geotechnical engineer can use but the need for a "skilled operator" is vital. It is important to keep in mind that a FE model only calculates what it is told to calculate, based on given input. An understanding of the model itself and the real problem is important to gain a reasonable result. There are different FEM softwares for geotechnics available on the market, such as Plaxis, Abaqus and Safe. Plaxis is a common tool to model soil and rock problems such as deformations and stability. It also includes interactions between structure elements, influence of ground water and temperature.

2.3.1 Comparison of modelling in 2D and 3D

Numerical modelling can be performed in both 2D and 3D inn Plaxis. In 2D, the user needs to choose how to model the out-of-plane direction. It can be divided to either a circular geometry or a continuing plane. The circular geometry, called axisymmetric, is used with a radial cross section. The only way to model a pile is by placing it along the y-axis of a axisymmetric model. Any other placement would extend to a circular wall, see Figure 2.5. The plane strain analysis extends the section infinitely in the out-of-plane direction which allows for any placement of structures.

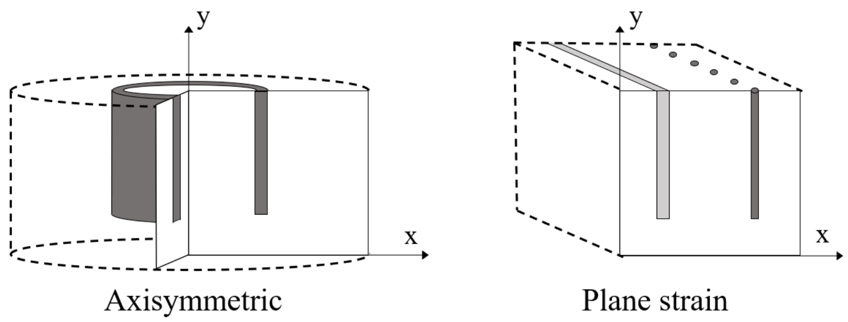


Figure 2.5: Drawing of a) axisymmetric model and b) plane strain model.

One important aspect in the difference between the models is how an induced displacement is interpreted as a volume and spread in the models domain. The extending area in a plane strain is only going in one direction whilst the extending of movement occurs in every direction for the axisymmetric model. This results in a faster decrease of the spread in displacements in two dimensions. Both axisymmetric and plane strain are two extreme cases for modelling a problem in 2D and the reality is rarely any of these two, but a combination between them. An axisymmetric model is preferable when modelling one object or source, such as a single pile which distributes equally in every direction, see Figure 2.6a. A plane strain model will be more applicable to a row of piles, which all acts as single piles and adding up to a uniform movement from the row, see Figure 2.6b.

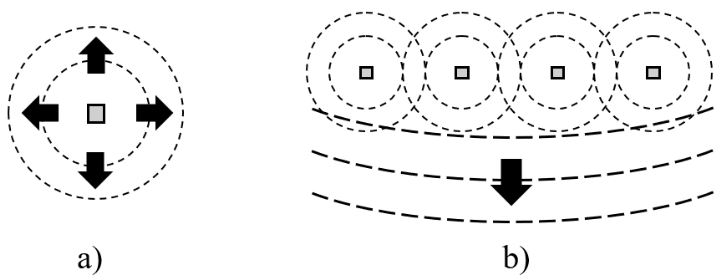


Figure 2.6: Example of spread of soil movement, seen from above, with application of a) axisymmetric mass distribution and b) plane strain mass distribution.

A single pile is likely to displace masses in an axisymmetric distribution, whilst a row of piles shares similarities with a plane strain distribution. The same theory can be applied to the distance from the source. A location close to a piling area is more similar to a plane strain case, compared to a location at greater distance where the distribution of mass displacement has more similarities to an axisymmetric case, see Figure 2.7.

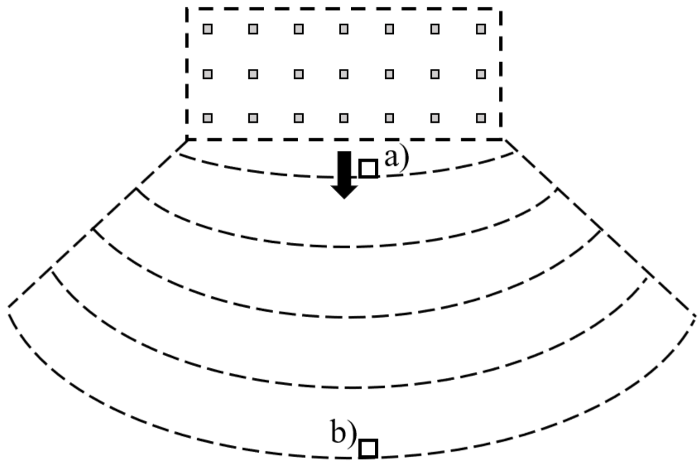


Figure 2.7: Conceptual illustration of when mass displacement from a piling area can be similar to a) a plane strain model and b) an axisymmetric model.

2.3.2 Soil behaviour

Soil behaviour is considered to be a complex phenomenon that can be difficult to fully capture in numerical modelling. Simplifications are usually made in schoolbook examples where the soil can be described with a linear elastic and perfectly plastic behaviour. The soil would in theory behave in a linear elastic manner until it reaches the yield point where it starts to behave with a plastic response. During the linear elastic state the deformation would recover if unloaded. As for plastic state, the deformations are irreversible.

In reality it is more complicated thus soil have been observed to behave in a highly nonlinear manner (Wood, 1991). In other words, the stiffness of soils is not constant but changes as the stress level change and depend on how the soil consolidate with time. It can harden or soften during the plastic phase, meaning that the soil gains or loses shear strength during yielding. In addition to this the soil can be structured in an anisotropic manner. That means that although the soil as a material may be isotropic, history of soil deposition and stresses creates an anisotropic soil layering (Wood et al., 2001). This can be due to how deposition of soils can create inhomogeneities in the soil structure and composition which will affect how the soil behaves in different directions (Budhu, 2011). It can also be due to how stresses in the past from different direction have made the soil stiffer in an anisotropic manner.

It will be apparent when discussing different constitutive models that not all these characteristics will be modelled properly and that it depending on the geotechnical problem can be more or less important.

2.3.3 Constitutive models

Constitutive models creates relationships between stress and strains in soil, which needs to be defined when analysing a geotechnical problem. The stress-strain relationship in soils can be expressed in different ways dependent on the stiffness of the material. Several studies have been conducted to more accurately analyse complex situations of mass displacement with the use of numerical modelling. It is essential that the choice of constitutive soil model is suitable for the conditions of the simulation to create an adequately accurate behaviour of the soil and in that way obtain reasonable results.

One of the more simplistic models is the **linear elastic model** which is derived from Hooke's law. In this constitutive model the user only needs to define the two stiffness parameters; Young's modulus (E) and Poisson's ratio (ν). This creates a linear elastic response with Young's modulus. As a linear elastic model does not consider plastic behaviour, this type of model is not always suitable for representing a soil material. It may however be used for stiff structures of concrete or solid rock that is shown to have a more linear elastic behaviour (Bentley Systems, 2023).

Another constitutive model is the **Mohr-Coulomb model**, a linear elastic perfectly-plastic model, which further includes an user-defined friction angle, cohesion, angle of dilatancy and shear strength of the soil. The linear elastic behaviour means that the soil will deform in a constant rate until the fixed yield point is reached (Atkinson, 2007). When the yield point is reached, the soil will behave in perfectly plastic manner, meaning that no further stress increase is needed for strains to occur and that the strains will be irreversible. This means that neither hardening or softening behaviour of the soil is possible with the Mohr-Coulomb model. Using Mohr-Coulomb the soil is modelled as isotropic, meaning that the undrained shear strength are the same in all direction. An advantage is that it is simple to use and there is no need for a great amount of soil parameters which might be difficult to obtain.

2.3.4 Drainage type

The drainage conditions needs to be defined according the specific case depending on the soils permeability, and whether the geotechnical problem is of short- or long term nature. A clay is often considered as a saturated soil which can be modelled as undrained in short-term and drained in long-term. Since soil movement imposed by pile installation is the most critical directly after installation and the soil is deemed incompressible in short-term only undrained analysis will be described. Plaxis allows for three different undrained drainage types (A, B and C) dependent on which input parameters that are available and what type of result is of interest.

Undrained A is an effective stress analysis which calculates the undrained shear strength dependent on input parameters. An effective stress analysis calculates excess pore pressures which is needed in consolidation is of interest. The strength parameters are effective cohesion (c'), effective friction angle (ϕ'), effective dilatancy (ψ') and the stiffness parameters are effective Young's modulus (E') and effective Poisson's ratio (v'). The calculation of undrained shear strength is based on conventional soil methods which tends to be overpredicted with effective parameters (Gouw Dr, 2014; Bentley Systems, 2023).

Undrained B is also an effective stress analysis but compared to undrained A, the undrained shear strength is now a constant input parameter. The strength parameters, ϕ' and ψ', equals to zero. It could be beneficial in some cases to not rely on the overpredicted undrained shear strength provided by the effective stress parameters in Undrained A. However, if a constant undrained shear strength is used, the consolidation analysis will be inaccurate because the increasing undrained shear strength during drainage is not considered in undrained B.

Undrained C does not use the effective stress approach but instead a total stress analysis. This results in no calculations of pore pressure in the soil, and no possible consolidation analysis.

See Figure 2.8 for graphical explanation of the different drainage types. The effective stress path (EST) and total stress path (TSP) is illustrated in a p'-q graph, where p' is mean effective stress and q is mean total stress.

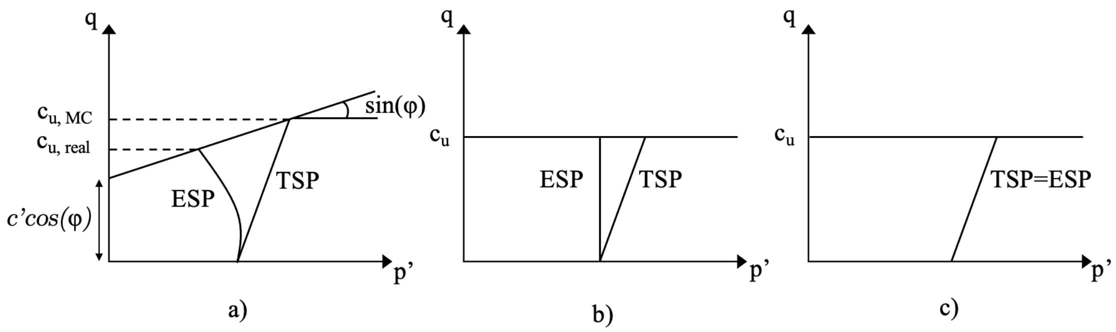


Figure 2.8: Different drainage types and their assumptions a) Undrained A b) Undrained B c) Undrained C.

2.3.5 Modelling of pile installation

A typical case where mass displacement is of relevance could contain such a significant number of piles that would be difficult to model in Plaxis due to the large dimensions and the complex geometry. A possible way to model installation of larger piling group is by simplifying the pile group to a total volume. This method uses the superposition principle adding up the influence from every single pile to one large pile.

In numerical modelling, the displacement from pile installation is modelled as a field pushing out from the pile. There are two ways to model this displacement field in Plaxis; first by Prescribed line displacement and second, by Volumetric strain expansion (Bentley Systems, 2023). Prescribed line displacement is a controlled line which imposes a displacement with a specific degree and direction. Volumetric strain expansion is applied to a soil cluster which expands with a specific percentage in selected direction. The volumetric strain expansion can also apply boundary conditions for the cluster in one direction while expanding towards another direction.

2.3.6 Modelling of structural elements

There are different ways to model structural elements in Plaxis in which has different possibilities and limitations. In this Thesis there is a need for modelling a pile row and a raft.

Relevant structural element are a plate element, soil polygon, a node-to-node anchor or an embedded beam row. A plate is a structural element that allows for bending and shearing, similar to a 2D beam and extends to a slender wall in the out-of-plane direction (Bentley Systems, 2023). The plate will give the possibility to define an axial stiffness (EA), a bending stiffness (EI) and to obtain structural forces in the plate. It is however limited in regard to soil movement; the plate creates a discontinuous mesh that let no soil through which is not adequate when modelling a pile row subjected to displacement field (Sluis et al., 2014), but can be suitable for modelling a raft.

A simple soil polygon can also be used as a structural element. It is usually used in purpose of creating soil clusters but with properties similar to a concrete slab it can represent a raft or a pile. The polygon is given a constitutive model, typically linear elastic for the purpose of a structural element. The same issue regarding a discontinuous mesh applies for a soil polygon, making it less suitable for modelling a pile row subjected to a displacement field.

The node-to-node anchor is simply a spring element that has two nodes at the two ends of the line (Bentley Systems, 2023). A node-to-node anchor will also provide the possibility to define an axial stiffness, but lacks the possibility to define a bending stiffness or obtain structural forces. While it does not separate the soil mesh as the plate element does, it also has no interface with the soil, therefore creating a less realistic structure-soil interaction (Sluis et al., 2014).

The embedded beam row is a one dimensional structure, extended as a row of beams in the out-of-plane direction. When using embedded beam row it is possible to define an axial stiffness, a bending stiffness and to obtain structural forces in the same way as for the plate element. However, unlike the plate element, embedded beam row contains interfaces by default to obtain a better interaction with the soil and enables a continuous mesh that allows soil to flow through (Sluis et al., 2014). Embedded beam row is primarily designed to catch the pile behaviour in the axial direction, with interfaces to represent both the shaft capacity and the end-bearing of a pile. However, lateral forces should be evaluated with caution due to limitations to the interfaces. The interfaces constitutes of springs which in horizontal direction lacks a plastic slider, in comparison to the axial direction and the pile base. This plastic slider is what represents the shaft capacity and end-bearing of the pile and works in such way that it defines where the springs change behaviour from elastic to plastic (Molendijk, 2018). That means no failure will occur in the embedded beam row laterally. However, according to the Plaxis 2D reference manual (2023) embedded beam row still provides realistic behaviour when exposed to a lateral displacement field. Analysing mass displacement would therefore be an acceptable case for the embedded beam row, even though its main purpose is axial loads. In addition to be able to define the axial- and bending stiffness for embedded beam material it is also possible to define the spacing between the piles in out-of-plane direction as well as axial skin-, lateral-, and base resistance. These last three are interaction properties which enables the possibility to define bearing capacity of the piles.

3 Method

The aim of this Chapter is to develop a model to enable the analyse of how existing foundation is affected by the installation of adjacent piles and how a nearby existing foundation affects mass displacement from piling. This study focus on quantifying the relative influence of existing piles on the soil movement from pile installation. Simpler methods such as Hellman/Rehnman or SSPM do not provide tools to analyse relevant parameters influencing the soil movements in detail. Therefore, the geotechnical problem has been investigated with numerical models in the geotechnical software, Plaxis, which allows for a comprehensive parameter study. Because of the complexity of numerical models, a 2D analysis was used. A pitfall with using 3D analysis is the large amount of input and modelling choices, which might mislead the result and well-anchored conclusions can therefore be hard to derive. Another reason is also the calculation time for 2D analysis, being much faster compared to 3D analysis.

Firstly, a free field model was created to capture the expected movement due to pile installation without surrounding obstacles, such as applied loads or adjacent structures. The free field model was compared to a real case for validation. When satisfying soil behaviour was achieved in the free field model, adjacent structures were added. A schematic approach was used to systematise relevant modelling scenarios and varying parameters. Three cases with different typical adjacent structures were studied. The modelling process which will be described in this Chapter is summarised in Figure 3.1.

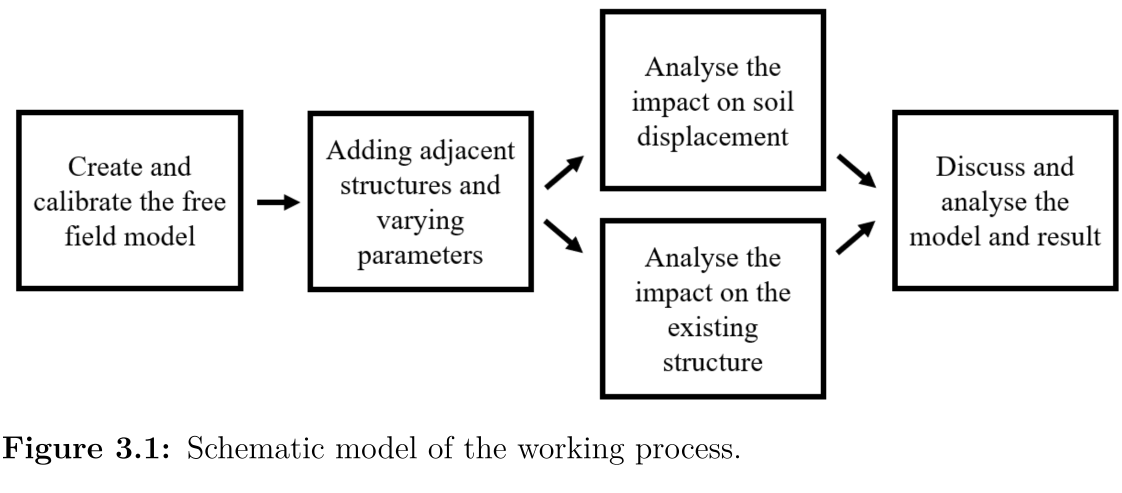


Figure 3.1: Schematic model of the working process.

3.1 Model setup

The finite element model created in Plaxis contain an installed pile in the centre which expands towards two directions. On the right side (positive x-coordinates) is the existing adjacent structure located. See Figure 3.2 for an illustration of the model.

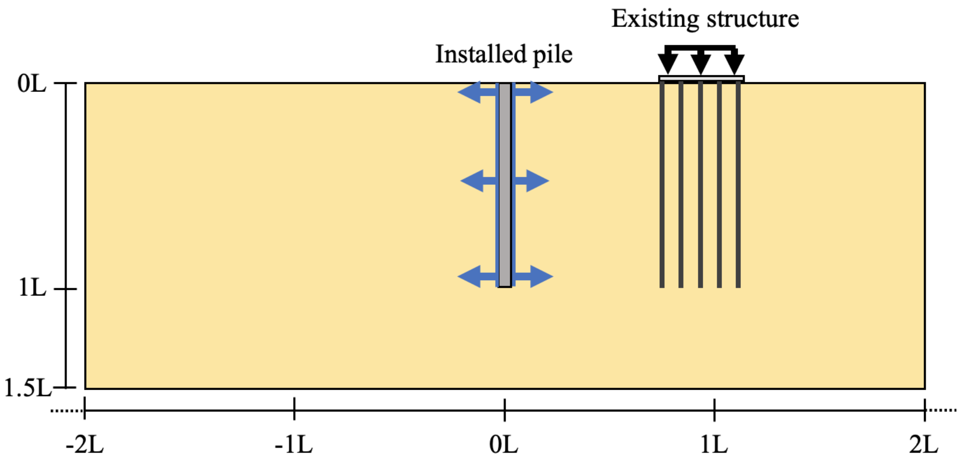


Figure 3.2: Sketch of the Plaxis model where the installed pile is placed in the middle where blue arrows represents an imposed displacement. To the right, the existing structure (in this case a piled raft).

The following bullet list contains a summary of relevant model setup approach for the standard case.

- Since the Thesis aims to analyse mass displacement related to adjacent structures, a **plane strain model** is to be preferred. An axisymmetric model will extend objects into circular volumes which was judged less adequate. An important consideration is that a 3D problem is being replicated in 2D, meaning that neither axisymmetric nor plane strain will represent a correct model of reality but rather acceptable simplifications for the purpose of the Thesis, see further in section 3.2 - *Pile installation*.
- Because the short-term case was of interest in this Thesis, an **undrained analysis** was performed. The time-dependent consolidation was not dealt with, but only the immediate deformations in the soil. Therefor the drainage type Undrained C provides a relevant total stress analysis with the undrained shear strength as a constant input parameter.
- The **dimensions of the model** were based on the lengths of the pile. The depth to 1.5 times the longest pile length and the length of the model to 6 times the pile length in each direction from the installed pile.
- The **phase build up** contains:
    1. Initial phase (free field)

2. Nil step (reset displacements and small strain)
3. Adding structure (raft or piled raft)
4. Adding load on structure
5. Nil step (reset displacements and small strain)
6. Pile installation (through volumetric strain)

- The result is based on **phase displacement** for the phase where the pile installation occurs. The total displacements from the initial phase and forward is not of interest but rather what happens in each specific phase. Therefor is only phase displacements analysed.
- By default, Plaxis provides 15-noded mesh elements, containing 12 Gauss points where stresses are calculated. The nodes are where the displacement is calculated meaning that the more nodes, the higher accuracy.

3.1.1 Mesh generation

The mesh was refined until the results converge, meaning that the result was not anymore affected by changing the size of the mesh. The mesh had been refined further close to detailed parts of the model, e.g. near piles/structures. There was also an option to update the mesh which is preferable if the mesh is significantly deformed. These measures aims to reduce uncertainties in the result due to the mesh itself. However, when using the updated mesh, it was observed that there was no significant change in the results. Final mesh used in Plaxis can be seen in Figure 3.3.

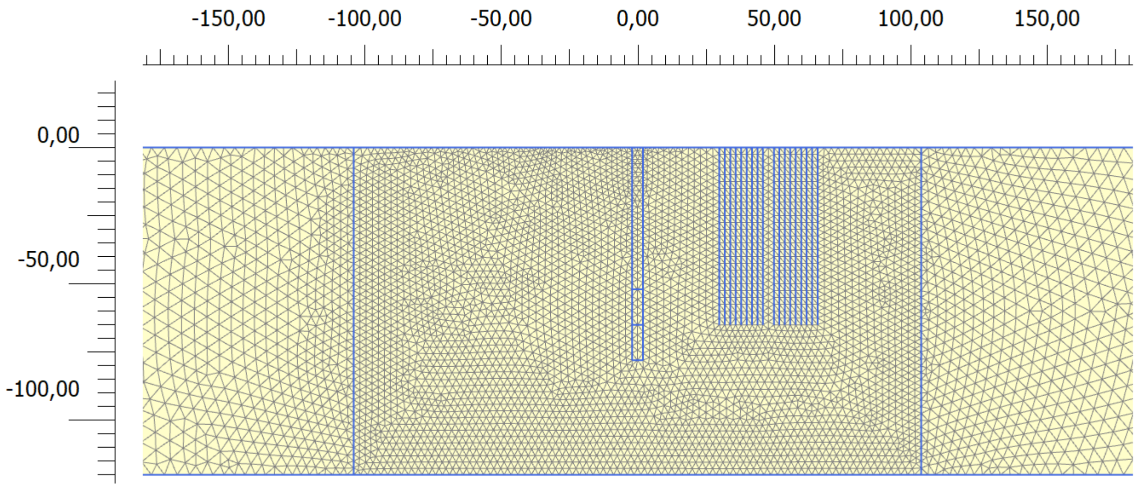


Figure 3.3: Generated mesh at the central parts of the Plaxis model.

3.1.2 Boundary conditions

Deformation boundaries can be set as fully fixed, normally fixed, horizontally fixed, vertically fixed and free. In this case, the top boundary(Y_{max}) was set as free, the bottom boundary (Y_{min}) as fully fixed, and the left and right boundary (X_{min} and X_{max}) as normally fixed. Normally fixed vertical boundaries implies that displacements only occur vertically, not horizontally. See Figure 3.4 for an illustration of the boundary conditions.

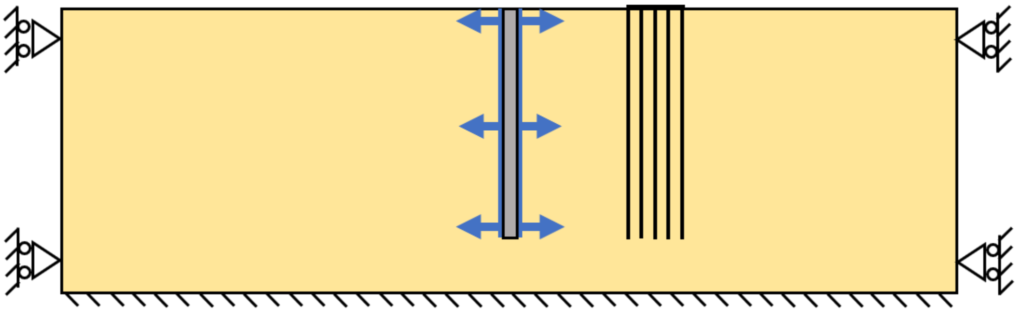


Figure 3.4: Boundary conditions for displacements in the Plaxis model.

3.1.3 Constitutive model

Both the linear elastic model and the Mohr-Coulomb model were tested at the start of the simulations for comparison. They provided similar results during pile installation in free field, but does differ when adding an adjacent structure. However, Mohr-Coulomb was chosen to continue the simulations with because of the possibility for plasticity. See appendix A.1 and for comparison of Mohr-Coulomb and Linear elastic in surface heave and horizontal displacements.

3.1.4 Model parameters

The parameters used were based on typical Gothenburg clay properties and are presented in Table 3.1. The model contains one soil layer with increasing undrained shear strength and stiffness with depth. The stiffness was chosen to $375c_u$, based to the empirical relation where the stiffness is dependent on the undrained shear strength with a constant depending on the plasticity of the clay. For a clay with high plasticity $E = 250c_u$, and for clay with low plasticity $E = 500c_u$ (Trafikverket, 2011). The undrained shear strength and stiffness is increased linearly with depth from ground surface. The groundwater is located at ground level and the initial stresses was calculated with K_0-procedure. The value of K_0 equals the effective stress ratio, that is σ'_h/σ'_v. However, since the drainage type Undrained C will be used, the K_0-procedure will dependent on the total stress ratio, σ_h/σ_v.

As mentioned in the theory, an incompressible soil will have a Poisson's ratio of 0.5. However, that would lead to an an infinite bulk modulus which is not possible in reality and can not be applied in Plaxis, therefor the value of 0.495 was used.

Table 3.1: Parameters used in the standard case in the Mohr-Coulomb model.

γ $[kN/m^3]$	$c_{u,top}$ $[kPa]$	$c_{u,inc}$ $[kPa]$	E_s $[kPa]$	E_{inc} $[kPa]$	ν	K_0
16	15	1.35	$375c_u$	$375c_{u,inc}$	0.495	0.85

3.2 Pile installation

Since the model must be in plane strain, the installed pile in 2D corresponds more to a wall continuing infinitely in the out-of-plane direction. The amount of piles and the piling area was translated to an "equivalent pile-soil wall", with corresponding volume, see Figure 3.5.

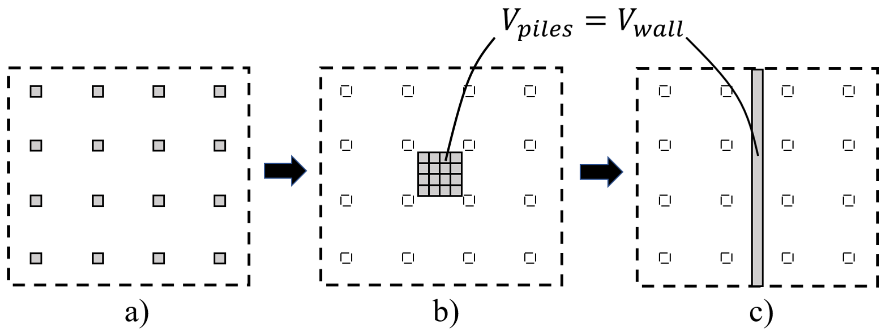


Figure 3.5: Conceptual model of how a pile group can be translated into an equivalent pile-soil wall where a) pile group b) superpile and c) equivalent pile-soil wall

The displacement from the pile installation contains only a horizontal movement in Plaxis, meaning an extension of the wall in two directions. The displacement on one side (w) equals half of the width of the equivalent pile-soil wall, demonstrated in Figure 3.6 with resulting equation 3.1.

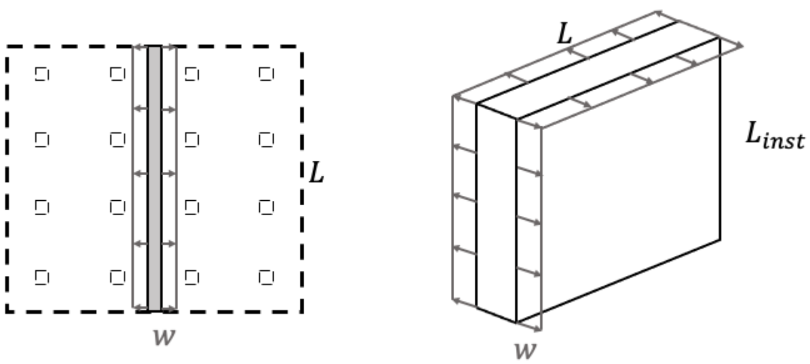


Figure 3.6: Conceptual illustration of displacement using an equivalent pile-soil wall.

$$V_{piles} = 2wL_{inst}L \rightarrow w = \frac{V_{piles}}{2L_{inst}L} \tag{3.1}$$

Where

V_{piles} - total volume of all piles

w - imposed displacement or half the width of the equivalent pile-soil wall

L_{inst} - installed pile length

L - length of pile area

The chosen displacement was used as an input in Plaxis to model a field pushing out from the installed pile. To decide a displacement and generate an accurate soil response, a real case was used for calibration of the Plaxis model. The calibration of the model was performed against measurements of deformations from piling works reported by Edstam (2011) conducted at Partihallsbron in Gothenburg, see Appendix A.2. The calibration resulted in a certain displacement based on this real case to use in the parameter study. It also resulted in a decision to use volumetric strain as displacement function in Plaxis. The resulting imposed displacement and volumetric strain based on this real case can be seen in Appendix A.3.

3.3 Adjacent structures

After calibration of the free field model, adjacent structures was added. The following three different scenarios was analysed to evaluate the effect of mass displacement on surrounding structure, and the structures influence on the displacements.

- Simple raft
- Piled raft
- Free standing piled raft

See Figure 3.7 for an illustration of the three modelling scenarios.

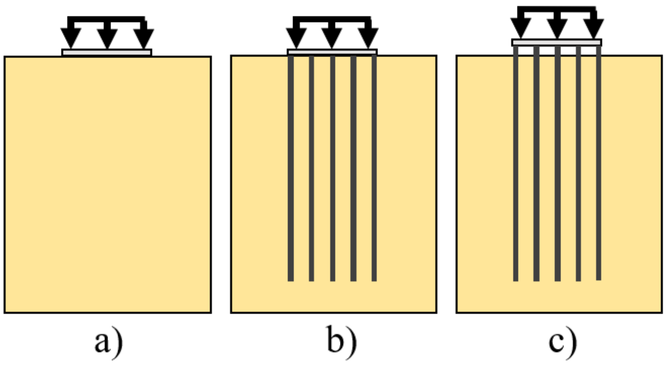


Figure 3.7: Illustration of the adjacent structure where a) simple raft b) piled raft c) free standing piled raft.

For the parameter variation a standard case was first modelled. The model was then iterated with one parameter variation at a time. The parameters was varied to see the influence on the displacement field, and the influence on the adjacent structure itself. The standard geometry can be seen in Table 3.2 with Figure 3.8 as an explanation.

Table 3.2: Geometry of the standard case of raft and piles.

Parameter	Value	Unit
Imposed displacement, w	40/20 (upper/lower)	mm
Width of superpile, b_{inst}	4	m
Installed pile length, L_{inst}	65	m
Existing pile length, L_{exist}	65	m
Width of raft, b_{raft}	16	m
Space between piles, $L_{spacing}$	4	m
Diameter of existing pile, D	0.31	m
Distance between installed pile and existing structure, d	30	m

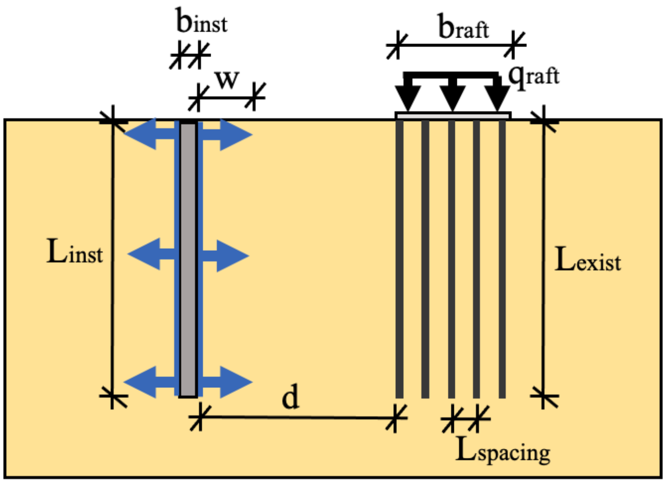


Figure 3.8: Schematic sketch of quantities of model geometry and varying parameters.

All modelling cases and varying parameters can be found in Table 3.3.

3.4 Varying parameters for the parameter study

Table 3.3: Varying parameters in the parameter study with different scenarios (raft, piled raft and free standing piled raft). Black crosses are standard parameters, red are a variation.

Scenario:			**Raft**				**Piled raft**										**Free standing**			
Varying parameters	**Value**	**Unit**																		
Displacement	40/20	mm	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X	X	X
	50/30	mm						X												
Installed pile length	52	m							X									X		
	65	m					X	X			X	X	X	X	X	X	X			X
	78	m								X									X	
Ctc of piles	2	m					X	X	X	X		X	X	X	X	X	X	X	X	X
	4	m									X									
Width of footing	16	m	X		X	X	X	X	X	X	X		X	X	X	X	X	X	X	
	32	m		X								X								X
Pile stiffness	32	GN/m^2					X	X	X	X	X	X		X	X	X	X	X	X	X
	48	GN/m^2											X							
Load	50	$kN/m/m$	X	X		X	X	X	X	X	X	X	X		X	X	X	X	X	X
	100	$kN/m/m$			X									X						
Soil stiffness	$375c_u$	kN/m^2	X	X	X	X	X	X	X	X	X	X	X	X		X	X	X	X	X
	$500c_u$	kN/m^2													X					
Distance	30	m	X	X	X		X	X	X	X	X	X	X	X	X		X	X	X	X
	50	m				X										X				

3.4.1 Simple raft

The first scenario contains only a raft loaded on the soil. The raft was modelled as an elastic plate with “unlimited” stiffness. The following parameters were varied to analyse the sensitivity and influence on mass displacement.

- Width of raft, b_{raft}
- Raft load, q_{raft}
- Distance between installed pile and existing raft, d

3.4.2 Piled raft

The pile raft was basically a loaded raft on cohesion piles. The study focuses on seeing the influence in changes of geometry or material properties and therefore are the following parameters varied.

- Imposed displacement, w
- Length of installed piles, L_{inst}
- Length of existing piles, L_{exist}
- Width of raft, b_{raft}
- Load on existing raft, q_{raft}
- Space between piles, $L_{spacing}$
- Young’s modulus of piles, E_p
- Young’s modulus of soil, E_s
- Distance between installed and existing structure, d
- Hinged or fixed top connection in piles

Notice that increasing the imposed displacement would have the same effect at increasing the cross section of the installed pile.

3.4.3 Free standing piled raft

The purpose of the free standing piled raft was to see the influence of the raft-soil contact. There was also a need for the free standing piled raft in terms of raft-pile connection to simulate a hinged connection between the pile head and the raft. The piles and raft share the same geometry and properties as above, however, the raft was located 0.1 metre above the ground surface, connected to the piles.

3.5 Structural elements

The model contains different structures which can be performed in different ways in Plaxis. The installed pile was not modelled as an actual structural element but as an expanding volume imposing a displacement field. However, the raft and concrete piles representing the adjacent structure was modelled as structural elements.

3.5.1 Existing piles

It is of interest in this Thesis to be able to evaluate the structural forces to understand how the mass displacement impacts the structure, while also maintaining a realistic soil movement. The plate function and node-to-node anchor function are therefore deemed inadequate when modelling the existing piles, since the first does not provide a continuous mesh, and the later do not enable the opportunity to evaluate structural forces. The embedded beam row enables analysing of structural forces and handles lateral forces in the most accurate way of the modelling functions mentioned for this specific case. Therefore the embedded beam row will be used when modelling the existing piles. Boundary conditions was applied for the embedded beam row in terms of the top connection, which was set to hinged.

The piles are elastic and have properties according to Table 3.4.

Table 3.4: Properties of the adjacent piles.

γ $[kN/m^2]$	T_{skin} $[kN/m]$	T_{lat} $[kN/m]$	E $[GN/m^2]$
24	$\pi c_u D$	$9 c_u D$	32

3.5.2 Existing raft

The existing raft is referring to the pile cap of the existing pile group or a simple raft without piles. The raft acts as a slab for the overlaying building. The structural parts of the raft was not necessary in focus of this study but can be important for the behaviour of the piles and distribution of contact pressure.

Both a plate and a soil polygon was tried out in purpose for the raft in Plaxis. Since there were no significant difference, the plate element were chosen.

The stiffness of the plate is of great importance for the distribution of the contact pressure, or more specific, the stiffness in the raft in relation to the stiffness of the soil (Bergdahl et al., 1993; Wood, 2004). An unlimited stiffness of the plate (large stiffness ratio) will distribute the load towards higher contact pressure at the perimeter of the plate. A more flexible raft would instead create an uniform contact pressure. A perfectly rigid foundation on an elastic medium would lead to a stress distribution below the raft that increases at the perimeter (Jendeby, 1986). Since the raft will be modelled as made of concrete, a plate with relatively large bending- and axial stiffness was chosen as to act rigid.

3.5.3 Existing building load

The load was modelled as an uniform line load on the raft, also called building load. The load was given a magnitude in the unit of kN/m/m and can be applied in different directions. The standard load used in Plaxis will be 50 kN/m/m in a negative y-direction. The unit of the load is stated without any set dimensions, meaning that to get the total building load, the value is multiplied by the width of the raft and the length of the raft in the out-of-plane direction. The load will be increased and decreased in the parameter study to analyse the impact on soil movement and existing piles.

4

Parameter study

This section contains the results gathered from the parameter study in Plaxis 2D with a continuous discussion. The presented results contain displacements in horizontal and vertical direction (heave) both in the soil and in the piles. The obtained displacements were normalised to facilitate an easier comparison with similar studies and to be able to observe patterns depending on the dimensions of the installed pile. The movements are represented in graphs with displacement on one axis and either normalised distance from installed pile or depth on the other axis. The distance from the installed pile is generally normalised with the installed pile length, except for when different installed pile lengths are analysed. This is because there might be a need to analyse the result normalised towards both installed and existing pile length. If the result is normalised towards the existing piles, this will be noted, otherwise the result will always be normalised towards the installed pile. To be clear, x/L_{inst} is the distance from the installed pile and y/L_{inst} is the depth. Similar for the displacements which will be normalised with the imposed displacement from the pile installation, w. The heave is represented by u_y/w and horizontal displacements; u_x/w. The paramters that will used for the normalisation can be seen in Figure 4.1.

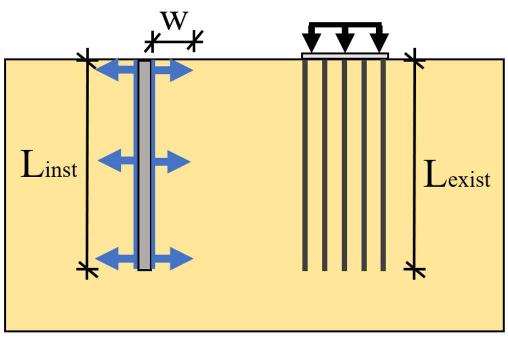


Figure 4.1: Parameters in which the result is normalised towards. Typically L_{inst} and w.

The result is also displayed in contour plots where different colours represent areas of different magnitude of displacement. In addition, axial forces as well as bending moments in the existing piles are shown.

The result is presented together with a reference image of the specific case modelled. This image aims to facilitate the current modelling setup with pile lengths and distances. An example of the piled raft - standard case can be seen in Figure 4.2. The installed pile is represented will blue arrows indicating the displacement field. The existing pile group is located to the right in the figure. The red dashed line is representing the location of the plotted data. For example, horizontal displacements at two sections, A and B, can be seen in Figure 4.2a, and heave at ground surface is displayed in Figure 4.2b. Figure 4.2c represents the piles in which the result is taken from, this case pile 1,3 and 5.

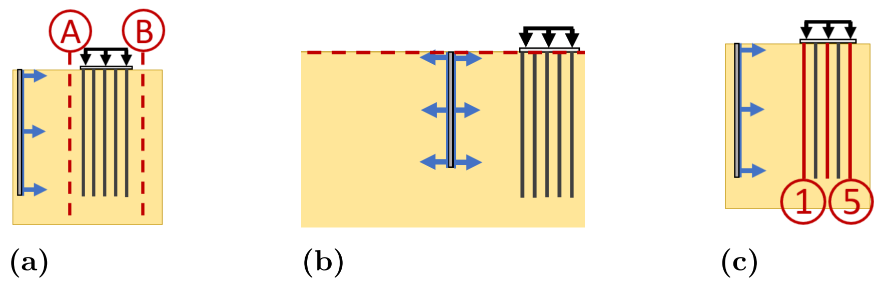


Figure 4.2: Example of mini figures used in the graphs to easier understand the current modelling scenario a) is an example of horizontal movement b) is an example of heave c) the graph is displaying results for pile 1, 3 and 5.

Since the aim is to analyse two different main objectives, the result is divided into 1) the influence from existing piles on soil movement during pile installation and 2) the influence from pile installation on existing piles.

4.1 Influence on the soil movement

The results for related to analyse of the soil movement is divided in to the simple raft, piled raft and free standing piled raft which wan be seen following in section 4.1.1 to 4.1.3.

4.1.1 Simple raft

The vertical and horizontal displacements from the standard case of the simple raft can be seen in Figure 4.3 and 4.4. The input values of the standard case was shown in Table 3.2 in Chapter 3 - *Method*. The simple raft show a very small difference compared to the free field case, both in heave and in horizontal movement, although the difference is nearly indistinguishable.

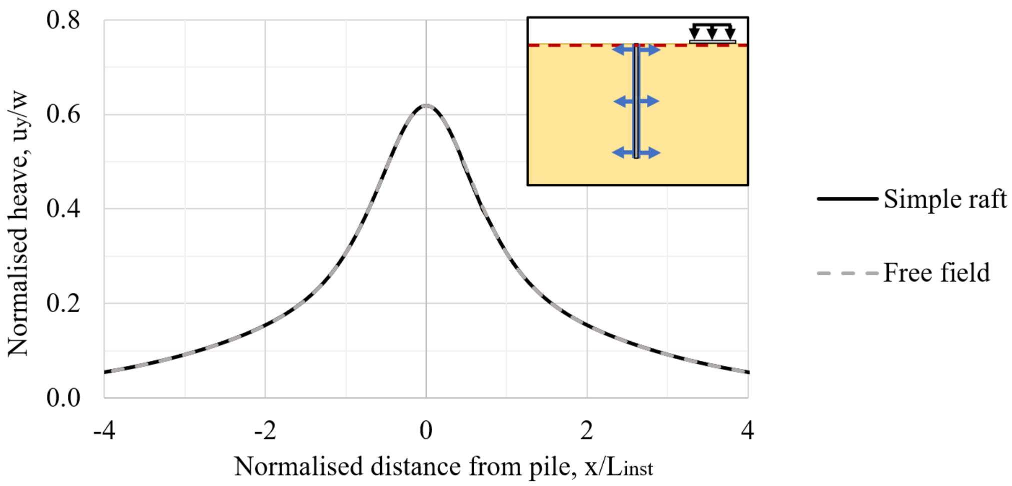


Figure 4.3: Heave for the simple raft in comparison with free field.

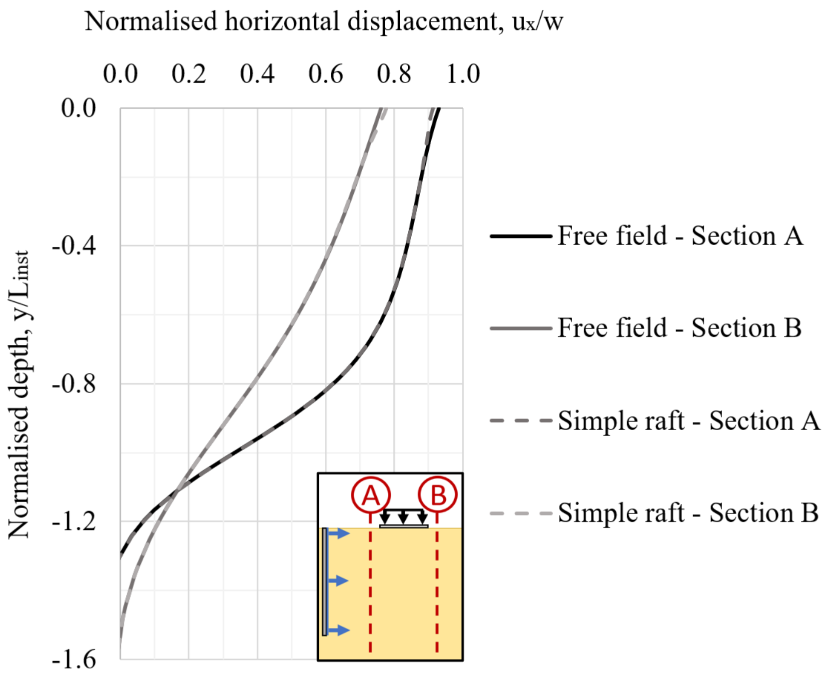


Figure 4.4: Horizontal displacements for the simple raft, Section A is 5 metre before (25 metre from pile installation) and section B is 5 metre after (51 metre from pile installation) the raft, in comparison with free field.

The building load applied on the existing structure was thereafter increased. The increase from 50 kN/m to 200 kN/m again showed only an insignificant difference in soil movements. Further increase of load results in a soil collapse or numerical difficulties before a redistribution of the displacement field can be distinguished.

One could argue that this small load of 50 kN/m or 200 kN/m can not possibly be enough to withstand the load from the large soil layer below. If one is to simplify the zone of soil layer it can be related to the simplified wedge shaped area from the Hellman/Rehnman method. Hellman/Rehnman assumes that the wedge shaped influence area reaches around one pile length at ground surface however according to L. Jendeby (personal communication, 2 February, 2023), this wedge have been shown to rather reach around 1.5 pile lengths in real cases. If the load of the raft, Q_{raft} would be compared to the load of the wedge shaped area, Q_{raft}, from the Hellman/Rehnman theory, assuming it reaches a distance of 1.5 installed pile lengths, there is a distinguishable difference. See equation 4.1 and 4.2.

$$Q_{load} = q_{raft} \cdot b_{raft} = 200 \cdot 16 = 3200kN \tag{4.1}$$

$$Q_{wedge} = \frac{L_{inst} \cdot 1.5 \cdot L_{inst}}{2}\gamma = \frac{65 \cdot 1.5 \cdot 65}{2}16 = 50700kN \tag{4.2}$$

See Figure 4.5 for explanation of the geometric parameters in the equation above.

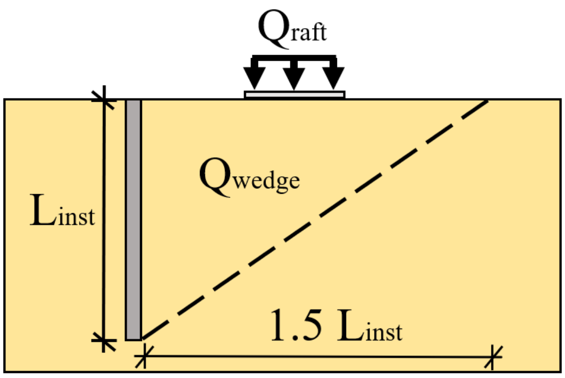


Figure 4.5: Illustration of geometric parameters in calculation the load of the wedge shape, from the Hellman/Rehnman method.

It is seen that the load on the raft is around 6-7% of the load of the wedge. This quick calculation of the load in the wedge also assumes a constant unit weight of the soil, when it actually increase with depth, which would cause the wedge load to be even higher. This calculation also provide the load for the wedge on one side, when one could argue that the wedge load should be doubled because both sides are covered by soil movements from the pile installation. Additionally, a load of a 20-floor building without piles is not practically reasonable in these type of soil conditions without piles, so the load on the raft in this case can be seen as extreme. With this argument, the result is deemed accurate and the remaining modelling cases for the simple raft in Table 3.3, will not be executed.

4.1.2 Piled raft

The vertical displacements from standard case of the piled raft can be seen in Figure 4.6 where the soil displacements are affected by the piles. The heave is redistributed, with a decrease of heave within, and close to, the piled raft and instead an increase of heave beyond the piled raft, but also on the opposite side of the installed pile.

Additionally, this leads to the location of maximum heave occurs further to the left in the Figure in comparison to free field, although this difference is minor. The heave was shown to be somewhat lower than the free field case up to a distance of 0.25 pile lengths from the edge of the raft to both directions.

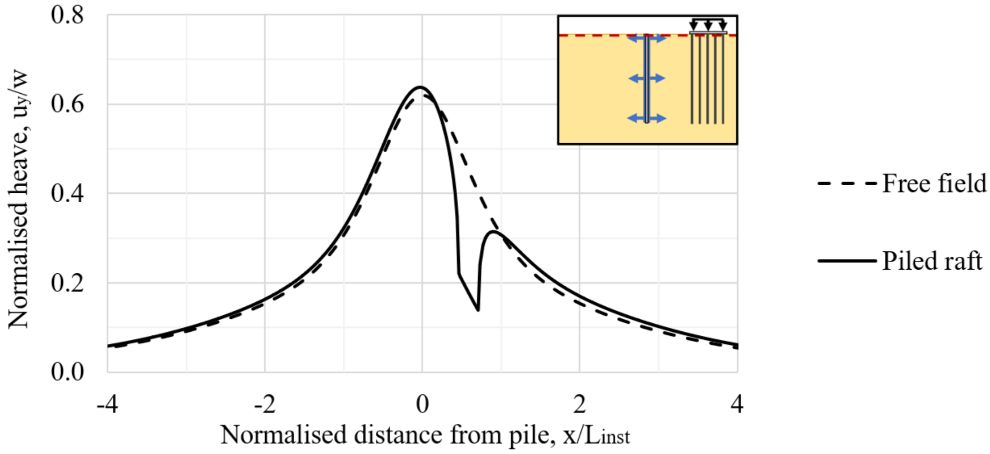


Figure 4.6: Heave for the piled raft in comparison with free field.

In comparison to the free field displacements, the horizontal displacements decrease before the existing piles and increase after the piling area, see Figure 4.7. The decrease of horizontal displacements before the existing piles can be due to the piles redistributing the movement by obstructing the soils capacity to move. Less movement before the existing piles can also be due to the fact that more soil will move towards the opposite side of the installed pile, which was shown in Figure 4.6. The increase of horizontal displacements after the piling area is probably due to the restriction of heave inside the piling area, leading to an increase of horizontal displacements.

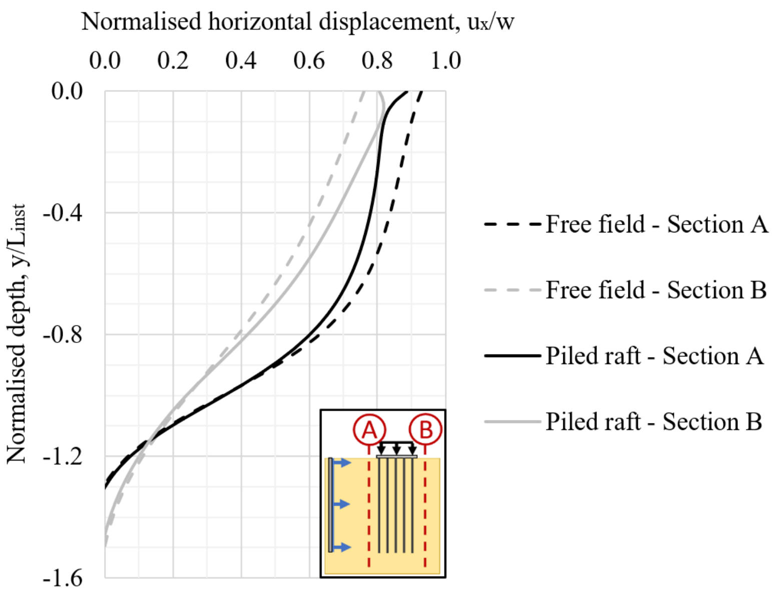


Figure 4.7: Horizontal displacements for the piled raft, at section A (5 metres before the raft) and section B (5 metres after the raft), in comparison with free field.

In Figure 4.8, the horizontal displacements is displayed as contour plots, for the free field case and the piled raft case. A difference can be distinguished in the distance of similar movement for the two cases. The existing piled raft forces the horizontal movement on the foundation side to greater distances compared to the free field. This is due to that the existing piled raft is restricting heave, leading to more horizontal displacements instead, especially closer to the ground surface.

This linear wedge shaped area, introduced earlier based on Hellman/Rehnman theory, is seen to be disturbed by the piles, causing the movement to also mitigate between the piling area and the existing piled raft. According to Figure 4.8 the displacement is seen to reach beyond one pile length (65 m) from installation at ground surface.

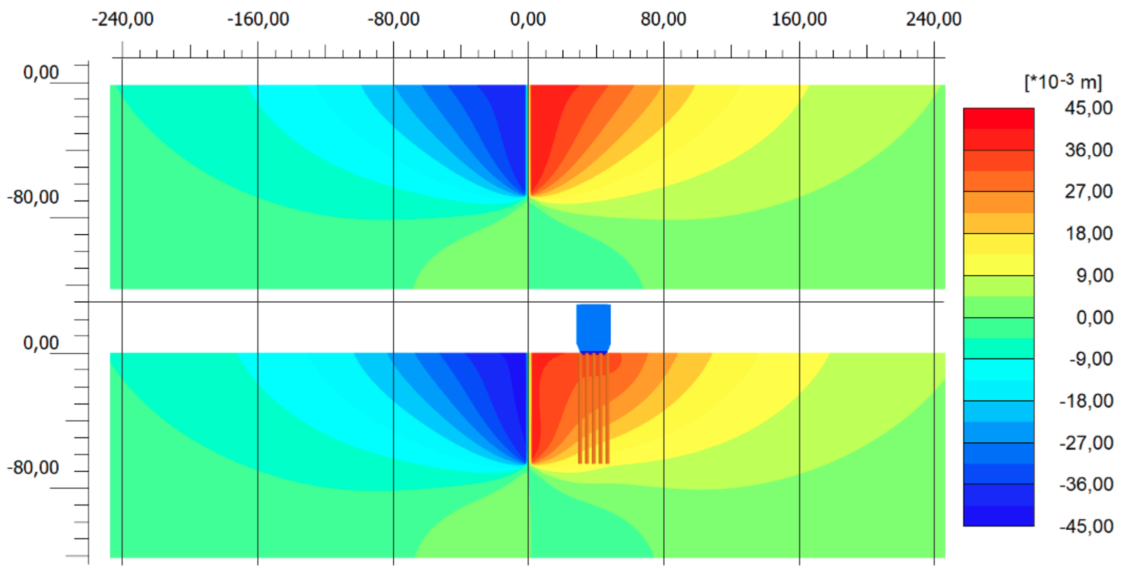


Figure 4.8: Horizontal displacements from pile installation, with the upper plot showing the free field case and the lower plot with the existing piled raft.

The vertical movement can also be seen in the same type of contour plot, see Figure 4.9. It is here highlighted that the increase of horizontal displacements further away from the existing piled raft also leads to more heave further away, which is reasonable since the displaced volume is constant. When comparing the vertical and horizontal movement, it is visible that the displacements decrease in a faster rate with depth, compared to distance from the pile.

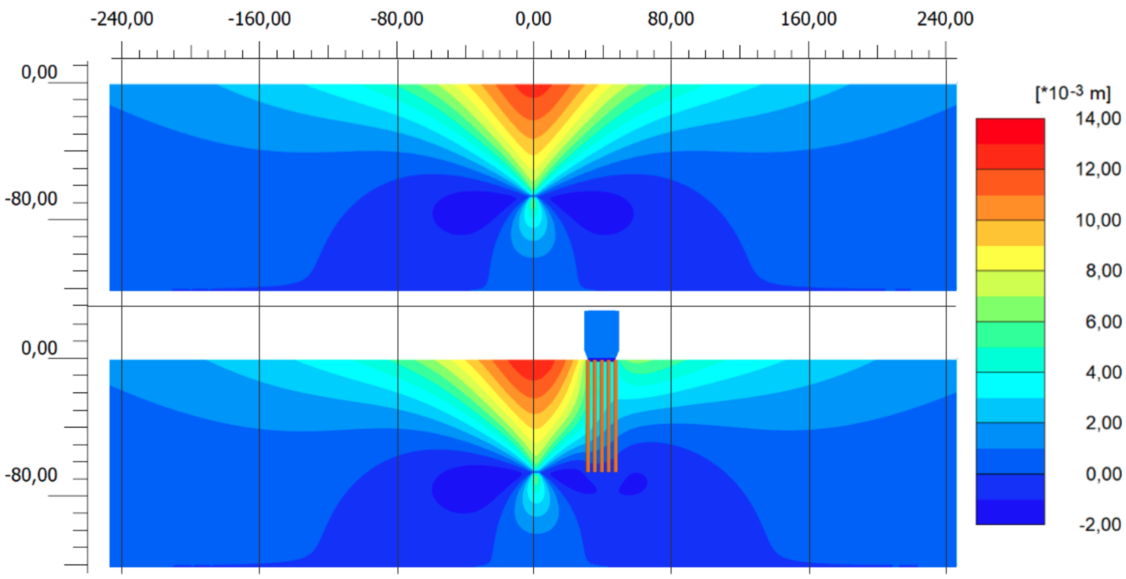


Figure 4.9: Vertical displacements for pile installation, with the upper plot showing the free field case and the lower plot with the existing piled raft.

The interpreted change in soil movement from free field to piled raft can be illustrated in Figure 4.10 following the simplified schematically wedge shape proposed by Hellman/Rehnman method. The piled raft almost pause the vertical displacement field which as a consequence reaches further away compared to the free field case. In reality, there is no specific line that cuts of like a slip surface but more of a scale, where there is a change in relative displacement which correspond to this simplified wedge shape. Therefore it is hard to define where to draw a line like this just by analysing the movement.

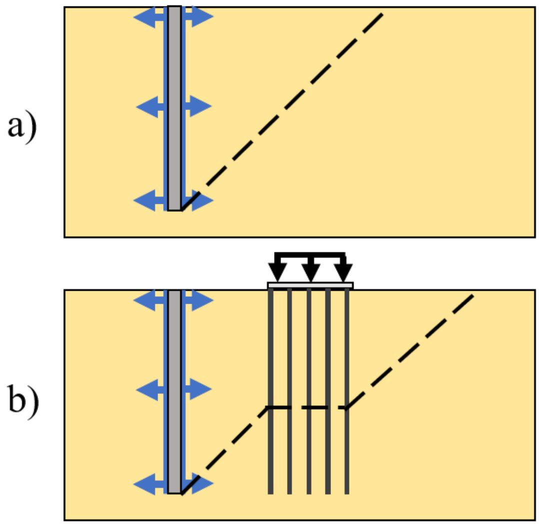


Figure 4.10: Simplified illustration of the influence area with a) free field and b) with piled raft.

4.1.2.1 Influence of increased displacement

When the displacement from the installed pile is increased with 50%, which corresponds to increasing the cross section of the installed superpile, it can be observed that no change in heave occurs, see Figure 4.11. Notice that the heave is normalised towards different imposed displacements and therefore converge. It can therefore be concluded that increasing the volume displaced (cross section of installed pile) does not influence the general results in a manner that could disturb the parameter study.

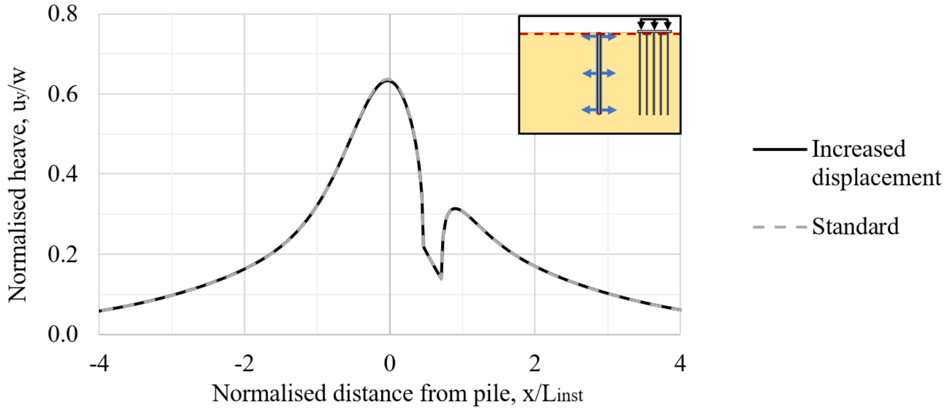


Figure 4.11: Heave after increased displacement by 50%.

4.1.2.2 Influence of load intensity

As shown previously, the load on the raft has a negligible impact on heave for the simple raft. The influence of the load was also studied for the piled raft with three different load levels corresponding to 0 kPa, standard 50 kPa and 200 kPa, see Figure 4.12. The difference on the heave is shown to be negligible when changing the load on the piled raft. However, the load is relevant for the forces in the structure, see further in section 4.2.

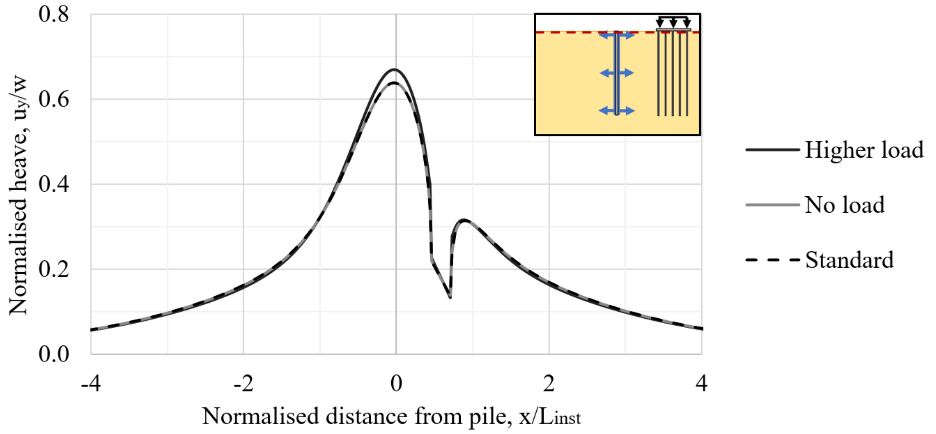


Figure 4.12: Heave for piled raft, with different loads on adjacent structure from 0 kN/m (no load), 50 kN/m (standard) to 200 kN/m (higher).

4.1.2.3 Influence of length on installed pile

The length of the installed pile affects the distribution of soil movement. Figure 4.13 and 4.14 shows heave for different lengths of the installed pile; the standard case of 65 metres ($1.0L_{inst}$), the shorter case of 52 metres ($0.8L_{inst}$) and the longer case with 78 metres ($1.2L_{inst}$) length. The existing piles remain as 65 metres. Notice that the distance is normalised towards the installed pile length which differs from case to case. It is visible that changing the installed pile length have an impact on the displaced volume. The heave within the existing piling area and directly beyond the existing piles also change dependent on the pile length.

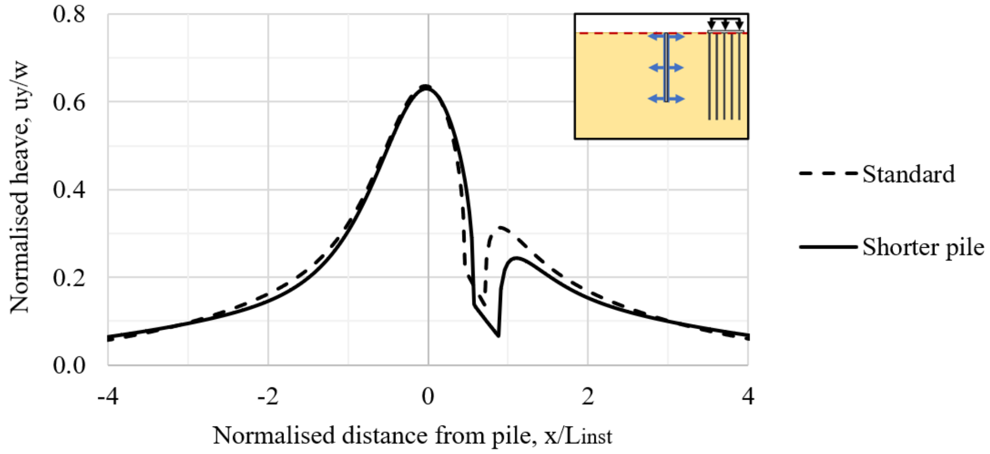


Figure 4.13: Comparison of heave with a shorter installed pile (52m). Existing pile length is 65 metres. Normalised towards the different installed pile lengths.

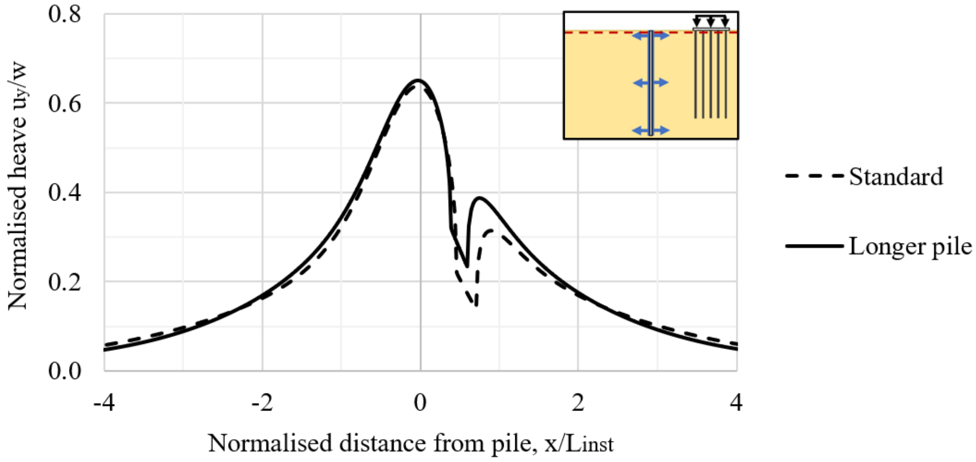
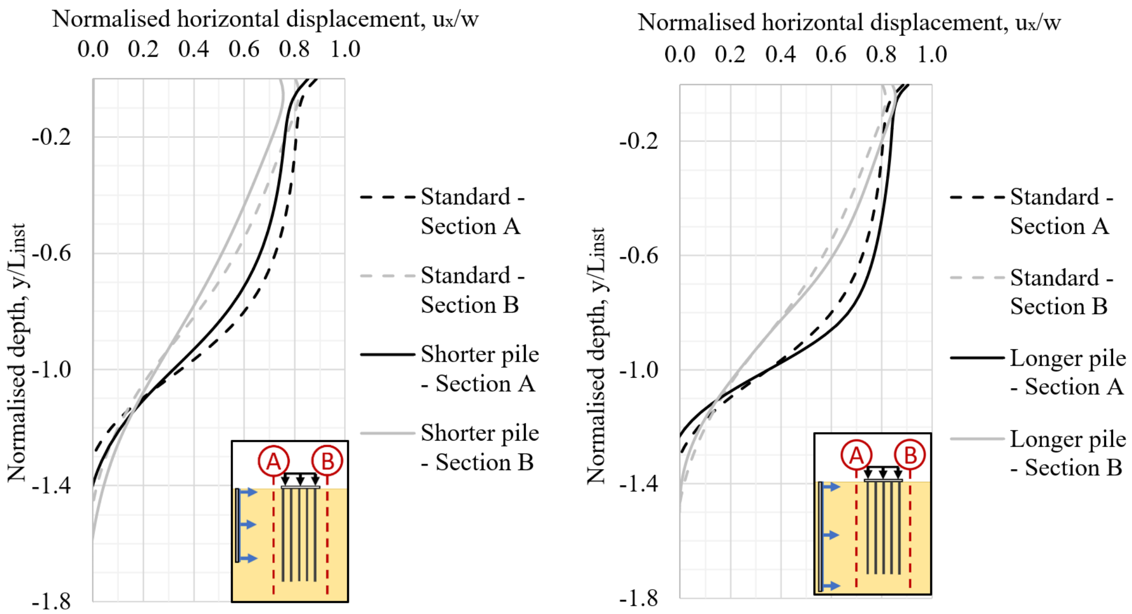


Figure 4.14: Comparison of heave with a longer installed pile (78m). Existing piles are 65 metres. Normalised towards the different installed pile lengths.

When comparing the redistribution of heave from increased displacement (Figure 4.11) and the case with increased pile length, (Figure 4.14), it can be seen that increased displacement lead to a more even increase of heave along the whole model, whereas longer installed pile leads to higher heave underneath the existing piled raft and beyond the installed pile and existing piles. It can be difficult to make any hard conclusions since the volume of mass displacements in these two cases are not equal, but they are relatively similar enough for one to observe this distinguishable difference of heave especially beneath the raft. Longer piles is seen to therefore not only lead to more mass displacement in total, but also an increase of displacements at further distance from the installed pile.

The horizontal displacements from the installation of different pile lengths is shown in Figure 4.15 and are normalised towards the installed pile length. However, keep in mind that in this case the installed pile lengths are different. The standard case is normalised towards 65 metre, and shorter and longer are normalised towards 52 metre respectively 78 metre. This provides a general result where the curves are dependent on the source of the movement. It can be distinguished that a shorter installed pile results in less horizontal displacements in general which is accurate because there is less installed pile volume. Vice versa for the longer pile. However, there is a change in behaviour where the longer installed pile creates a larger decrease in horizontal displacements below 0.8 pile lengths and more curvature in the graph. The shorter pile generates the opposite behaviour where the displacements have a more even curve-shape, almost linear for section B.



(a) **(b)**

Figure 4.15: Horizontal movement for a) shorter installed pile (52m) and b) longer installed pile (78m). Existing adjacent piles are 65m in both cases. Normalised towards the different installed pile lengths.

4.1.2.4 Influence of distance between installed pile and existing piles

Increasing the distance from 30 to 50 metres between the installed pile and existing piled raft gives similar heave patterns, see Figure 4.16. Although the uplift of the raft is lower and the inclination is less when the raft is located at longer distance. This is reasonable since the heave decreases and flattens out with distance from the installed pile.

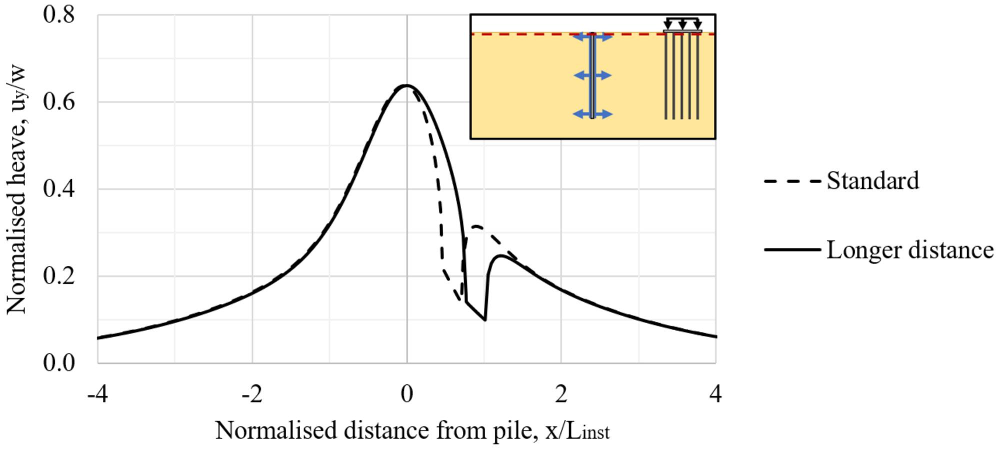


Figure 4.16: Comparison of heave when existing piles is located further away, with a distance of 50 metres instead of 30 metres (standard).

It can be seen in Figure 4.17 that the horizontal displacements at ground surface is 30% lower for section C than in the standard case where the piled raft is closer. Since the distance to the raft is changed, and the sections are placed 5 metres before respectively beyond the piled raft, their placements are also changed. Section C is here placed at 45 metres distance from the pile installation, which represents an 80% increase of distance. At section D, which is at 71 metres distance, little difference can be seen. It is therefore highlighted that horizontal displacements does not decrease rapidly with distance. It can be seen that the difference in horizontal displacements from section C to D is significantly lower when the piled raft is located further away, which is what to be expected.

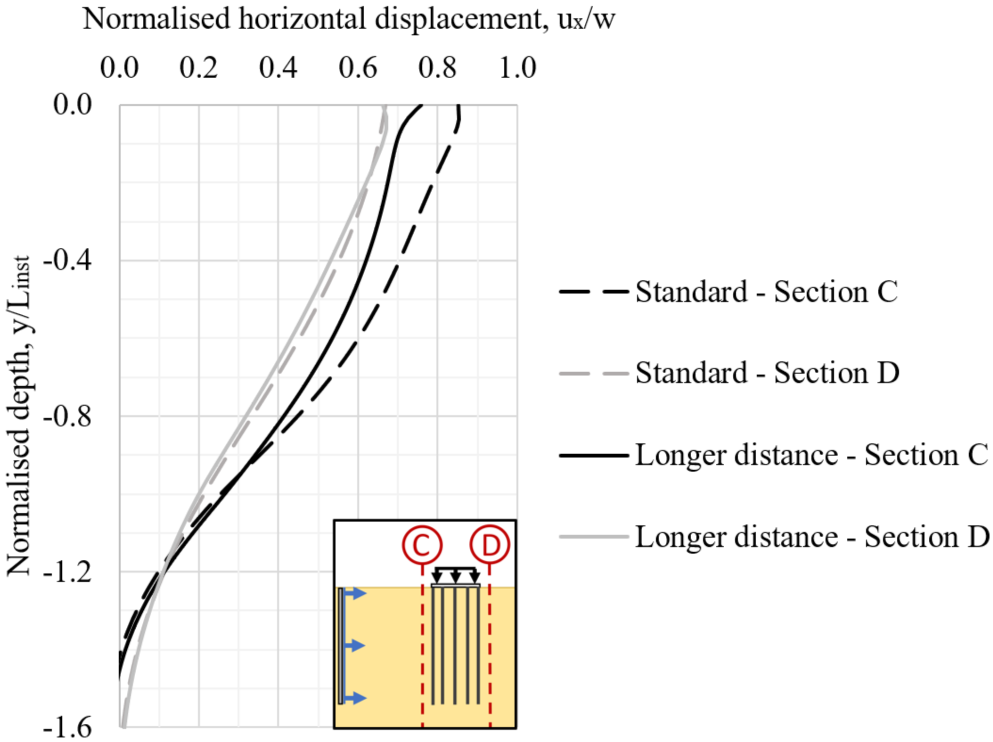


Figure 4.17: Comparison of horizontal movement when existing adjacent structure is located further away, with distance being 50 metres instead of 30 metres (standard).

4.1.2.5 Influence of lower spacing between piles

Lowering the spacing between piles in the existing piled raft, and therefore also increasing the number of piles, brings a significant decrease of uplift in the raft, see Figure 4.18. This is because the increased number of piles creates a stiffer structure restricting the movements. The heave within 0.4 pile lengths to each side of the piled raft is lower when compared to the standard case.

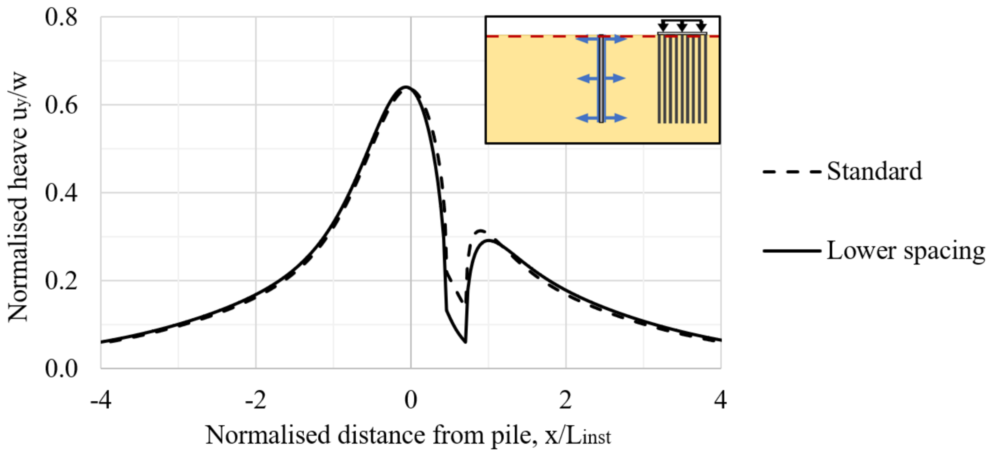


Figure 4.18: Comparison of heave with existing adjacent piles with lower centre-to-centre spacing at 4 metre instead of 2 metres as for the standard case.

The heave between installed pile and pile group decreases, but increases slightly beyond the pile group. There is also an increase to the opposite side of the installed pile. This agrees with the horizontal displacements which decrease before the existing piles, and increase beyond the existing piles, see Figure 4.19. Again, it should be noted that the total volume of heave will always be the same, since the soil is modelled as incompressible. This means that a decrease of heave at one place will lead to more at another.

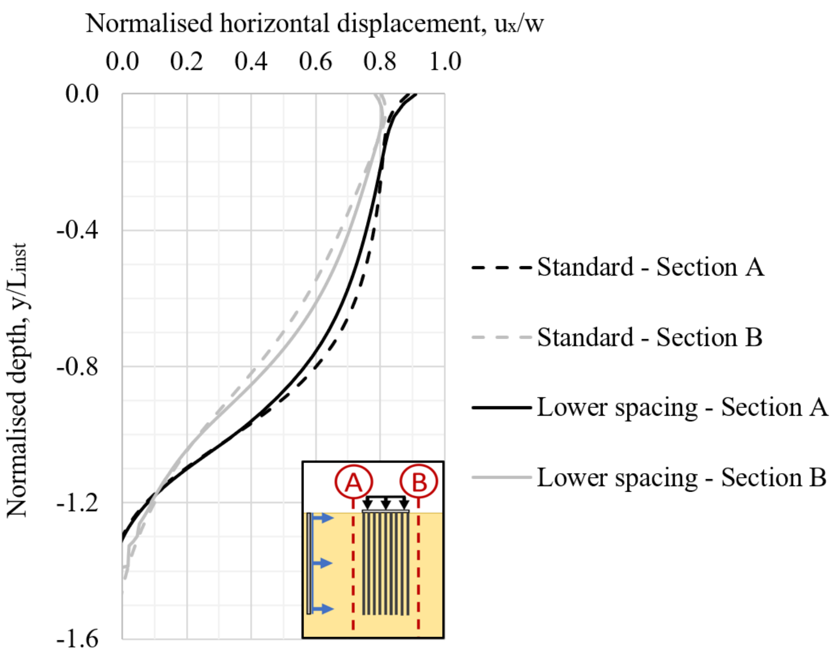


Figure 4.19: Comparison of horizontal movement with existing adjacent piles with lower centre-to-centre spacing. Section A is 5 metres before the raft and section B is 5 metres after the raft.

4.1.2.6 Influence of wider raft

Widening the piled raft from 16 to 31 metres shows very similar results in regard to heave, keeping the same magnitude and pattern of overall heave as well as uplift of the piled raft, only restricting the uplift for a wider area, see Figure 4.20.

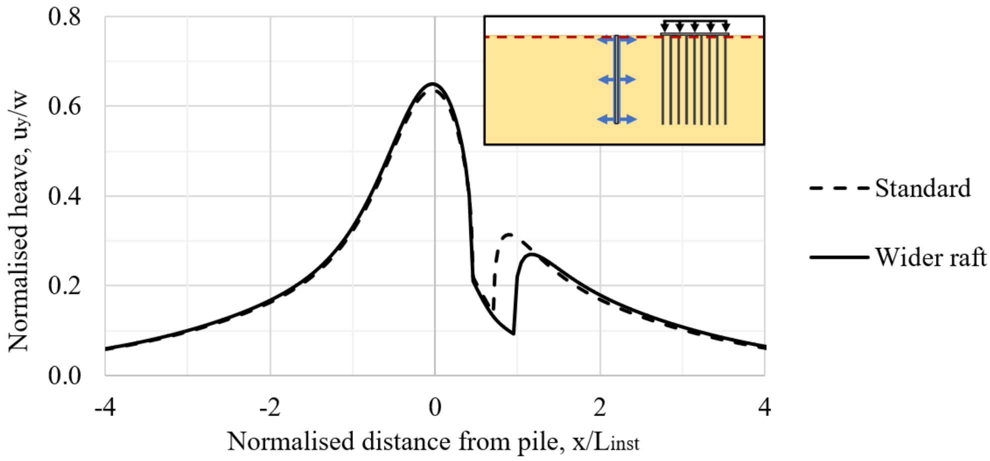


Figure 4.20: Comparison of heave with different width of existing piled raft. Standard case has a width of 16 metre while the wider raft is 32 metres.

The horizontal displacements in Figure 4.21, show a similar pattern as the standard case, but the effects of the piled raft are increased. The decrease in horizontal displacements before the existing piles are even further decreased and horizontal displacements after are more increased.

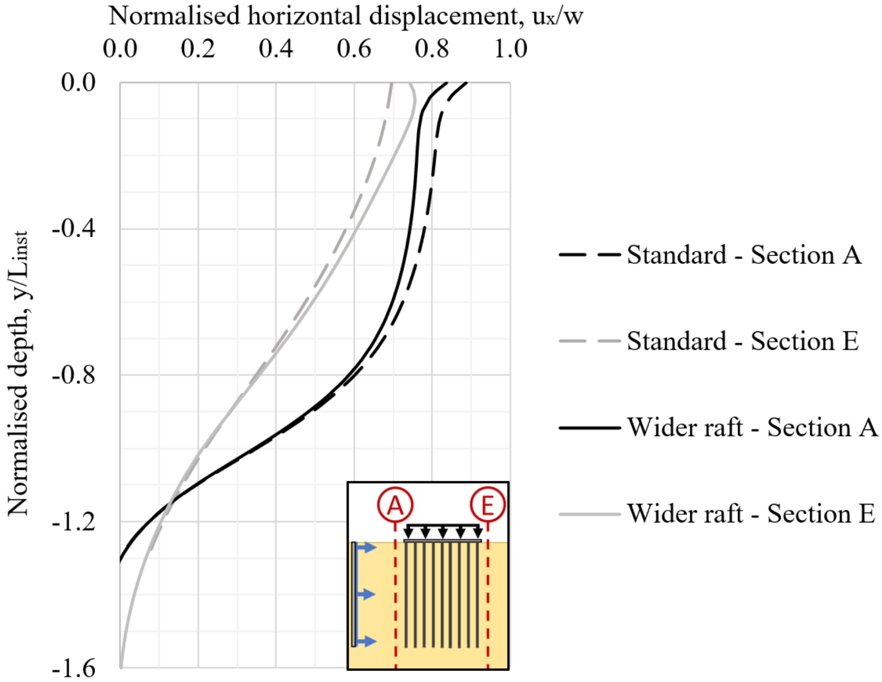


Figure 4.21: Comparison of horizontal displacements with different width of existing piled raft. Section A located at 25 metre distance (5 metre before the piled raft) and section E located at 67 metre distance in both cases (5 metre beyond the wider raft).

4.1.2.7 Influence of other parameters

Changing the stiffness of the soil or the pile has little to no influence over the soil movement. It can be assumed that this will be the case as long as the pile stiffness is much higher than the soil stiffness. The same result applies when changing the top connection between the raft and the piles (fixed/hinged), which did not have an impact on the soil movement either.

4.1.3 Free standing piled raft

Soil displacements of the free standing piled raft shows heave in between the piled raft and the free field displacements which can be seen in Figure 4.22. The main difference in heave can be seen within the existing piled area, where the ground surface heaves more with a free standing piled raft compared to the piled raft. This is feasible considering the confinement from the raft.

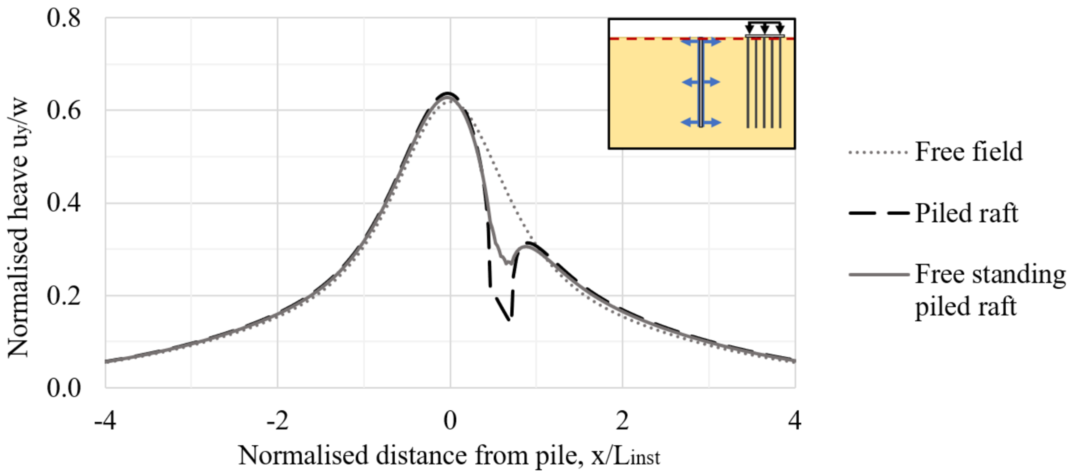


Figure 4.22: Heave for the piled raft in comparison with free standing piled raft and free field.

The horizontal displacements for three different scenarios is shown in Figure 4.23 where the free standing piled raft differs from the simple piled raft at the upper 0.4 pile lengths part of the pile. The free standing piled raft shows larger displacements before existing piles and less displacements afterwards. At a depth corresponding to about 1 pile depth the horizontal displacement is equal for all scenarios.

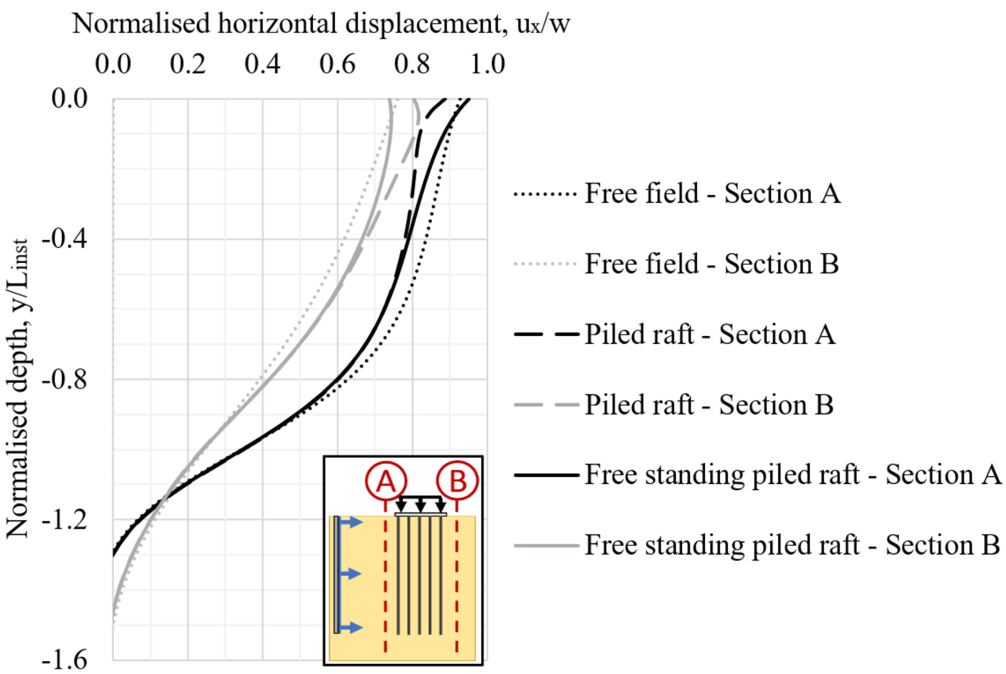


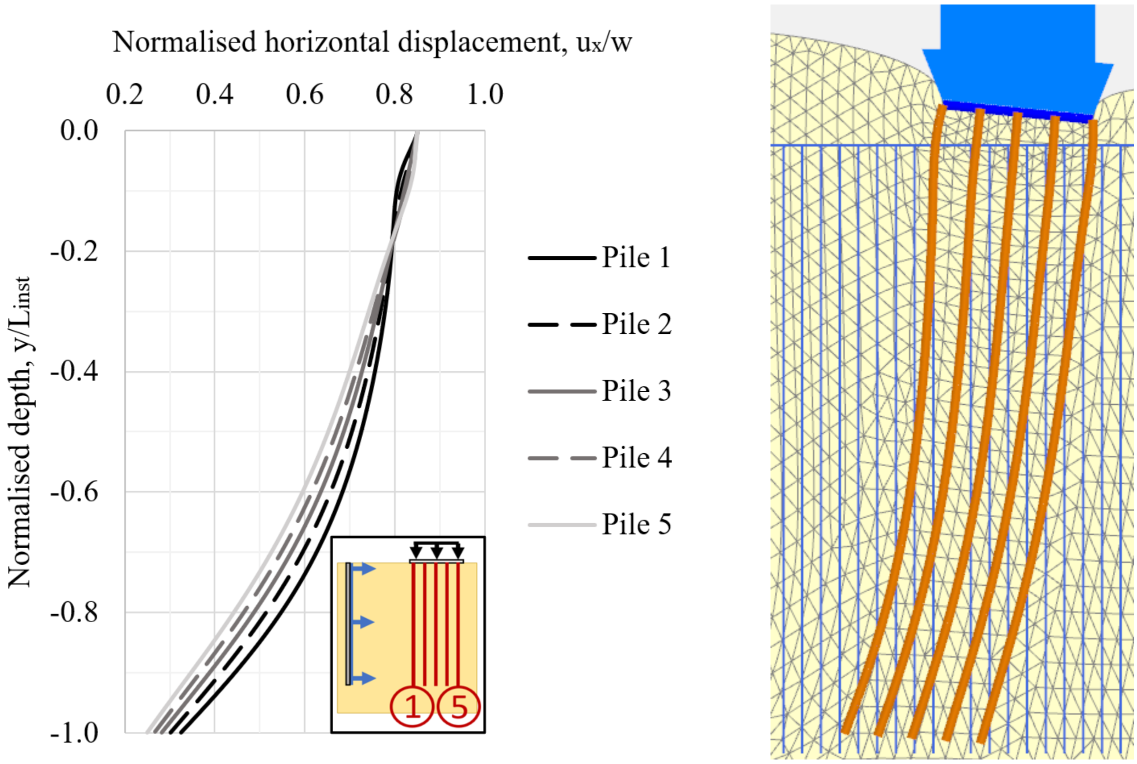
Figure 4.23: Horizontal displacements for piled raft in comparison with free standing piled raft and free field.

4.2 Influence on the existing piles

This Chapter will investigate the impact on existing piles from the installation of a neighbouring pile group.

4.2.1 Piled raft

Figure 4.24 show the horizontal displacements of the piles within the existing pile group in the standard case, together with an illustration from Plaxis of the up-scaled total deformations.



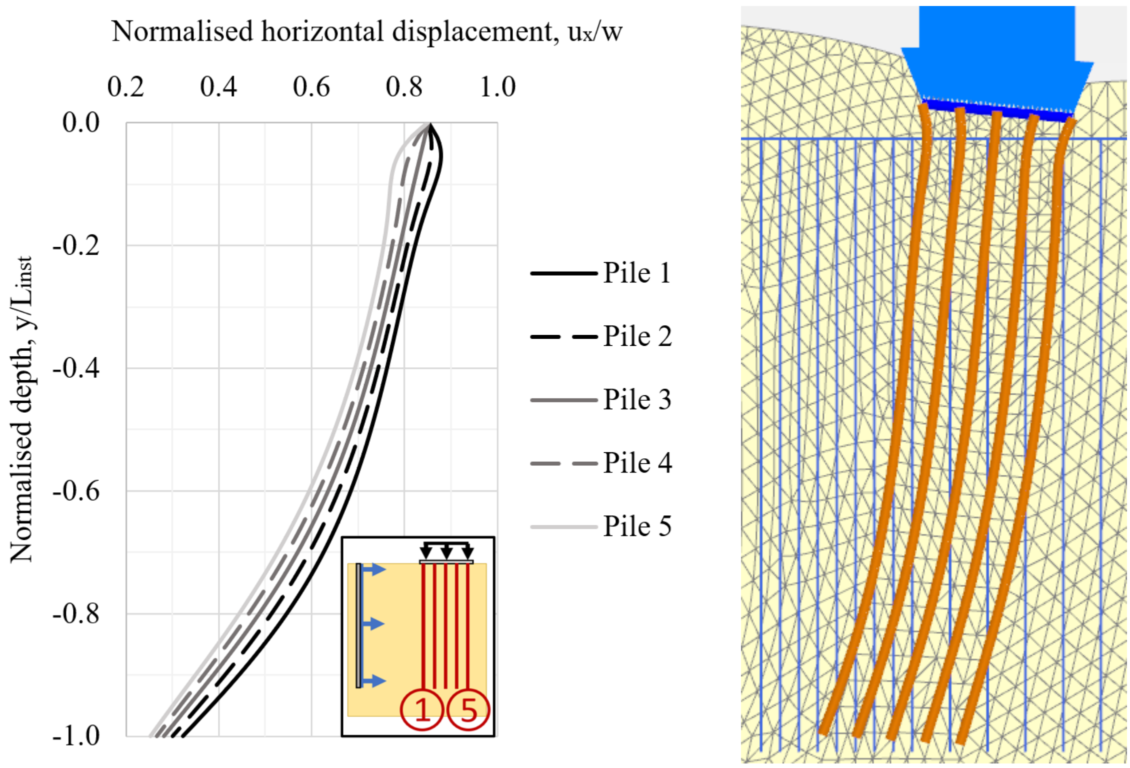
(a) (b)

Figure 4.24: Horizontal displacement in piles in the piled raft. Pile 1 is closest to the pile installation, a) normalised horizontal displacement b) 500 times up-scaled displacement figure.

The horizontal displacement of the outer piles is bending outwards at the top, approximately to the depth of 0.2 pile lengths. This could be a possible displacement for the piles with a fixed top connection. However, the phenomenon of outwards horizontal displacement was seen to be unaffected whether the top connection was set to hinged or fixed, and the reason for this is so far unclear. The only visible change was the bending moment which, as expected, started from zero at the top when set to hinged.

4.2.2 Free standing piled raft

A influence from boundary condition in horizontal displacement behaviour was seen when modelling a free standing raft, where the outer piles instead was bending inwards at the top, see Figure 4.25. A hinged top connection is more common in practise and that the free standing raft showed a behaviour more align with that. It was therefor decided that the free standing raft is better to focus on when examining the influence on the structures from mass displacement. The free standing piled raft will also transfer the load from the raft directly to the piles and therefore providing a more isolated analysis in regard to examination of the piles.



(a) (b)

Figure 4.25: Horizontal displacement in piles in the free standing piled raft. Pile 1 is closest to the pile installation, a) normalised horizontal displacement and b) 500 times up-scaled displacement figure.

From figure, 4.25, it is seen how the piles are bending inwards towards the piling centre above the depth of 0.2 pile length, which can be related to induced bending moments which can be seen in Figure 4.26. Notice that the unit is stated dependent on the out-of-plane distance. Meaning that in this case, when the distance between piles are four metres, the bending moment in every pile should be multiplied with four.

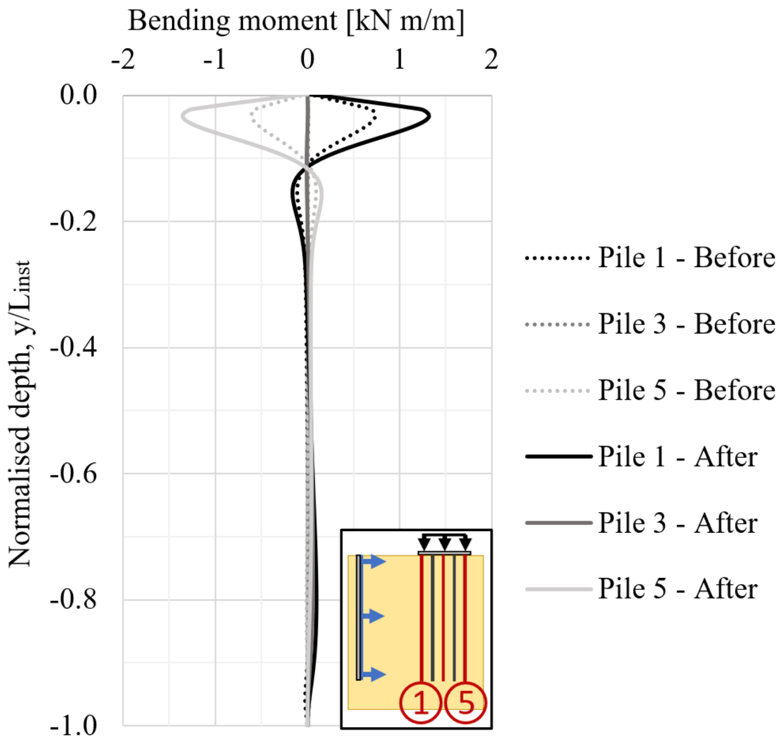


Figure 4.26: Bending moment in pile 1, 3 and 5 for the free standing piled raft, before and after pile installation.

Bending moments are closely correlated to horizontal displacement, and an increase in bending moment for pile 1 and 5 is most pronounced at the upper 0.2 pile length i.e. the same section of the pile where the highest curvature of the pile is found. This can be due to a few reasons. It can be see that all piles have the same magnitude of movement at the top, which is to be expected since they are attached to a stiff raft. The lower part of the piles will follow the displacements induced by the soil on the individual piles in which differs from the combined movement in the raft. Pile 1 and 5 are exposed the most to a difference in movement between the lower part of the pile, unaffected by the raft, and the top of the pile, which causes bending moment. It can also be argued for that pile 3, in the middle, has the same magnitude of displacements as the raft because the bending moment is zero in Figure 4.26. This more pronounced bending moment at the outer piles (1 and 5) occur already before the pile installation, indicating that the part of the effect can be attributed to other reasons than pile installation, such as the applied load. However, notice that the actual value of the bending moment is quite small (around 1 kNm) which is probably because the displacements from the pile installation is also quite small.

Figure 4.27 show a schematic illustration the relative difference of movement in the raft and piles. Zone A is where the imposed displacement in the soil pushes on the first pile, creating horizontal movement throughout the pile. This horizontal movement is largest in the first pile and is decreasing towards the last pile. At point B, a horizontal movement is introduced in the raft, and due to the stiff raft, the same displacement occurs at point C. The soil displacement within zone D is smaller than in zone A, due to geometrical spreading. However, since point C moves as much as point B, the soil in zone D will restrict the movement in the lower part of the piles to the right.

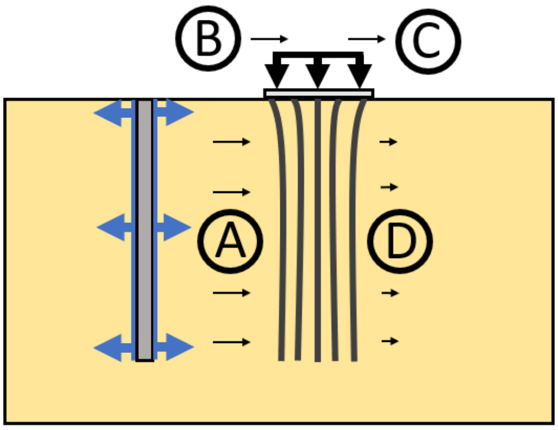


Figure 4.27: Illustration of horizontal displacement within the piled raft.

Figure 4.28 show the axial force in all five piles. The unit of the axial forces is stated in the same way for the bending moment, which depends o the distance in the out-of-plane. So the force in every pile should be multiplied with the centre-to-centre distance, in this case four, to get the axial force in the pile. The change in axial force is generated by differences in relative movement between the soil and the pile. When a movement is imposed by the pile installation, the existing piles can either follow this movement or restrict it. The piles, which tends to restrict the movement, will create a change in relative movement which generates forces. The interface between soil and piles decide the force transfer. All piles transfer the load to the soil with depth. Meaning that the slope of the axial force-curve decides how much load that transfers to the soil at ay given depth. In Figure 4.28 it is indicated that existing piles exposed to a pile installation will transfer load higher up in the soil.

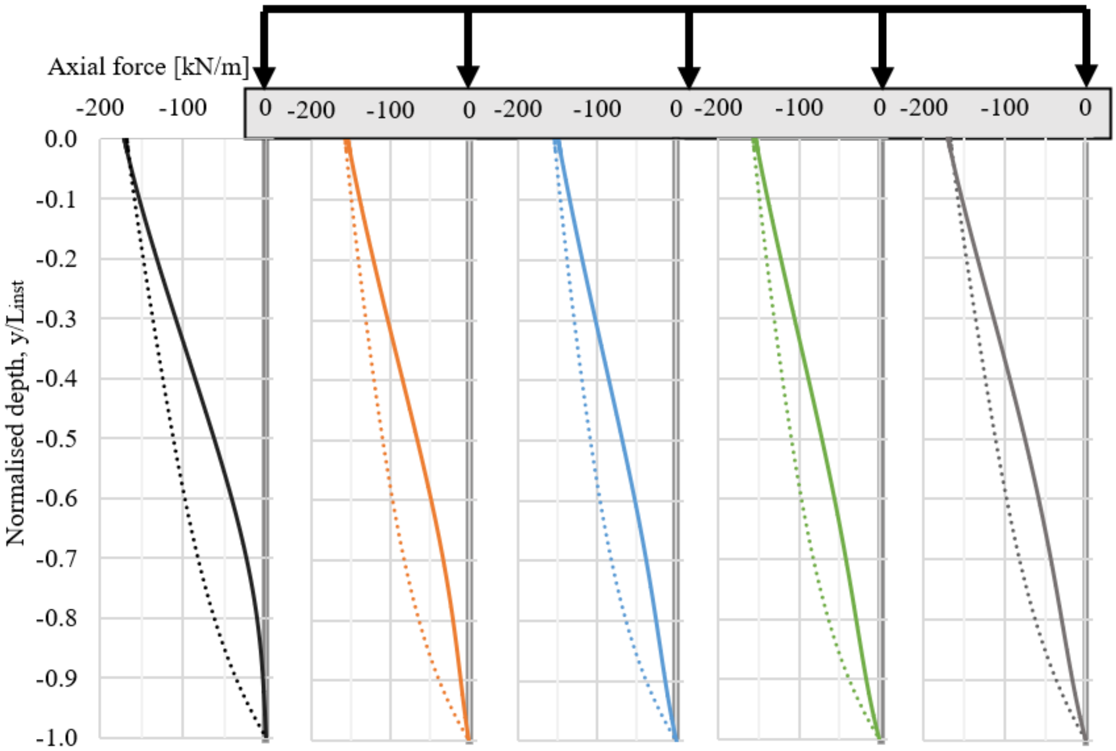
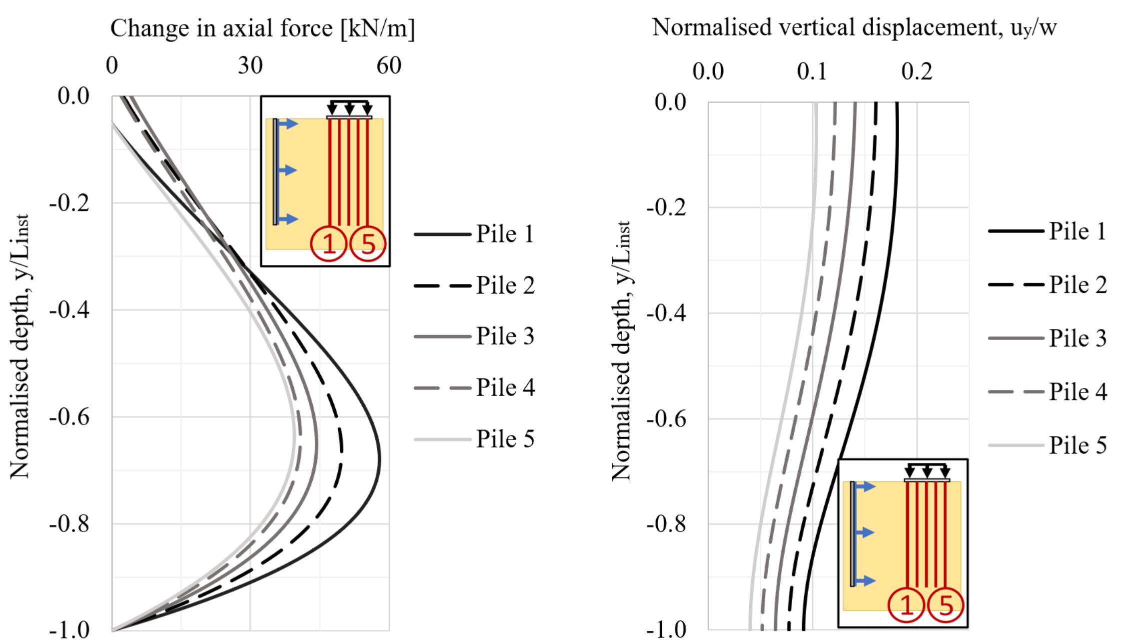


Figure 4.28: Axial force in the piles in the free standing piled raft, standard case. Pile 1 to 5 from left to right. Dotted line is before pile installation, solid line is after pile installation. Negative axial force means compression and positive is tension.

Pile 1 and 5 has around around 15% larger maximum compression compared to pile 3 meaning that the load spreads towards the outer piles.

It is interesting to see how the displacement from pile installation results in less unloading of the existing piles. Pile 1 experiences the most change as seen in Figure 4.29a where the difference in axial force before and after pile installation is presented. Together with the change in axial force, the vertical movement in all piles in seen plotted against depth, Figure 4.29b.



(a) **(b)**

Figure 4.29: Structural results from piles in existing free standing piled raft where a) is the change in axial force from before and after pile installation and b) is the vertical movement in all piles after pile installation.

The largest change in axial force occurs, as expected, around the depth where the vertical movements are changing the most, at around 0.7 pile lengths. Pile 1 with the largest vertical movements also has the most change in axial force. The piles are transferring load to the soil, higher up when exposed to neighbouring pile installation. This could be related to a type of reverse down drag, where the soil acts similar as downdrag but instead upwards.

The observed phenomenon can be compared to the wedge shaped influence area according to the Hellman/Rehnman method. The maximum change in axial force can then represent a transfer zone from forces uplifting the soil and forces resisting the uplift. This transfer zone can be simplified with the wedge shaped influence area. When going more in to detail, this maximum change in axial force is located at a depth of 0.67 pile lengths in pile 1 and at 0.64 pile lengths for pile 5. Meaning that there is a slight inclination of the wedge shape within the pile group. Figure 4.30 shows the horizontal movement from pile installation. The wedge shape is drawn from the tip of the pile towards the first piles maximum change in axial force at 0.67 pile lengths and then towards pile 5 maximum change in axial force at 0.64 pile length, and the with the same angle as before the pile group, up to the ground surface. However, judging by the colour plot the patters of the soil does not act in a similar way as the wedge and therefor not supporting this theory. This indicated that this simplification might not be generally valid for the soil displacement.

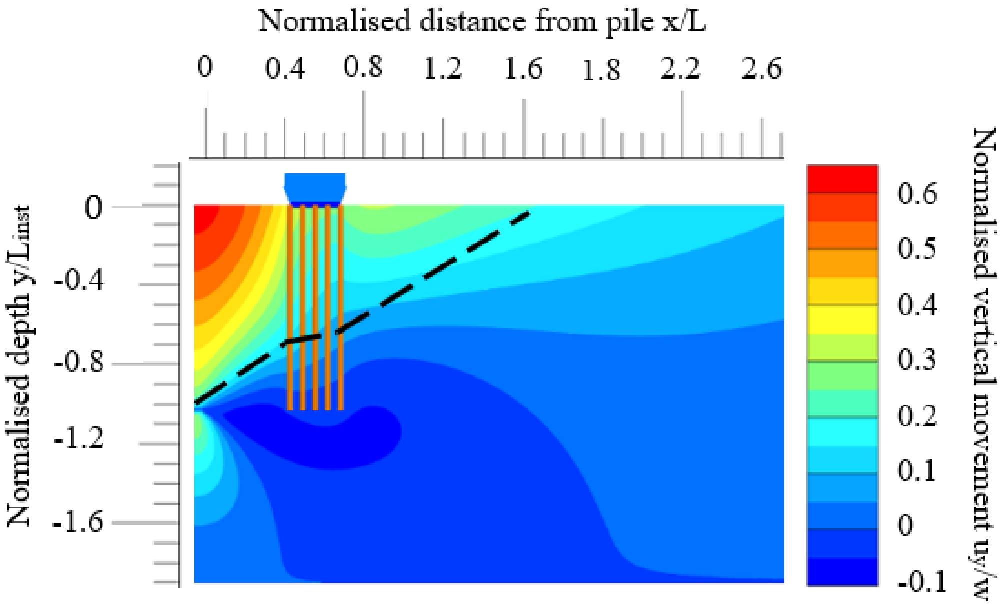


Figure 4.30: Vertical displacements from pile installation towards the existing free standing piled raft with a line representing the wedge shaped influence area.

The phenomenon caused by change in axial force and vertical movement in piles can thus be illustrated as in Figure 4.31. The tilted line represents the wedge shaped influence area from Figure 4.30, where zone A is affected by a heave motion which transfer to the piles by cohesion. At the same time, in zone B, the piles are attached in soil layers which experience less heave movement and therefore restricts the vertical motion and creating a change in relative movement, resulting in tension.

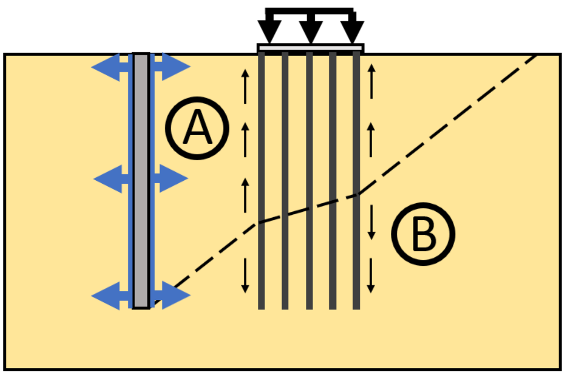


Figure 4.31: Illustration of relative vertical pile movement and explanation of the phenomenon that occurs by differences in vertical movement from pile installation.

4.2.2.1 Influence of increased displacement

When increasing the displacement with 50% (increased cross section of installed pile), the axial compression decreases even further compared to the standard case, see Figure 4.32. This means that the larger displacements imposed by pile installation, the more load is transferred to the soil higher up in the pile.

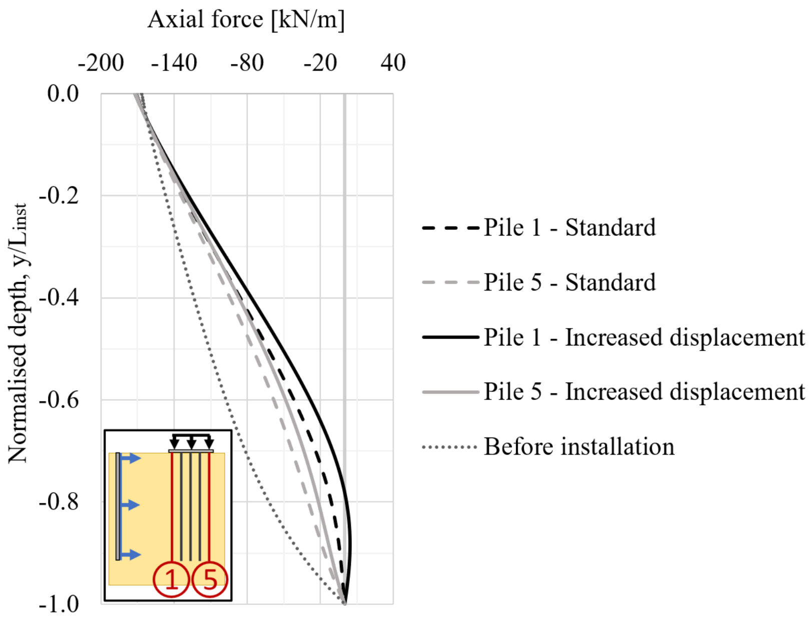


Figure 4.32: Axial force in the existing piles 1 and 5 with increased displacement with 50%.

The difference can be easier to view in the change of axial force before and after pile installation, see Figure 4.33. The change in axial force follows the same trend as for the standard case but the maximum change is increased by 23% in pile 1. This increase in displacement created a increase in maximum bending moment with 13%.

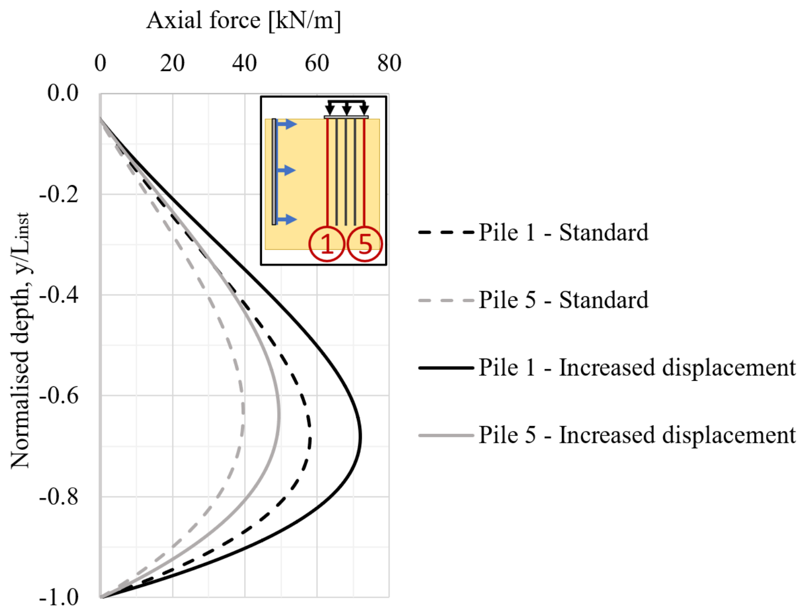


Figure 4.33: Axial force in the existing piles 1 and 5 with increased displacement with 50%.

4.2.2.2 Influence of load intensity

Earlier it was shows that the soil movement was not affected by differences in load. However, the axial force in the piles experience large changes, see Figure 4.34 when the building load was set to 0 kN/m and 200 kN/m instead of 50 kN/m (standard).

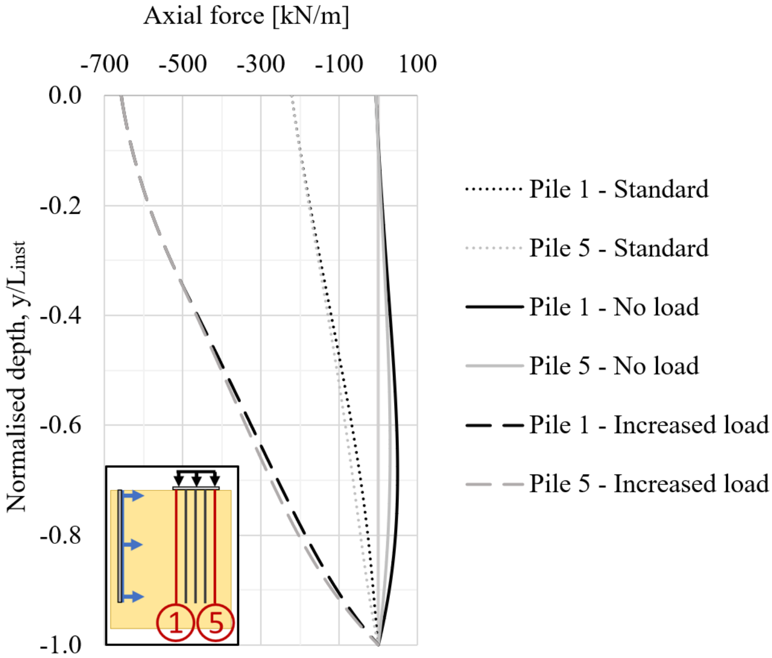


Figure 4.34: Axial force in the existing piles 1 and 5 with change in building load where standard is 50 kN/m, increased load is 200 kN/m and no load is 0 kN/m. All forces are after pile installation.

A four times larger building load creates an almost four times larger compression and an increase in bending moment with 126%, compared to the standard case. Reducing the load to zero creates actual tension in the piles. Applying zero load decreases the bending moment with almost 50%. There were no significant change in horizontal displacement when changing the load, similar to previous findings in this Thesis.

4.2.2.3 Influence of installed pile length

Moving on to change in length of the installed pile, which has an impact on the horizontal displacements. Figure 4.35 shows less displacement in the piles when the installed pile is shorter (52m) compared to the standard case (65m). Both figures show the same results but normalised towards different lengths. Figure 4.35a is normalised towards the length of the existing pile (65m) and Figure 4.35b is normalised towards the installed pile length (52m for shorter and 65m for standard). When looking at Figure 4.35a where both results are normalised according to the same length, the physical change in the soil can be seen where the shorter installed pile causes less horizontal displacements below 0.8 pile lengths, which is accurate because there is less installed pile volume. In Figure 4.35b, where the results are normalised according to different installed pile lengths, a more general result can be seen. The curves now have a similar pattern which suggest that they act similar no matter the depth of the installed pile. Only the magnitude of horizontal displacements change.

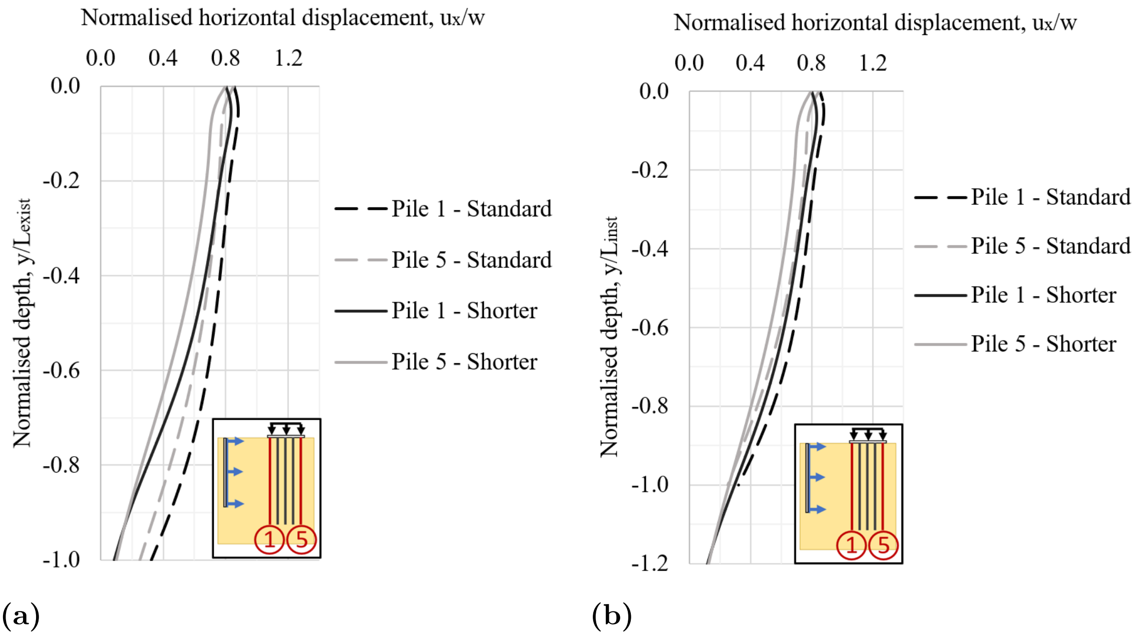
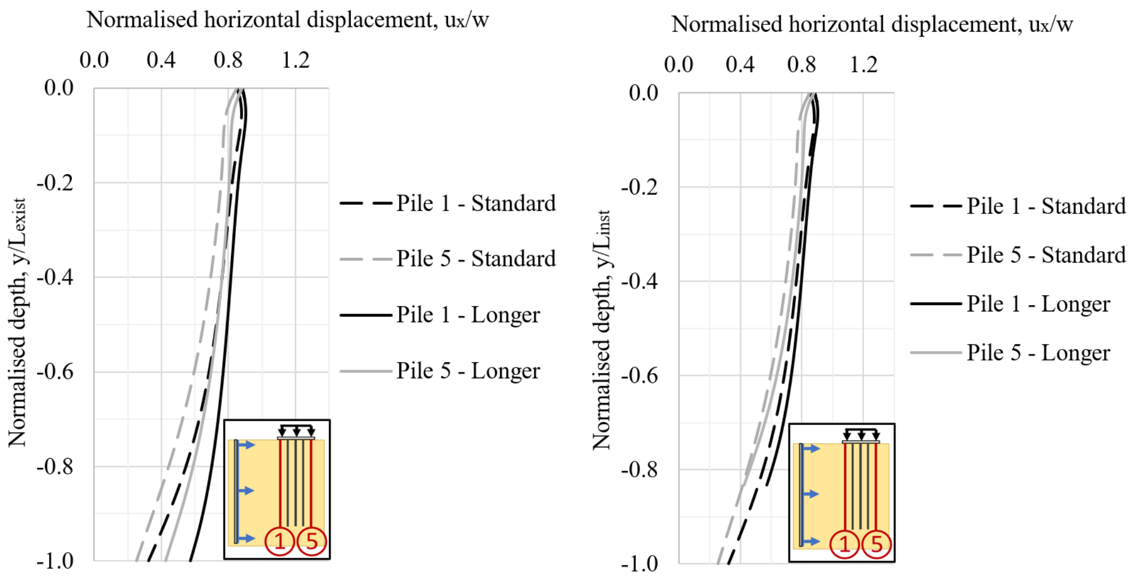


Figure 4.35: Horizontal displacement in pile 1 and 5 when installed pile is shorter (52m) compared to the standard case (65m) for a) when depth is normalised according to existing pile length (65m) and b) when depth is normalised according to installed pile length (52m for shorter and 65m for standard).

The same pattern applies for a longer installed pile (78m) where the physical difference can be seen in Figure 4.36a. The longer pile results in larger horizontal displacement which reaches further down with a larger difference between pile 1 and 5. The pattern in Figure 4.36b is similar to Figure 4.35b when the result is normalised towards the separate results imposed displacement. Notice that the longer piles in Figure 4.36b is not reaching a depth of 1 pile length because it is normalised towards a pile length of 78 metres but the actual pile is only 65 metres.



(a) **(b)**

Figure 4.36: Horizontal displacement in pile 1 and 5 when installed pile is longer (78 m) compared to the standard case (65 m) for a) when depth is normalised according to existing pile length (65 m) and b) when depth is normalised according to installed pile length (78 m).

The maximal bending moment increases with shorter installed piles and decreases with longer piles. Both differences are with around 10% of the bending moment in the standard case.

Change in installed pile length affect the difference in axial force between pile 1 and 5. Figure 4.37 shows the different cases, normalised towards the existing pile length. Compared to the standard case, the shorter installed pile causes a larger difference in axial force between pile 1 and 5. Vice versa occurs for the longer installed pile where both pile 1 and 5 show a similar pattern in the shape of the curve.

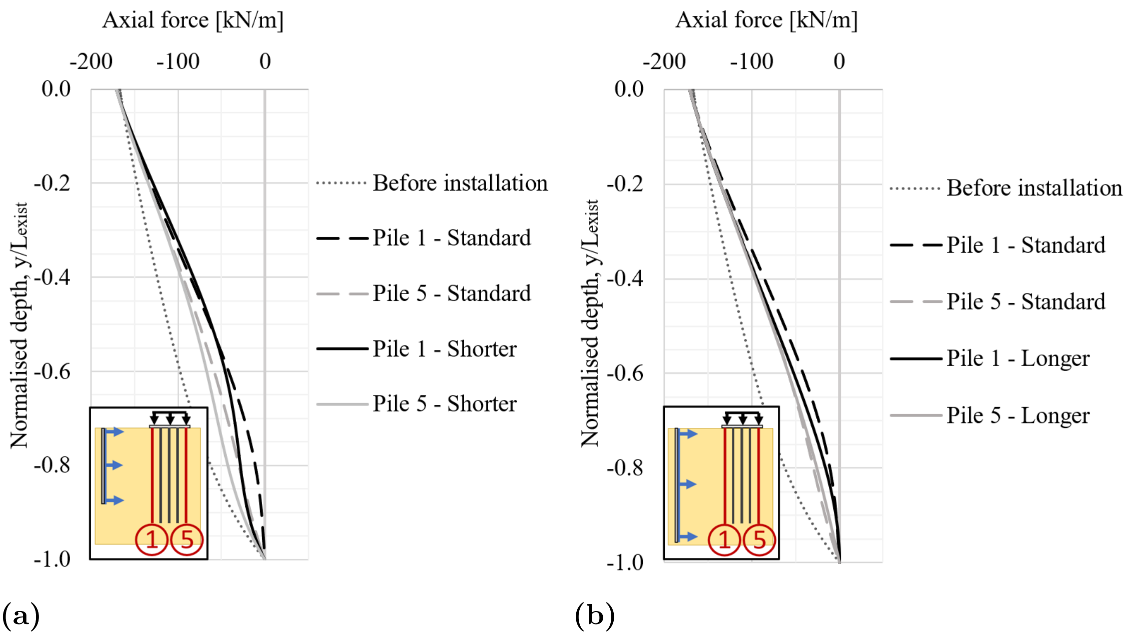
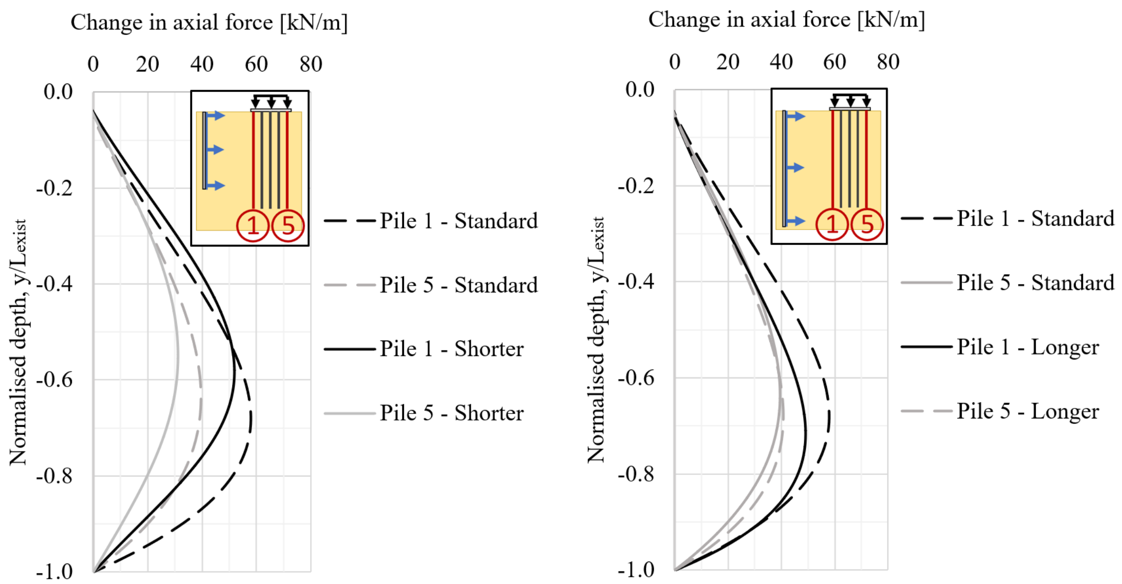


Figure 4.37: Axial force in pile 1 and 5 with different length on installed pile where standard length is 65m (1L), a) is shorter, 52m (0.8L) and b) is longer, 78m (1.2L).

The result might be easier to analyse in the change of axial force from before and after pile installation. Figure 4.38 displays this change in axial force the shorter and longer installed pile. The maximum change in axial force is equally large in when the installed pile is shorter and longer. However, the maximum change occurs at different depth. Shorter installed pile causes the change to occur at a depth of around 0.55 pile lengths, and for a longer installed pile; around 0.7 pile lengths. However, it is interesting that the standard case, where installed and existing piles are of the same length, have the highest magnitude of change in axial force.



(a) **(b)**

Figure 4.38: Change in axial force from before and after pile installation in pile 1 and 5 when exposed to both a) shorter and b) longer installed pile. Normalised towards existing pile length.

4.2.2.4 Influence of stiffness

Changing into stiffer piles, from $32GN/m^2$ to $48GN/m^2$, does not have a significant impact on the horizontal displacements, axial force or bending moment. Changing the soil into stiffer, from $375c_u$ to $500c_u$, has an impact on the axial forces, see Figure 4.39.

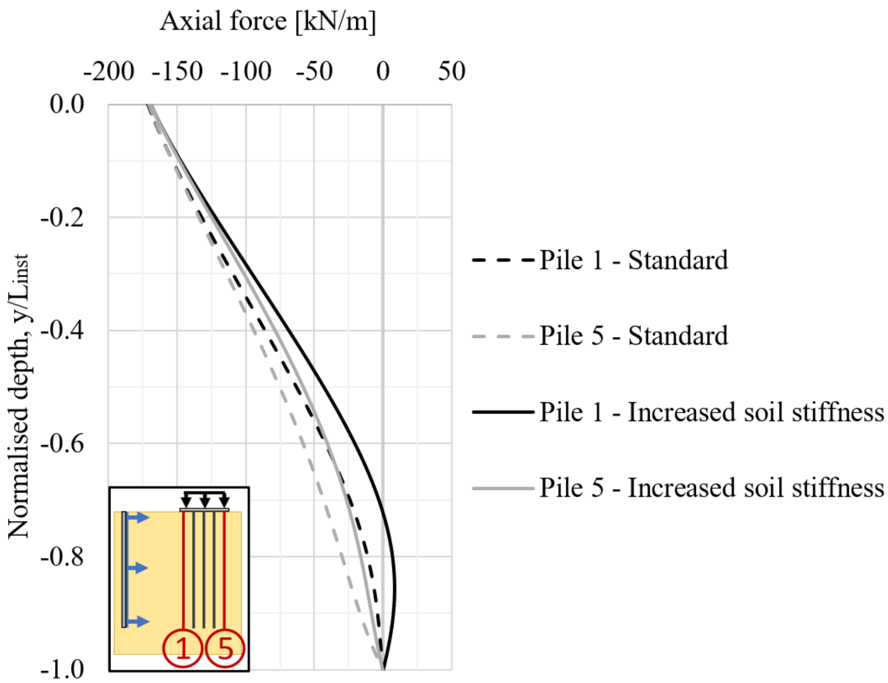


Figure 4.39: Axial force in pile 1 and 5 with increased soil stiffness($500c_u$) compared to the standard case ($375c_u$).

Higher soil stiffness creates a higher stiffness in the interface between piles and soil. This leads to larger shear forces when the relative movement between soil and piles emerges. Since the movement from the pile installation will move the existing piles upwards, the decrease in compression is larger.

4.2.2.5 Influence of wider raft

One last parameter iteration was the width of the raft and piles, which was made double the size, from 16 to 32 metres. A wider raft increase the effects on the adjacent structure that have been seen in previous results. Figure 4.40 shows the horizontal displacement in every other pile where pile 1 and 9 are the outer piles. The difference in horizontal displacement is now larger compared to the standard case. This increase in horizontal displacement at the top section of the outer piles results in a 75% larger maximum bending moment. The horizontal displacement in the existing piles is larger because the relative movement between raft and piles becomes larger with a wider raft. The longer distance from the middle of the raft, the more changes the relative movement which induces the larger horizontal displacement.

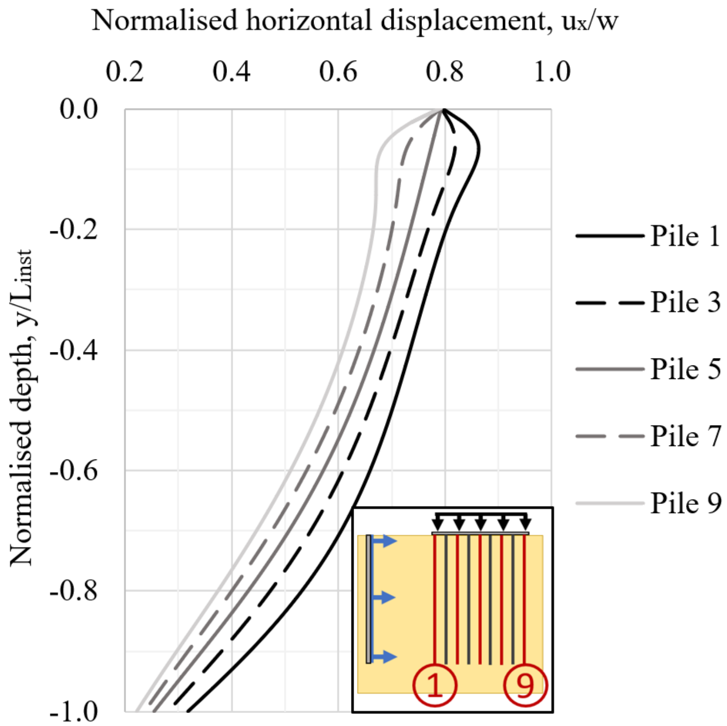


Figure 4.40: Horizontal displacements for every other pile at a raft with the double width (32m).

The axial force is also larger which is accurate because of the increase of total load with the wider raft. In the standard case, the outer piles had around 15% more maximum compression compared to the middle pile. For the wider raft, the change is 67%. It can also be seen that the descending compression in the first pile, at around 0.7 pile lengths, which is decreasing below the compression in the fifth pile meaning that the first pile is closest to reach tension. This phenomenon could be seen for the standard case too but is much more visible with the wider raft.

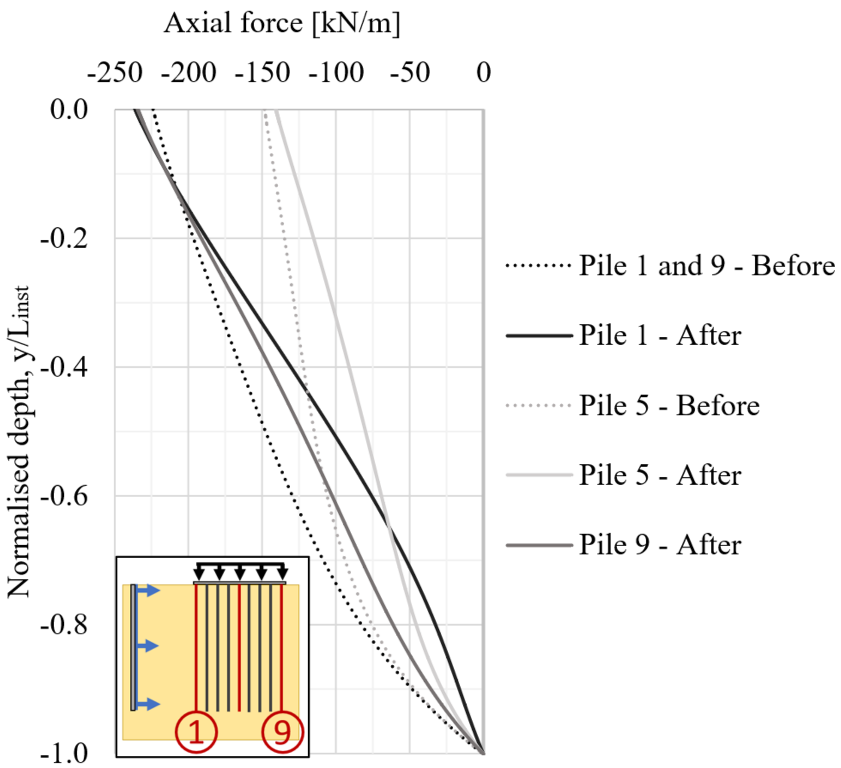


Figure 4.41: Axial forces in pile 1, 5 and 9 for a wider raft (32m). Before and after pile installation.

4.3 Summary of result

The parameter study can be summarised in Table 4.1 below. The Table show how much the different parameters have been varied in terms of percentage, and how that affect main parts of the result. The parameters have been referred to in terms of a percentage, i.e the displacement was increased with 50% or the installed pile length was increased and decreased with 20%. The main parts of the result have been chosen to maximum heave, heave in the raft, minimum axial force (maximum compression) and maximum bending. Those parameters that have a large impact on the main results (change with more than half of the percentage of the parameter variation) are marked in red.

Table 4.1: Summary of results and how much a change in different parameters affect the main results in terms of maximum heave, heave in the raft, maximum axial force and maximum bending moment.

	Parameter variation [%]	**Maximum heave [%]**	**Heave in raft [%]**	**Minimum axial force [%]**	**Maximum bending [%] moment**
Imposed displacement	50	50	50	0	13
Inst. pile length	20	2	57	0	-11
Inst. pile length	-20	-1	-44	0	3
Ctc of piles	-50	0	-51	20	192
Width of raft	100	2	-9	-38	80
Pile stiffness	50	0	-11	0	0
Soil stiffness	30	0	10	0	3
Building load	-100	0	0	104	-40
Building load	400	5	0	-385	130
Distance from inst. pile to exist. structure	67	0	-31	0	0

5
Discussion

This chapter presents a general discussion of the results obtained. The discussion will contain potential risks with mass displacement and comparisons with other studies. The magnitude of displacement in the soil and piles could be considered low. However, it is important to keep in mind that the Thesis seeks to capture and analyse the behaviour when installing piles to an adjacent piled structure rather than exact values. Based on the results, a risk with pile installation is that the adjacent piles could experience tension and/or excessive bending. There is no increased risk for exceeding the bearing capacity in compression of the piles, because the compression decreases due to the soil movements from the nearby pile installation. The worst case scenario would be if the pile failed by excessive tension or bending. Additionally, the induced horizontal displacement in the top of the pile will increase the potential of the piles to buckle. The bending is most critical at the top parts of the pile where the bending moment is the largest and where the piles are attached to the raft and therefore prevented to move.

The possible damage on the existing structure is also dependent on wether the building is during construction or completed. If the adjacent structure is during construction, there might only be a piled foundation without the actual building on top. This is a possible situation in a rapidly developed urban area. If the existing structure only contains of a pile foundation there is little load on the piles. As have been seen in the result, less load can then lead to tension and vertical displacements in the piles within the existing piling area.

5.1 Comparison with field measurements

There are inclinometer measurements of horizontal displacements from pile installation in the city centre of Gothenburg, which can be used for comparison and discussion of the result in this Thesis (COWI, internal communication, 5 May 2023). The inclinometer measurement was performed at the location of an existing structure, about 20 metres from a site where around 1000 piles was installed. Figure 5.1 shows a simplified illustration of the area were the field measurement were performed. Proportions of the illustration are correct, but not the structure itself. The installed piles were around 80 metres, and the width of the piling area around the same distance. The piling area continues around 100 metres in the out-of-plane direction. The existing structure was almost 70 metres wide, but had piles of around

30 metres in length and a basement. Section A in the illustration represents field measurements of displacements from an inclinometer.

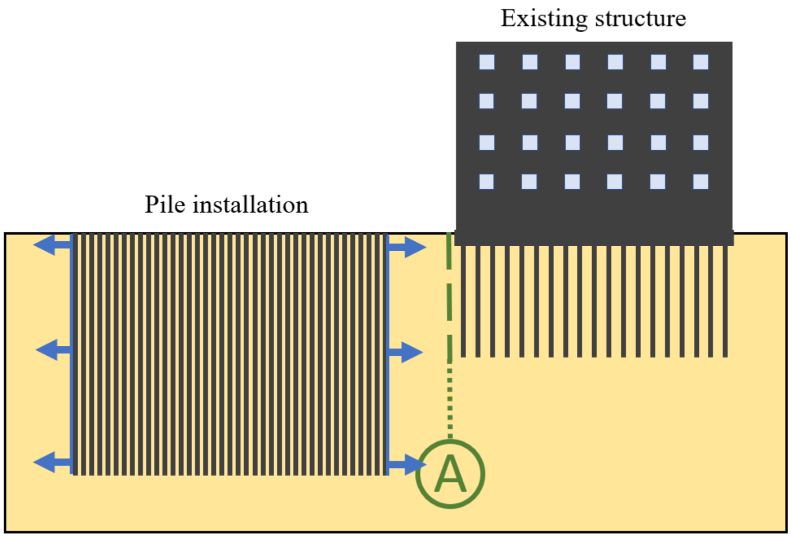


Figure 5.1: Illustration of the real case with from inclinometer in section A. Proportions of the illustration are correct, but not the structure itself

The measurements from the inclinometer can be seen in Figure 5.2. The soil movement moves inwards the existing piling are in which corresponds to results in this parameter study in this Thesis. Inclinometer A has a relative uniform movement from 0.1 pile lengths depth to 0.3 pile lengths depth. The top of the inclinometer is close to the building perimeter, which does not move horizontally as much as the soil, therefor creating the bending inwards the piling area.

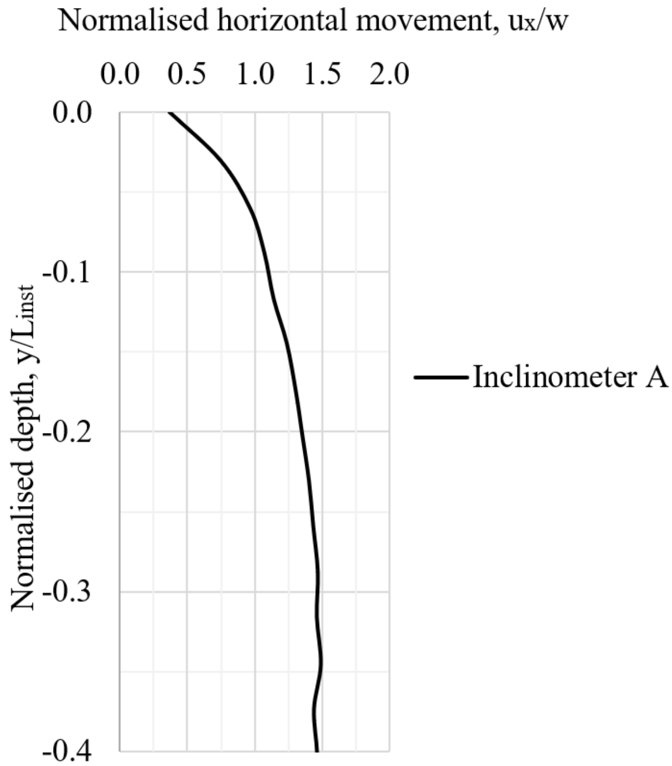


Figure 5.2: Horizontal displacements from field monitoring by inclinometer. The depth is normalised according to the depth of the installed pile of 70 metres while the inclinometer reaches only 30 metres depth.

There was an attempt to recreate this case in Plaxis, based on the model used for the parameter study, but with dimensions of this case. The same problem as previous where a free standing piled raft was needed to get this hinged behaviour of the piles. Therefore was the basement of the existing building not modelled in Plaxis. The inclinometer data together with result of horizontal displacements from the Plaxis model can be seen in Figure 5.3.

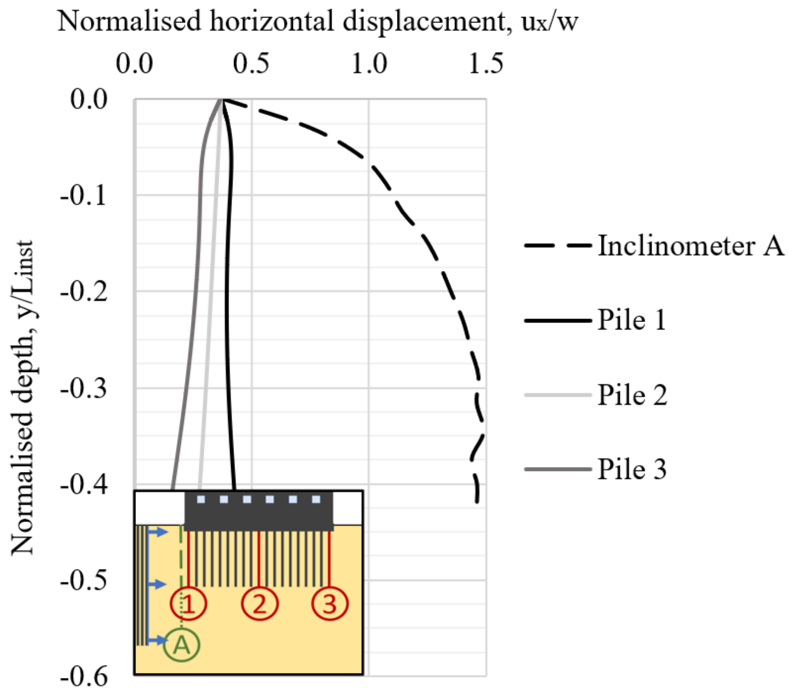


Figure 5.3: Illustration of the data from inclinometers act in the structure. Note that the displacements are scaled up according to the surrounding proportions.

The results from numerical modelling showed little similarities with the inclinometer data. The imposed displacement in Plaxis was set to align the horizontal displacements at ground surface in the model with the horizontal displacements for the inclinometer data. This was to focus more on the behaviour of the model excluding the question of how to capture of the magnitude. There was little bending inwards of the piles compared to the measured values in the inclinometer. This emphasised the fact that investigating mass displacement is complicated. The larger bending could be due to many reasons. One is possibly the basement which was not modelled in Plaxis. A basement limits the area beneath the existing building, which would probably lead to a larger horizontal movement because the heave is further restricted. Another important factor is that this installed pile group is not the only one in this specific area and therefore it might be interesting to create a 3D model where more adjacent structures could be added to see the influence from different directions. Because of time restrictions, this modelling case was not further investigated but it would be fruitful to deep dive in to how to recreate this field measurements in an accurate manner.

5.2 Comparison with other methods/studies

The Hellman/Rehnman method have been discussed through out this Thesis and is a useful tool for mass displacement in free field. As mentioned, the Hellman/Rehnman method provide the option to include influence from nearby structures through the inclusion of countervailing factors αx, βx, γx and δx. These factors give the possibility to define relative weight of a nearby structure. By examining the distribution and ratio of heave towards each side of the installed pile in the plane strain model, a comparison can be done to the countervailing factors. It has been observed in this parameter study that the inclusion of structures only affects the distribution of heave slightly. For instance, by calculating the integral of the heave curves, the distribution of heave from side to side is observed to only change from 50%-50% in the free field scenario, to 53%-47% when this specific piled raft is added into the model. Thus, when including this adjacent piled raft 3% of the heave redistributes to the free field side. It has also been observed that changing the geometry of the adjacent structure or the installed pile-group only affects the ratio with a few percentages and changing the load having an almost negligible effect. Therefore, it is important to highlight that using the countervailing factors in Hellman/Rehnman should be done with caution, to not overestimate the effect on the redistribution. For instance, if a factor is chosen close to 0, implying a heavy building, little to no heave would occur in that direction. It is apparent that this would require an extreme or unrealistic size of the adjacent structure. The definition of the countervailing factors as heavy- or light buildings is therefore debatable. The parameter study also shows that the actual building load makes little to no difference on the heave. Instead the dimensions and stiffness of the foundation has a significant impact and that should be the focus when judging the effect of neighbouring structures, since the foundation has a restricting effect on the heave due to the skin friction of the piles holding the structure down.

Another interesting study comparable to this Thesis is made by Zhou et al. (2020). The study investigated the lateral displacement from the installation of a pile and its affect on an existing pile. The cavity expansion method was used for modelling the soil movement, with the p-y curve method for creation of the the pile-soil interaction. The parameter study included penetration depth, pile spacing, pile diameter, fixity of pile head, undrained shear strength and soil stiffness. An interesting part of the parameter study was when the length of the existing pile was changed. The installed pile was kept to 12 metres, while the existing pile was varied from 5 to 30 metres length. The distance between the piles was constantly 1.5 metres, which is a considerably lower spacing between piles compared to the one used in this Thesis. Figure 5.4 shows the lateral displacement for each pile length. The existing pile which is shorter than the installed pile, (L=5 metres and L=10 metres), moves uniformly with the imposed displacement. The existing piles, longer than the installed one (15-30 metres), behaves more flexible. The flexible behaviour comes from the lower parts of the piles in which the surrounding soil is resisting the movement. This can be related to the wedge shaped influence area that have been discussed previously. The shorter piles (5 and 10 metres) are located within the wedge shaped area and will therefore only experience the lateral motion throughout the pile and move uniformly with the soil. While the longer piles (15-30 metres) are located partly above and partly below the wedge shaped area. They will therefore experience the lateral force but with the resistance from skin friction to the soil, create this bending shape.

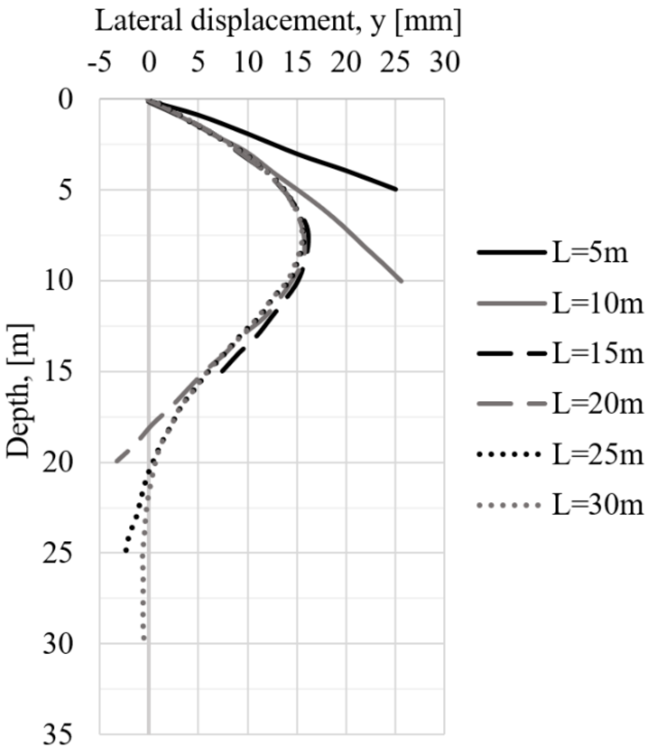


Figure 5.4: Lateral displacement in existing pile from a parameter study. The existing pile was varied from 5 to 30 metres and the installed pile was set to 12 metres. The distance between installed and existing pile was 1.5 metres. After Zhou et al. (2020).

Even if this result is from just one installed pile affecting another pile, and not a pile group which is the focus in this study, it is interesting to see the maximum bending in Zhou et al.'s study. The bending occurs at a depth of 7-8 metres and is clearly visible which can be compared to the change in angle of the horizontal displacement in the result of this Thesis. However, the bending is less visible, probably because of the long distance from the installed pile. Figure 5.5 emphasise this by showing horizontal displacement with the raft at 2 different distance away from the pile installation. It can be seen that the change in angle around a depth of 0.7 pile length becomes less visible with distance, where the horizontal displacement in a piled raft with longer distance has a more linear shape.

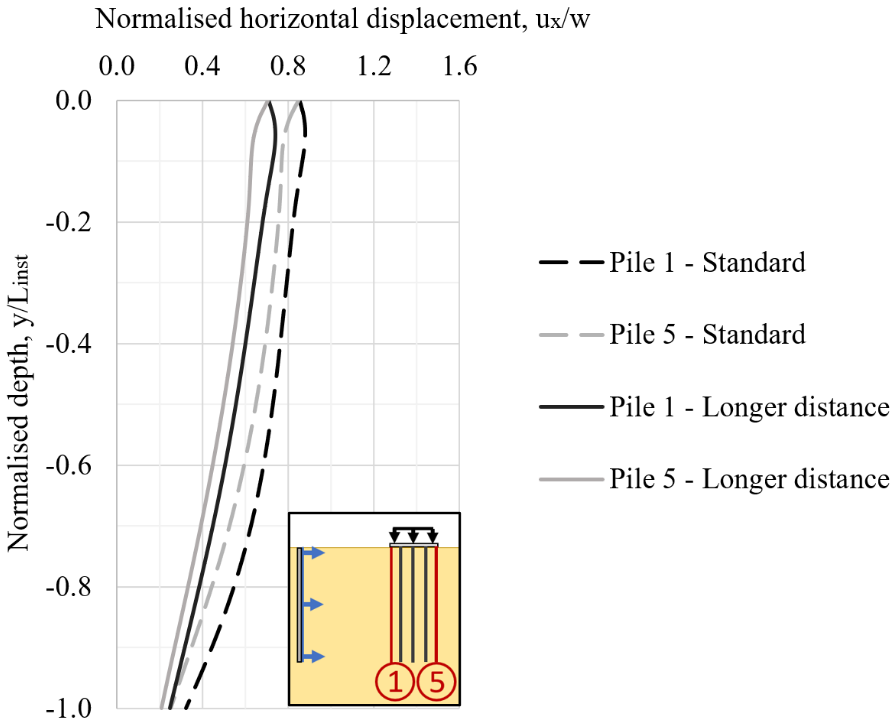


Figure 5.5: Horizontal displacement for pile 1 and 5 at a free standing piled raft with a longer distance (50 m) from the pile installation compared to the standard case (30 m)

6

Conclusions and further studies

The aim of this study was to better understand how pile installation affects adjacent structures, and how adjacent structures affects the distribution of soil movement. This has been investigated with numerical modelling in the geotechnical program, Plaxis 2D, with a parameter study. In the study, the scope was to investigates these effects in a deep layer of soft soil, e.g. Gothenburg clay. All cases analysed have long piles of 52-78 metres, and the existing building is founded on 65 metres long piles. The following conclusions can be drawn from this Thesis.

- The load from adjacent buildings have a negligible effect on the soil movement from a nearby pile installation. Thus, heave and horizontal displacements will act similar to a free field case. A supporting theory is that weight from the moving soil will commonly be larger than the weight of the overlaying structure.
- An adjacent piled raft has an impact on the soil movement from pile installation, compared to a free field case. Heave is decreased within the piled raft area, (restrained), but increased beyond the adjacent piled raft, and to the opposite side of the installed pile. Horizontal displacements are decreased before the existing piling area, and increased beyond the piling area. This effect requires the length of the installed pile to be sufficiently long compared to the distance to the adjacent piled raft
- The axial forces in adjacent piles will be reduced with depth, due to vertical displacements from pile installation, which may lead to tension in piles. Tension did, however, not occur with the moderate installed pile volumes used in this study.
- The risk for tension increases with less load on adjacent structure, more installed piles, wider raft or smaller relative difference in stiffness between soil and piles.
- The horizontal displacements in the top of existing piles, connected to the same pile raft, will be similar. Thus the raft is preventing the movement of the top of the first pile and pushing the last pile leading to an inward bending of the piles in a group.

Some further studies interesting for the development of understanding mass displacement from pile installation.

- One drawback with the modelling is how to properly model the displacement in plane strain. The heave caused by volumetric strain or prescribed line displacement in Plaxis diverge from field measurements at different locations. The real case scenario in which was used for calibration of the free field model, had a heave that spread in a similar pattern as an axisymmetric model. This axisymmetric spread of displacements were not possible to recreate properly with the tools available in Plaxis 2D for the plane strain case. This problem could be solved with a 3D model where the movement will spread in a more reality based way.
- During the work with the Thesis questions arose regarding the impact the raft could have on the result, which should be further investigated. In the scenario where the raft was directly placed on the soil, unexpected local results were generated, which might be due to the load transfer from the raft to the soil, as well as that the piles was not accurately modelled.
- A piled foundation is only one type of structure that could be damaged by mass displacement from pile installation. In a dense urban area, large utility infrastructure is present in the ground. These utilities have individual tolerances for movements. There can also be excavations or tunnels which might behave different due to adjacent pile installation. These other structures should be further investigated.

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A

Appendix

A.1 Comparison of Linear elastic model and Mohr-Coulomb model

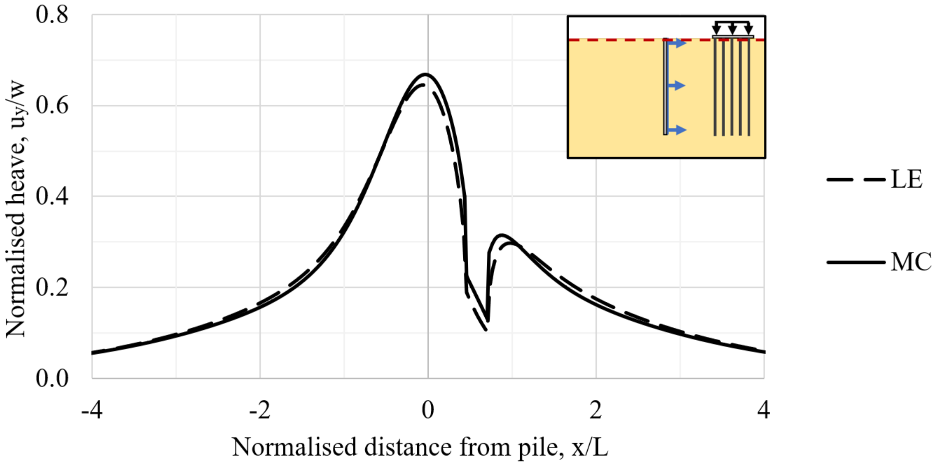

Figure A.1: Heave at ground surface from pile installation. A comparison of the linear elastic model (LE) and Mohr-Coulomb model (MC).

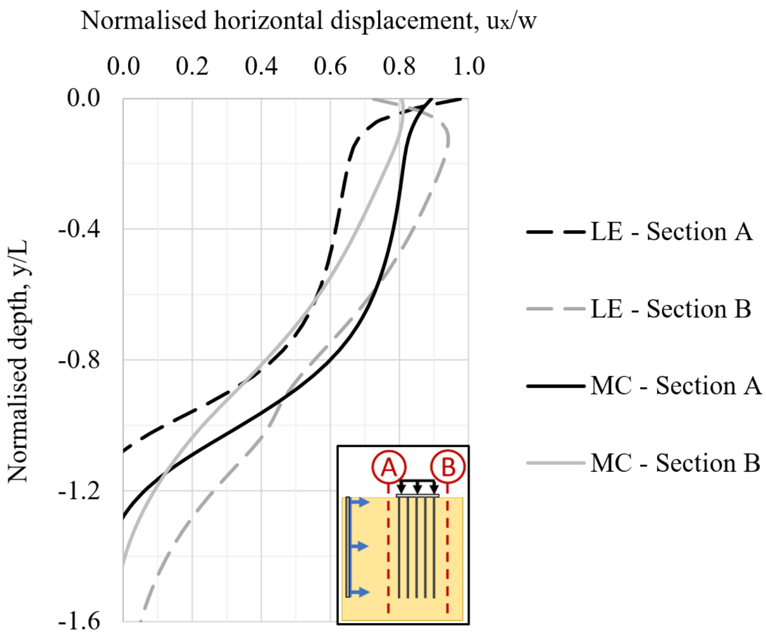

Figure A.2: Horizontal movements from pile installation at 5 metres before existing piling area (section A) and 5 metres after (section B). A comparison of the linear elastic model (LE) and Mohr-Coulomb model (MC).

A.2 Calibration of free field model

The imposed displacement, calculated with equation 3.1, assumes that the volume of the piles moves towards only two directions. In reality, soil displacement is more complex and will take place both within the piling area, and towards other directions. Neglecting spreading in other directions will overestimate the displacement. The plane strain displacement needs to be adjusted since reality is not completely plane strain, as motivated in figure 2.7. A reference case have been used to get an understanding of how pile installation in free field can be represented in the 2D plane. Edstam's report "*Massundanträngning i samband med pålslagning i lera*" (2011) about pile installation of Partihallsbron is a well documented case with field data which can be used as calibration for the free field model. Geometry of Partihallsbron can be found in table A.1

Table A.1: Geometry of Partihallsbron.

Parameter	**Value**	**Unit**
Amount of piles	60	
Piles cross section	275x275	[mm]
Pile length	52	[m]
Ctc distance	1.3	[m]

The movements are represented in graphs with displacement on one axis and either distance from installed piles or depth on the other axis. The distance is normalised to the installed pile length. Meaning that x/L is the distance from the installed pile and y/L is the depth. This makes it easier to discuss and draw conclusions in terms of pile-lengths instead of metres.

To get a quick estimation of the calculated displacements, hand calculations with shallow strain path method(SSPM) is used for the plane strain and axisymmetric case (called simple wall and simple pile in Sagaseta et al. (1997)). The results for the free field case of Partihallsbron can be seen in figure A.3 and show good agreement with the axisymmetric model. The displacement for plane strain is calculated with equation 3.1 and axisymmetric displacement is derived from the radius of a cylinder with the same volume as the total pile volume. SSPM is used, in figure A.3, to get a quick estimation of the soil movement.

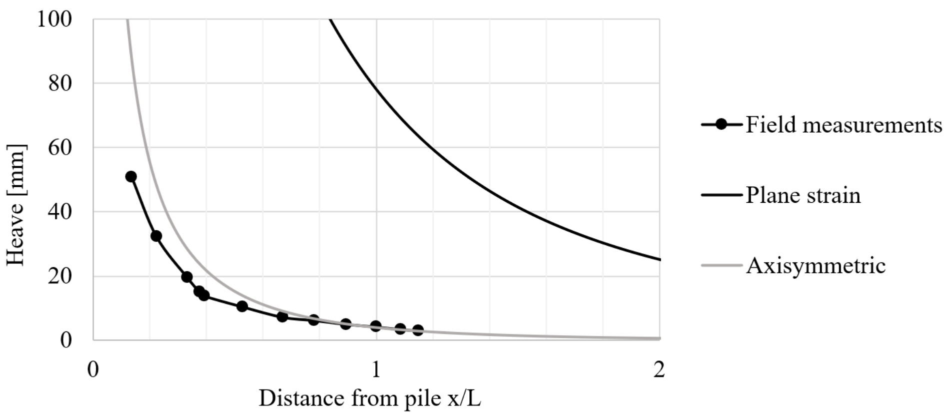

Figure A.3: Comparison of plane strain and axisymmetric model, by calculation with SSPM, compared with field data from Partihallsbron, at specific distances from piling centre.

The plane strain model overestimates the heave because there is no spread of displacements in other directions. The plane strain displacement needs to be reduced with a correction factor to achieve a lower mass displacement to better correspond to the measured heave. This correction factor can not be applied as one specific value, but changes for every specific case, depending on the geometry. The translation of plane strain to axisymmetric, and what is more suitable for each specific case, is a large research question by itself (Carter et al., 1979; Castro & Karstunen, 2010). However, this is not the main focus of this study and an assumption is needed to continue with the main question.

Plane strain SSPM for Partihallsbron is reduced with 90% and 95% to analyse the sensitivity of the correction factor and which is most suiting. Further on, the 90% reduction will be called "upper displacement" and 95% reduction will be called "lower displacement". Appendix A.3 contains a table of the calculated valued of displacement and reduced displacements. The corrected SSPM plane strain-curves are displayed in figure A.4 with the original plane strain and axisymmetric cases.

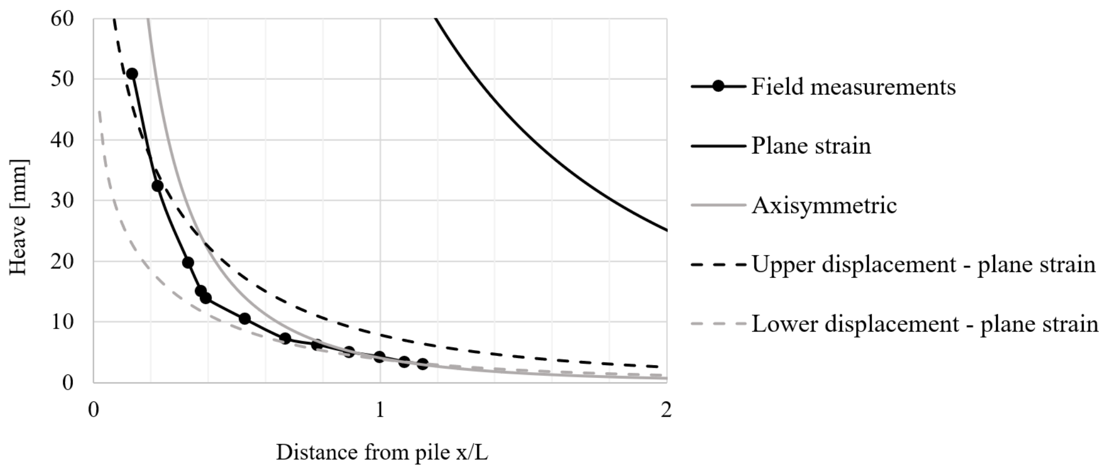

Figure A.4: Heave calculated with SSPM for upper (plane strain reduced with 90%) and lower (plane strain reduced with 95%) displacement.

Both the upper and lower displacement of plane strain is acceptable and this reduced displacement will be used in Plaxis. The installation process of a pile can be modelled using the prescribed line displacement (PLD) or volumetric strain (VS). Both methods will exclude the downwards movement, causing a less detailed representation of the installation process in proximity to the pile. However, the generated horizontal movement for both methods is assumed to be accurate for soil in the area further away, which is the area of focus. A comparison between the PLD and VS, with corrected displacement, have been done and can be seen in figure A.5. VS creates a more accurate peak closer to the pile (<50m) which is of interest because close by adjacent structures are of interest. The lower displacement for both VS and PLD is more fitting to the curve in the area of focus, which is at a distance of adjacent structures (around 30-60m).

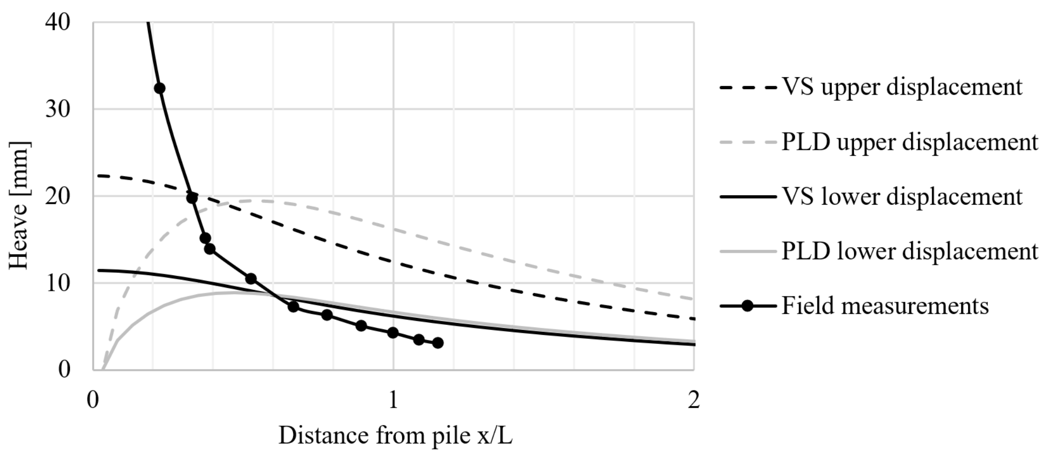

Figure A.5: Comparison of heave for volumetric strain (VS) and prescribed line displacement (PLD) for upper (displacement reduced with 90%) and lower (displacement reduced with 95%) displacement.

The horizontal movement can also be derived from the numerical modelling and compared to field measurements from Partihallsbron, see figure A.6. The upper displacement aligns better with the field measurements compared to the lower displacement which tends to underestimate the movement. There is no significant difference in the shape of the curves, PLD compared to VS, only that VS results in overall lower displacements. Once again, this Thesis aims to capture the right trend of the displacement field from pile installation, not necessary the exact right value.

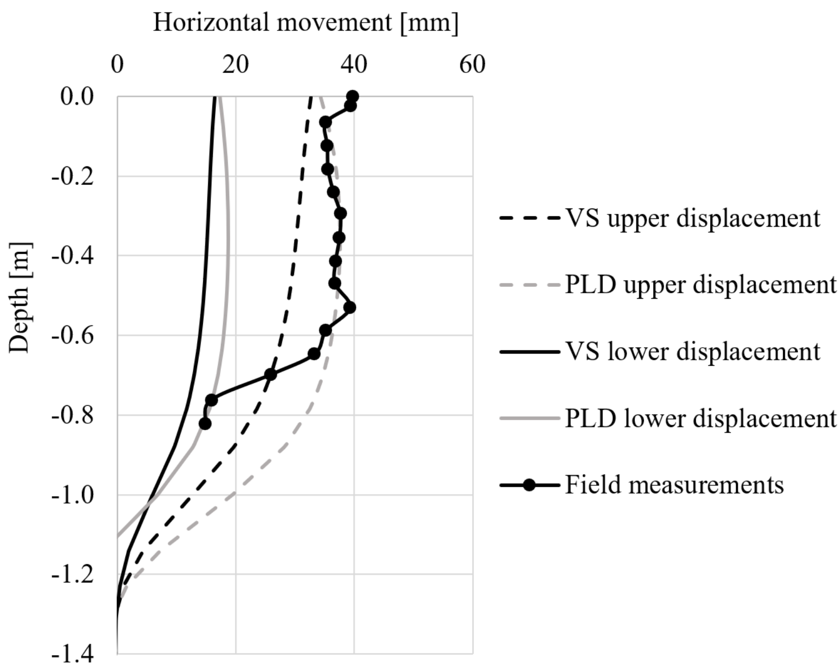

Figure A.6: Comparison of horizontal movement at 17 meters from pile, for volumetric strain (VS) and prescribed line displacement (PLD) for upper (displacement reduced with 90%) and lower (displacement reduced with 95%) displacement.

To conclude about choice of displacement; the original plane strain curve must be reduced towards the axisymmetric case to recreate the displacements from Partihallsbron at the specific distance i focus. VS creates a better agreement with the field data, compared to PLD. A reduction factor of $90-95\%$ is valid. When analysing heave the lower displacement is accurate (95% reduction) and when analysing horizontal movements, the upper displacement is accurate (90% reduction).

A.3 Reduced displacement - Partihallsbron

Table A.2 shows the calculated displacement for Partihallsbron and the reduced displacement cases which are used in the Theis.

Table A.2: Calculated displacement and reduced displacement used in Plaxis, for Partihallsbron.

	Original	**Lower displacement**	**Upper displacement**
Reduction factor	0	0.95	0.90
Displacement	0.35	0.02	0.04
Volumetric strain	20.92%	1.046%	2.092%

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