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Soil displacements resulting from piling activities

With focus on displacements of the Götaälvbron

Master's thesis in Geology and Geotechnics

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Department of Architecture and Civil Engineering
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Cover:
Building site for the Hisingsbron

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ABSTRACT

Deep foundations in form of piling are sometimes required to transfer load from a superstructure down to a stiffer layer when building on soft soils. When displacements piles are installed, i.e. piles that are installed without the removal of soil equivalent to the pile volume, it results in horizontal and vertical soil displacements. These soil displacements can in turn affect existing constructions in the nearby area. This was the case in the spring of 2017 when piles were installed, for the Hisningsbron among other projects in the central area of Gothenburg, which gave rise to displacements in the nearby Götaälvbron.

To ensure that surrounding constructions are not negatively affected by the installation of displacement piles, a prediction is needed to estimate the magnitude of the soil displacements. Thus, the aim of this report was to investigate how the installation of a pile group will affect existing piles, with respect to horizontal and vertical displacements, shear forces and bending moments, with the piling work for the new Hisingsbron as a case study.

The study was conducted using a finite analyze approach in the software program Plaxis 2D. The induced soil displacements for the Hisingsbron were modeled as a prescribed line displacement and the existing piles for the Götaälvbron was modeled using the embedded beam row feature in Plaxis. The obtained results were compared with field measurements provided from the database *Projektnav GG* from the Traffic office of Gothenburg city.

The study area is complex, with a lot of unknown input data, which limits the possibility to achieve a result that reflects the reality perfectly. However, the results reflect the expected soil kinematics rather accurately. The vertical displacement could not be modeled properly using the presented model setup, and further investigations are needed to model the surface heave correctly in a 2D model. However, if the concrete structure that overlays the piles for the Götaälvbron was set to be fixed or stiff to move in a horizontal direction, values for horizontal displacements close to those measured in the field was obtained.

Keywords: Soil displacements, Displacement piles, Plaxis 2D, Götaälvbron, Hisingsbron

Massförträngning från pålning
Med fokus på förflyttningar av Götaälvbron
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SAMMANFATTNING

När en konstruktion uppförs på finkorniga jordar kan djupa fundament i form av pålar krävas för att överföra laster från överbyggnaden ner till styvare jordlager. Om massförträngande pålar installeras, dvs. pålar som installeras utan att motsvarande jordvolym avlägsnas, resulterar detta i horisontella och vertikala förskjutningar av jorden. Denna massförträngning kan i sin tur påverka redan befintliga byggnader i närområdet. Detta var fallet under våren 2017 där pålar installerades för bland annat Hisningsbron i centrala Göteborg, vilket ledde till förskjutningar av den närliggande Götaälvbron.

För att säkerställa att omgivande konstruktioner inte påverkas negativt av massförträngande pålar måste en prognos tas fram för att uppskatta effekten av massförträngningen. Därför var syftet med denna rapport att undersöka hur installationen av en pålgrupp bestående av massförträngande pålar kommer att påverka befintliga pålar i backen med avseende på horisontella och vertikala förskjutningar, skjuvkrafter och böjmoment, med pålningsarbetet för den nya Hisingsbron som fallstudie.

För att genomföra studien användes finita element metoden i mjukvaruprogrammet Plaxis 2D. De inducerade jordförskjutningarna från pålningen för Hisingsbron modellerades som en föreskriven linjeförskjutning och de befintliga pålarna för Götaälvbron modellerades med hjälp av det inbyggda "embedded beam row" elementet i Plaxis. De erhållna resultaten jämfördes med fältmätningar som tillhandahölls från databasen *Projektnav GG* från Trafikkontoret i Göteborg.

Studien är komplex med många okända parametrar, vilket begränsar möjligheten att uppnå ett resultat som perfekt återspeglar verkligheten. Resultaten reflekterade dock de förväntade jordrörelserna som observerats vid litteraturstudier. Den vertikala förskjutningen kunde dock inte modelleras korrekt med den använda systemuppbyggnaden och ytterligare undersökningar behövs för att modellera hävningen av markytan korrekt i en 2D-modell. När betongstrukturen som vilar ovanpå pålarna för Götaälvbron var fixerad eller ansatt som stel mot förflyttningar i horisontell riktning, erhölls värden som korrelerade väl med de uppmätta i fält.

Nyckelord: Massförträngning, Massförträngande pålar, Plaxis 2D, Götaälvbron, Hisingsbron

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Preface

In this report soil displacement due to piling activities for the Hisningsbron are investigated. The effect on the existing piles for the Götaälvbron in terms of horizontal and vertical displacements as well as bending moments and shear forces are modeled.

The thesis has been carried out at the Division of Geology and Geotechnics, Chalmers University of Technology, in collaboration with COWI during spring 2018. The thesis was initiated by Leif Jendeby at COWI and Minna Karstunen at Chalmers. The thesis has been supervised by Minna Karstunen and Jelke Dijkstra, professors at the Division of Geology and Geotechnics at Chalmers, who are also the examinators.

We would like to thank Minna Karstunen and Jelke Dijkstra, for the thoughtful feedback during the process. We would also like to thank Leif Jendeby for answering all our questions and providing us with interesting research questions. In addition, we would like to thank our families, friends and colleagues at Chalmers for support throughout the work.

Gothenburg, June 2018

Anna de Bourgh & Emma Jägryd

Nomenclature

Subscripts

sat	saturated
unsat	unsaturated
x	horizontal direction in Plaxis 2D
y	vertical direction in Plaxis 2D

Greek letters

κ	modified swelling index (-)
λ	modified compression index (-)
ϕ	friction angle ($\circ$)
ψ	dilatancy angle ($\circ$)

Roman lower case letters

a	cavity radius (m)
c	cohesion (kPa)
k	permeability (m/day)
r	position of soil element (m)
υ	Poisson's ratio ($-$)

Roman capital letters

A	surface area (m^2)
D	pile diameter (m)
E	Young's modulus (MPa)
F	base resistance (MPa)
I	moment of inertia (m^4)
K	coefficient for earth pressure ($-$)
L	pile length (m)
Q	shear force per meter-width (kN/m)
T	skin resistance (kNm)
U	displacement (m)

1 Introduction

To ensure sufficient stability and serviceability when constructions are built on soft soils, sometimes deep foundations in form of piling is required, to transfer load of the superstructure to a stiffer layer. When piles are installed in the ground, the surrounding soil gets disturbed (Hintze et al., 1997). The pile installation leads to horizontal soil movements and heave of the ground surface, which in turn may affect already existing constructions in the nearby area. This was the case in the spring of 2017 where piles were installed in the central area of Gothenburg, which gave rise to displacements of the nearby Götaälvbron to such a degree that the Traffic Office of Gothenburg City warned contractors in the area that further piling could cause damage to the bridge (see Figure 1.1 for location) (Bouzas, 2018). During this time, several construction works were performed by various contractors. The affected projects were the construction of the new Hisingsbron, the building Kv Platinan and the rebuilding of road E45. To ensure that no undesired damage would occur to the Götaälvbron, a cooperation between the different consultants and contractors involved in these projects was initiated. This group supervise the soil displacements from piling activities and implements technical solutions to ensure that the Götälvbron will stay in place.

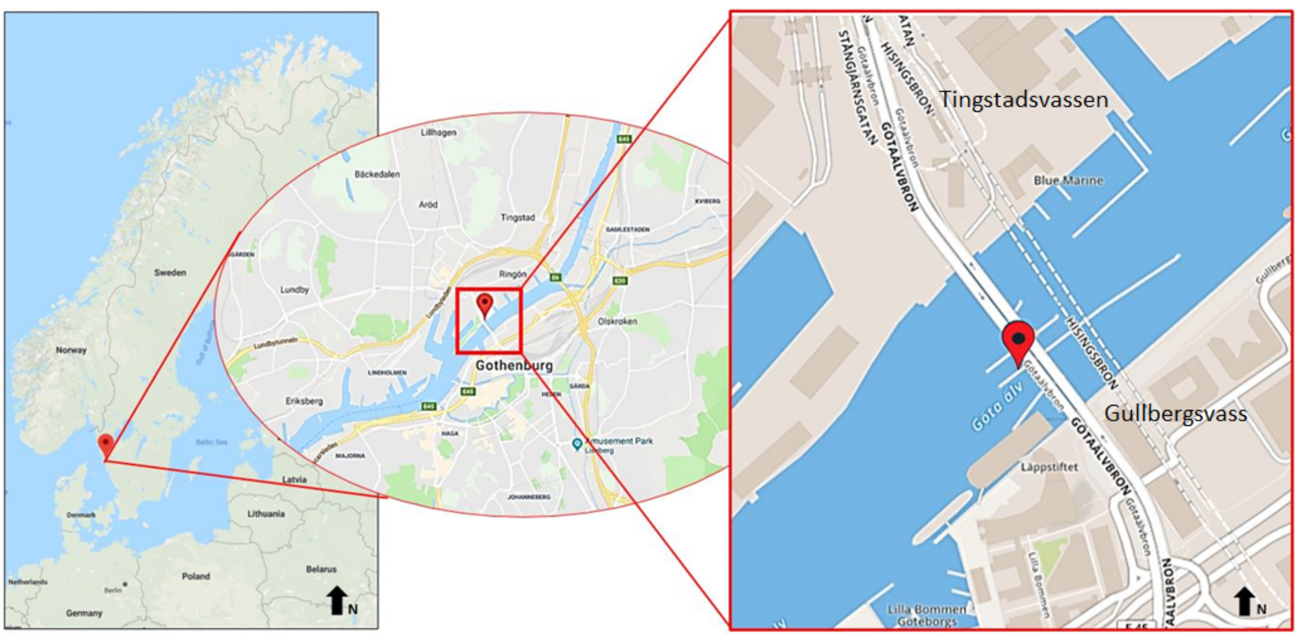


Figure 1.1: The location of the Götaälvbron and the Hisingsbron. Retrieved from Kartdata©2018 Google (Google Maps, 2018) and (Göteborgs Stad, no date). Reprinted with permission.

1.1 Background

The Götaälvbron that runs over the river Göta älv and connects the mainland of Gothenburg with Hisingen is getting old and needs to be replaced (Siewertz, 2014). Therefore, a new bridge called Hisingsbron is under construction. The new bridge will be located upstream of the old bridge, see Figure 1.1, and is planned to be ready in 2020. The southern part of the bridge is in the district of Gullbergsvass. The area of Gulbergsvass was originally a wetland that was converted into land between the 19^{th} and 20^{th} century through the addition of fill material (Vilumson, 2014). The fill material consists mainly of dredging material, sand and clay and its thickness varies between 2.5–5 m in the area. Beneath the fill layer, there is a clay layer that is thicker than 50 m and could probably be over 100 m thick (Siewertz, 2014). The north part of the bridge is in the district of Tingstadsvassen at which the uppermost part of the soil is a fill layer, consisting of sand and stones with a varying thickness between is 0.5–1 m. Under this layer there is a dry clay crust down to about 1.5 m below the ground surface, followed by a clay layer with a thickness around 50 m. Due to the fill material and the deep clay layer the ground will settle when loads are applied, therefore, ground improvements beneath the bridge supports are required. To perform sufficient ground improvements for the southern land connection for Hisingsbron, a large number of floating displacement piles of lengths between 52 to 101 m are installed (Bouzas, 2018). Together with the hundreds of thousands installed pile meters from the other projects in the area, this has resulted in a large volume of installed piles, which in turn has given rise to soil displacements that have influenced the displacements of the Götaälvbron (Wallgren & Sabattini, 2018).

To ensure that surrounding constructions are not negatively affected from the installation of displacement piles and ensure that the work is performed in a sustainable manner, a prediction is conducted to estimate the soil movements and impact on existing ground foundations. A first step into understanding the effects of soil displacement is to understand the soil kinematics that occurs as a result from the pile installation process. In addition, piles are usually installed in groups, thus to find the right amount of soil displacement it is important to scale the displacements from the installation of a single pile to a group of piles. The next step consist of understanding what happens to existing structures in the ground when soil displacements occurs.

There are several methods available for predicting the displacements due to the installation of displacement piles, where both analytical, numerical and physical models can be applied. An extensive literature study has been conducted to evaluate different numerical and analytical models to find a proper model for assessing the soil displacements caused by installation of piles. Analytical methods that has been proposed, and will be described further in Section 2.3, are the Cavity Expansion Method (CEM), the Strain Path Method (SPM) and the Shallow Strain Path Method (SSPM) (Randolph, Carter, & Wroth, 1979; Baligh, 1985; Sagaseta, Whittle, & Santagata, 1997). Nevertheless, all of these methods may only be used for assessing soil displacement caused by pile installation of a single pile, and do not consider how these displacement will affect existing objects in the ground. The common practice in Sweden for assessing the environmental impact is the Hellamn/Rhenman method (Hintze et al., 1997). This method enables the possibility to assess the effects on existing structures, however, it is a simplified method that might be rather inaccurate. A numerical method is the finite element method (FEM) (Edstam, 2012), which allows for assessing the effects on existing structures. There are many different FEM softwares developed to solve geotechnical issues, for example Plaxis 2D/3D, Abaqus and Optum G2/G3.

The mentioned prediction methods make it possible to assess soil displacement due to the installation of piles. Nevertheless, it is uncertain how the soil displacements will affect existing piles in the area. A model that allows for measuring the impact of the soil displacement at a pile at a certain distance from the piled area is required. A FE model is believed to be the most applicable for this case. Thus, the FE software Plaxis 2D will be used in this report to model the displacements of the Götaälvbron due to the piling activities for the Hisingsbron.

1.2 General aim

The aim of the report is to investigate how the installation of a pile group will affect existing piles, with respect to horizontal and vertical displacements, shear forces and bending moments, using the piling work for the new Hisingsbron as a case study.

1.3 Objectives

In order to reach the general aim of the report the following objectives will be investigated:

- Gain an understanding about the soil kinematics due to displacements from installation of a single pile.
- Be able to scale the displacements from a single pile to a pile group in an accurate manner.
- Gain an understanding of how the installation of a pile group will affect already existing piles in the surroundings, regarding bending moments, forces and deformations in the existing piles.
- Be able to apply the knowledge on a real case through modelling in Plaxis 2D.
- Create a Plaxis model of a chosen piling section for the deep foundation for the Hisingsbron and compare and validate the modeled scenario with measurement data collected in the field.

1.4 Limitations

The study area is exposed to several ongoing foundation works. Therefore, in this study the case area is limited to installed and existing piles for two neighboring bridge supports, one for the Götaälvbon and one for the Hisingsbron, within a specific limited area and time-frame. Surrounding foundation works are not modelled but taken into consideration regarding soil displacements when validating modelled result from Plaxis 2D.

The area is delimited to a manageable geometry to enable modeling. Furthermore, it is analyzed as a two-dimensional (2D) problem even though in real life it is a three-dimensional (3D) problem. Another limitation is the reliability of the input data and performed measurements of the displacements in the field.

2 Theoretical background

This Chapter will give a brief introduction to classification of piles with focus on displacements piles, which are the ones used in the area of interest. Thereafter, information about the displacements patterns that are formed during pile installation for both a single pile and a pile group is given. After that, methods used for prediction of soil displacement due to piling activities, CEM, SPM, SSPM and FEM are described including their origins, usability, assumptions and constrains. Finally, information about the software Plaxis 2D will be presented, discussing different features in this program that could be used to model the case study.

2.1 Piles types

Piles are elongated structures made of concrete, steel or timber, that transport loads to stiffer layers. They are classified by material, impact on surrounding, functioning and performance of installation as shown in Figure 2.1.

The function group in Figure 2.1 are mainly divided into floating piles or end bearing piles (Viggiani, Mandolini, & Russo, 2012). The end bearing piles carries most of the load at the tip, transporting the load down to a stiffer soil layer or the bedrock. The floating pile transfer load along the shaft due to skin friction and thus the tip takes almost none of the load. An important parameter for the shaft resistance of a floating pile is the slenderness. The slenderness can be described by the slenderness ratio, L/D, which is the quota between the length and diameter or width of the pile (Knappett & Craig, 2012). The slenderness of a displacement pile affects the shaft resistance along the shaft since it, partly depends on the adhesion parameter, which in turn depends on surface conditions along the pile and the pile installation. This implies that the higher the L/D parameter is, the lower is the adhesion parameter, which gives a lower interface shear strength and thus a lower shaft resistance.

Piles are divided into displacement piles and replacement piles due to their impact on the surrounding. This factor is strongly correlated to the amount of soil displacements that occurs during pile installation.

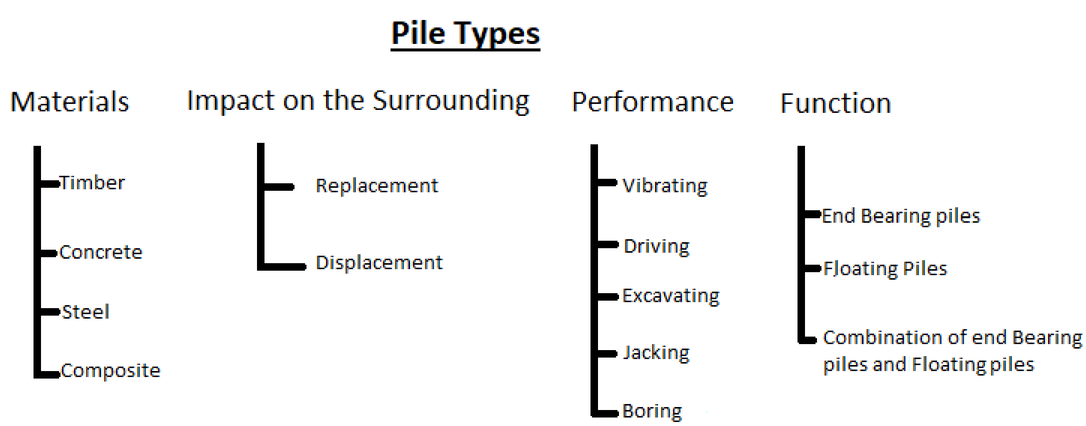


Figure 2.1: Schematic picture over pile types.

2.1.1 Displacement piles

Displacement piles are usually installed by vibration or driving (Viggiani et al., 2012). When installed in the ground, the soil gets forced aside. In loose saturated sandy soils, the vibratory method is suitable and is often used to install sheet piles. The driving method is performed by having blows from an impact hammer hit the top of the pile, forcing it into the ground. Displacement piles are usually prefabricated made out of timber, steel or concrete.

The timber piles come in circular forms with decreasing diameters from top to tip (Viggiani et al., 2012). A constrain with these is the durability regarding exposure to water and drying, there are methods for prevention of this, but these are not 100 % proof. Steel piles got high resistance regarding driving and management and they come in different shapes such as H, tube or square profiles and they can be shortened or extended to desired lengths. However, a problem with steel piles are the risk of corrosion. Concrete piles usually have solid square, hexagonal or octagonal cross sections, with variations in lengths. These are manufactured in plants and are then delivered to the actual location to be installed. To reach desired depth the piles can be jointed together to make longer piles.

Alternatives to the displacement piles are the replacement piles. They are either percussion or rotary bored, thus soil is removed from the ground to make room for the piles (Viggiani et al., 2012). This results in less volume change and reduces the risk for larger soil displacements. Basically, the soil is removed, and not pushed aside, by different boring techniques and then the hole is casted with concrete. The different augering techniques allows for different sizes and lengths. The displacement and replacement method can also be combined.

2.2 Soil displacement from pile installation

The total volume of displaced soil due to pile installation corresponds approximately to the volume of the installed piles (Hintze et al., 1997). However, this volume may be modified through the removal of soil due to pre-augering, or the usage of replacement piles instead of displacement piles. Thus, the magnitude of the displacements depends on the geometry of the pile, the amount of soil removed and the total amount of piles that has been installed. The soil will be displaced in the direction where the resistance to soil displacement is the least. Therefore, the stress conditions in the soil and the geometry of the area together with the conditions in the surrounding environment are of major concern when assessing the direction of the displacements (Olsson & Holm, 1993). Other factors that influence the soil displacements are the soil layering and the inclination of the ground surface. In case the pile is installed in clay, the sensitivity of the clay will influence the displacements. The more sensitive the clay, the less heave will be evidenced in the ground surface (Hintze et al., 1997). The radius of the influenced area, due to displacement caused by pile installation, differ according to different literature sources. The Hellman/Rhenman method suggest that displacements occur within one pile length from the spot where the pile is installed. However, in a report by Edstam (2012) it is reported that soil displacements happen at a distance further away than one pile length. This suggestion is confirmed by Massarsch and Wersäll (2013b) who reports that soil heave may be detected at a distance of four pile lengths from the piling area.

2.2.1 Soil displacement from installation of a single pile in clay

When a displacement pile is installed in soft soils, the soil deforms outwards from the pile which causes remoulding and distortion of the soil (Ottolini, Dijkstra, & van Tol, 2014). This displacement of soil results in an increase of the mean total stress in the ground. The installation process is usually seen as an undrained case since the installation speed is fast and no volume change takes place which leads to an increase in excess pore pressures. After the pile installation, the excess pore pressures dissipate with time through outward radial flow from the pile to the far field. This causes volume changes and thus consolidation takes place.

In an axisymmetric setup in a geotechnical centrifuge test, the soil displacement from a single floating open-ended pile was observed (Ottolini et al., 2014). This test indicates that soil is radially displaced, away from the pile base, during pile installation. The extent of the displacement varied along the pile, with displacements up to 4.5 times the pile diameter at the top of the pile and twice the diameter at the pile base. As the pile penetrated further into the ground, the soil beneath the pile base was pushed upwards next to the pile shaft, due to the displacements occurring in deeper soil layers. Slightly beneath the pile base, at a distance about half of the pile diameter, the soil was displaced downwards in the same direction as the pile penetration.

2.2.2 Soil displacement from installation of a pile group

In the case where not only one pile, but a whole pile group is installed, complex displacement patterns will be formed. The direction of the displacement at the ground surface depends on the order in which the piles are installed (Massarsch & Wersäll, 2013a). When a pile is installed, horizontal displacement occur which will result in lateral movements in already existing adjacent piles. The existing pile will move away from the installed pile. This means that the first pile in a pile group will be displaced in different directions depending on the order in which the following piles are installed and the last installed pile will not be displaced. Massarsch and Wersäll (2013a) suggest that the lateral resistance to horizontal ground movements for already installed piles is very small and may therefore be neglected. Furthermore, the soil displacement outside the piling area will most likely be symmetrical directed away from the pile group.

Regarding vertical deformations in the form of surface heave, the most important parameters when assessing the heave outside and inside a pile group is the length and the spacing of the piles (Massarsch & Wersäll, 2013b). The pile length influences the zone around the pile group in which heave occurs. The larger the pile length, the larger is the radius of influence. In case of a large pile group with short piles, approximately half of the volume of displaced soil will give raise to surface heave within the pile group. However, if the pile length is large, the amount of heave within the pile group will be less and most of the heave will occur outside of the pile group. The soil heave is likely to be largest outside of the most recent installed piles. When considering pile installation next to already installed piles, soil heave tends to increase between these piles and decrease beyond.

2.2.3 Passively loaded piles due to soil displacement

When soil displacement occurs and there are existing structures in the ground, for example piles, the moving soil will act as a passive lateral load on the structures (Bauer, Kempfert, & Reul, 2014). The passive lateral loads can be induced by (except from soil displacement resulting from pile installation) loading or unloading from a nearby embankment, excavation, tunneling operation or piles installed for slope stabilization. The opposite to passive lateral loading, i.e. active lateral loading, happens when the pile is subjected to a lateral load at its head, i.e. from the superstructure above. Passive loading is thus often considered as a hidden loading. The magnitude of the lateral pressure on piles subjected to soil displacements depends on numerous of parameters, like the roughness, the shape and the flexibility of the pile, as well as the velocity of the soil that moves around the pile.

Passive lateral loading on a pile can result in deflection of the pile, and induce axial and lateral forces as well as bending moments (Poulos, 1994). The axial forces are a result of the vertical soil displacements, and the bending moments are due to the lateral soil displacements. These moments and forces could in turn affect the structural performance of the pile and have severe impact on the serviceability state and even the ultimate limit state. Bending moments could, e.g. create cracking of concrete piles. Axial forces may induce tensile failure, as well as axial movements that result in a lift of the pile tip from the bearing stratum or a separation of pile joints.

The lateral passive load should be considered during the installation of a pile group to ensure that the structural performance of the installed piles is not impaired. The following actions are recommended according to Poulos (1994):

- Have a sufficient spacing between the piles (more than three times the pile diameter).
- Perform pre-boring to minimize soil movements.
- Re-drive piles that heave overly much when adjacent piles are installed.
- Not restrain the piles before every pile inside the area of influence, which is about ten times the pile diameter, has been installed.

2.3 Prediction methods for soil displacement

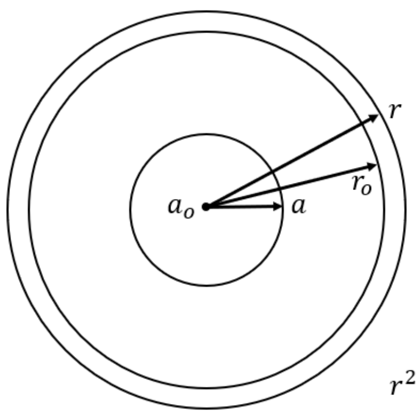
The following sections introduces the previous mentioned techniques, Hellman/Rhenman, CEM, SPM, SSPM and FEM, to perform predictions of soil displacement. The origin and basic principles of each method is described.

2.3.1 Hellman/Rhenman

The Hellman/Rhenman method is used for predicting soil displacement in form of heave and lateral movements from the installation of a pile group (Olsson & Holm, 1993). The method is built on the assumptions that lateral movements decreases linearly with distance from the piling area and that the radius of influence only extends one pile length from the outer edge of the installed pile group. By assigning relative weights to nearby buildings, an assessment of the displacement occurring in nearby structures is enabled. According to Edstam (2012) this method tends to be inaccurate and should only be used to provide a rough estimation of the magnitude of displacements caused by pile installation.

2.3.2 Cavity Expansion Method (CEM)

The theory of CEM was introduced by Bishop et al. (1945) whom described a theoretical method for calculating the required pressure to enlarge a spherical and cylindrical hole in a strain-hardening material. Thus, since it was shown that once there was no friction in an elastic-plastic metal material, the required pressure of creating a deep hole was equal to the pressure needed to expand a cavity of the same volume (Bishop, Hill, & Mott, 1945; Yu, 2000). CEM was then applied in geotechnical engineering for estimating displacements and changes in stresses and pore water pressure during expansion and contraction of cavities due to penetration of soil. When using CEM to analyze soil displacement due to pile installation, a symmetrical cavity is assumed to be expanded where the pile penetrates the soil. The radius of the cavity, which is equal to the pile radius, is assumed to be proportional to the soil displacement see Figure 2.2. Undrained conditions are adopted and excess pore water pressures are assumed to dissipate with outward radial flow, perpendicular to the pile shaft (Randolph et al., 1979). Thus, the situation is simplified to a one-dimensional (1D) problem. A concern when using the CEM is to assess the initial radius, a_0 properly. Limitations of using conventional CEM is that the soil material is assumed to be homogeneous and isotropic (Baligh, 1985). Vertical deformations are neglected and the direction of the penetration cannot be determined. Furthermore, the calculation gives soil displacement from the pile installation process only, and thus it is not possible to model how existing structures in the ground are influenced by the soil displacement.



$$r^2 - r_0^2 = a^2 - a_0^2$$

Figure 2.2: The principle of cavity expansion. When the cavity is expanded from a_0 to a, the soil element at position r_0 is expanded to have radius r to the center of the cavity (figure not to scale).

2.3.3 Strain Path Method (SPM)

SPM is an analytical method developed for analyzing soil kinematics in deep penetration that includes solutions with total stresses for anisotropic clays, rough piles, compressible and frictional soils (Baligh, 1985). The method was developed during the 1980s by Baligh. The pile installation is modelled as a penetrating source which is assumed to emit a volume corresponding to the pile volume from the ground surface down to the full pile length. The deep penetration into the soil causes disturbance that affects the shearing and structure of the soil. With this knowledge and due to the kinematics limitations in deep penetration it was suggested that the soil displacements and strains mainly are independent of the shearing resistance. This makes a deep foundation problem primary strain controlled. This allows for the use of streamlines for the solution of retrieving parameters such as soil displacement, strains, stresses and etc. (Baligh, 1985; Sagaseta et al., 1997).

The SPM was further developed to the Shallow Strain Path Method (SSPM) by Sagaseta, Whittle and Santagata (Sagaseta et al., 1997). This model includes both the deep and shallow aspects of pile penetration by including the displacement effects along the whole pile, i.e. the tip, shaft and parts close to the surface. The SSPM method does not take any characteristics parameters of the soil into account, since it is assumed that the displacements due to the penetration are similar in all type of incompressible soils. When accounting for the presence of a ground surface, the problem is no longer at steady-state, since the surface is considered to be a traction-free boundary. Therefore, the SSPM solution is modified from SPM by adding corrective surface tractions to the calculations. The SSPM method includes solutions for both wall, circular and tubular elements. This method tends to give rather accurate results for soil displacement caused by pile installation in comparison with field measurements (Edstam, 2012). Nevertheless, the SSPM approach is just like SPM and CEM a method for assessing soil displacement due to penetration and cannot give information about how existing objects in the ground are affected by the soil displacements.

2.3.4 Finite Element Method (FEM)

In the 1950s the Finite Element Method (FEM) was initiated by Ray W. Clough, University of California, Berkeley among others, and was initially aimed for the aircraft industry (Nationalencyklopedin, no date). The FEM computes approximate numerical solutions of partial differential equations and integrals. By discrete elements into smaller "finite elements" simpler equations can be derived which then are assembled together to a large equation system (Comsol, no date).

FEM models have a wide applicability and may be used for solving both linear and nonlinear problems. In general, the problems to be solved can be divided into two subgroups; solid mechanics and fluid dynamics problems (Zienkiewicz, Taylor, & Fox, 2014; Zienkiewicz, Taylor, & Nithiarasu, 2014). The specific division is due to that fluids in rest can only support a pressure or a mean compressive stress and no deviatoric stresses. In contrast, solids can carry structural forces and other stresses.

The problems can also be defined by assumptions of small strains or large strains. The assumption of small strains is based on that the deformation after displacement are very small and therefore neglected. Meanwhile the large strains assumption takes deformations due to displacement in consideration in the calculations (Munjiza, Rougier, & Knight, 2014). In the small strain method equilibrium is used from the initial geometry, while large strains use equilibrium from deformed geometry. The large strain assumption treats non-linear aspects of deformations, whilst the small strains assumption does this too, but the displacements are so small that they can be considered as linear. Since both soil and structures can be seen as solids, and permanent deformations occurs when piles are installed, large strains are suitable to use. This implies that a pile-soil interaction problem can be interpreted as a solid mechanic large strain problem.

FEM is implemented in several software programs which has been developed for different causes. One example of software program in which geotechnical problems may be analyzed is Plaxis. In this program, either a 2D or 3D model may be setup, depending on the program license. Thus, FEM modeling in Plaxis enables setup of complex geometries, which opens for the possibility to model existing structures being subjected to lateral loading from soil displacement. However, it is important to process the input data right, because the program will only provide accurate results if accurate input data is used.

2.4 Plaxis 2D software

Plaxis 2D is a computer-aided design resembling software program with several features to model geotechnical issues. It enables analyzes of deformations and stability in geotechnical problems (Plaxis, no date). In the program, soil profiles are created using the borehole feature, and then materials can be assigned by adding specific soil properties. In the structures tab, different structural objects can be defined as well as loads and prescribed displacements. A finite element mesh of different quality can be generated depending on desired accuracy and computational time. In the output window, the results are presented in forms of displacements, forces, stresses, flow data, vector plots and iso-surface plots.

The program provides two options of node setups, one with 6 nodes and one with 15 nodes both having triangular elements (Plaxis, 2017a). The 15-noded element is more precis than the 6-noded element, but take more memory and time when calculating. In Plaxis 15 nodes is set to default. Plaxis allows for modelling of both linear problems as well as strongly nonlinear problem, as a plane strain or an axisymmetric analysis model, see Figure 2.3.

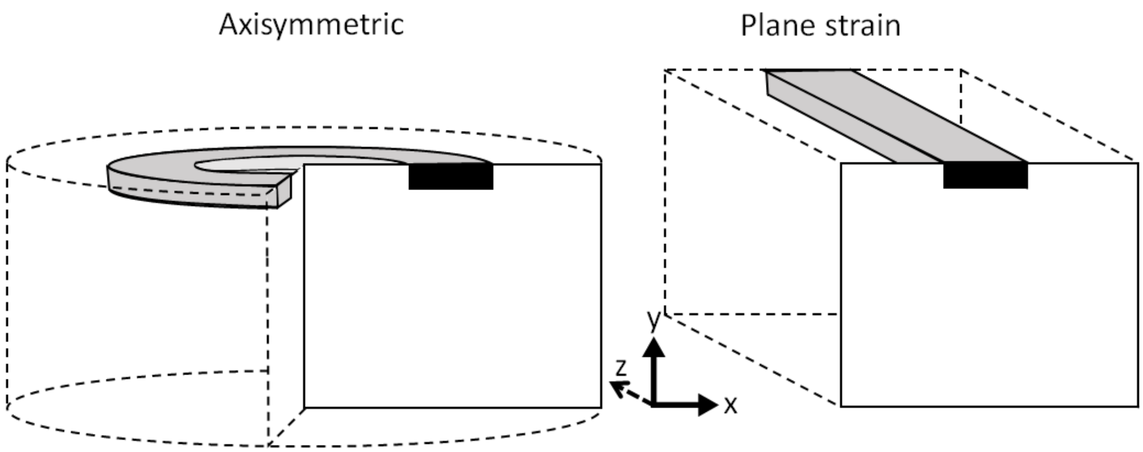


Figure 2.3: The concept of axisymmetric and plane strain model.

For geometries with a cross section that is, or nearly is, constant and that has stresses and loads over a specific length perpendicular to the cross section, the plane strain model can be used (Plaxis, 2017a). The cross section is in the z-direction and thus there is assumed to be no displacements and strains in that direction. However, the normal stresses in that way are still considered. The coordinate system in the plane strain model is based on the Cartesian one from 3D, thus the stress in the z-direction is the out of plane stress. When calculating forces that are due to prescribed displacements, the plane strain model gives the result as forces per unit length in the z-direction.

For circular structures with a radial cross section that is, or almost is, constant and got symmetric deformations and stresses in its radial directions, axisymmetric models can be used (Plaxis, 2017a). In the axisymmetric model the coordinate system is, as in the plane strain, based on the Cartesian 3D system. Although the x-direction represents the radial coordinate, the y-direction is equal to the axial coordinate and the z-direction is the tangential direction. In the axisymmetric case the model has a boundary equal to a circle part with an angle of one radian. It is at this boundary that the calculated forces act on and they should be multiplied with 2π to obtain the corresponding forces for the entire problem. However, the rest of the output in the axisymmetric problem are shown per unit width.

2.4.1 Material properties

In the following subsection the linear elastic, Mohr-Coulomb and Soft Soil material models are described, including their required input parameters, as well as their usability in different cases. These three material models are the ones used when modelling the case study in Plaxis 2D. In addition, there are several others material models available in Plaxis which can be further viewed in the Plaxis manual (Plaxis, 2018). The differences between the different material models are basically the parameters assigned for the strength and the stiffness, the shape assumed for the yield surface, as well as the hardening laws assumed in the model. Other input data that could be assigned for a material are for example, unit weights, permeability, thermal properties, interface strength and initial K_0-settings.

Linear elastic

The linear elastic model constitutes of Hooke's law of isotropic linear elasticity and are mostly to simple to use when modelling soil. This is due to the nonlinear behavior exhibited by soils. However, for stiff structures linear elastic model can be applied (Plaxis, 2018). Only two parameters are required for this model, as are shown in Table 2.1. Depending on the type of analyses (drained or undrained), these are either based on effective stress parameters or total stress parameters.

Table 2.1: Parameters for the linear elastic model.

Parameter	**Name**	**Unit**
Stiffness:		
Young's modulus	E	kN/m^2
Poisson's ratio	v	-

Mohr-Coulomb

The Mohr-Coulomb material model is often used for an initial assessment of a geotechnical problems, due to quick results when using constant stiffness for the soil. The model consists of an elastic and a perfectly plastic part. The elastic part is based on the liner elastic model and Hooke's law of isotropic elasticity and the plastic one is based on the Mohr-Coulomb failure criterion (Plaxis, 2018) combined with associated or non-associated flow rule. When using the Mohr-Coulomb model in Plaxis, five parameters are needed, two stiffness parameters and three strength parameters, see Table 2.2. The cohesion and friction parameters can be retrieved from the Mohr-Coulomb failure curve. A yield function defines if plasticity takes place or not, and in this model the Mohr-Coulomb failure condition is used as a yield surface.

Table 2.2: Parameters for the Mohr-Coulomb model.

Parameter	Name	Unit
Stiffness:		
Young's modulus	E	kN/m^2
Poisson's ratio	ν	-
Strength:		
Cohesion	c	kN/m^2
Friction angle	ϕ	°
Dilatancy angle	ψ	°

Soft Soil model

The Soft Soil model can be used when modelling normally consolidated soft soils and are best implemented with conditions of primary compression. In the Soft Soil model, the stiffness is stress dependent and there is a difference made between primary loading, unloading and reloading. A logarithmic connection between changes in volumetric strains and effective stress is adopted (Plaxis, 2018). The pre-consolidation pressure is memorized and the Mohr-Coulomb failure criterion applies here too. The modified swelling index and Poisson's ratio for unloading and/or reloading are used as input parameters for the elastic part of the model. Plastic volume strains in isotropic compression are described by a cap yield surface that seals the elastic region for compressive stress paths. The plasticity is defined by a combination of the cap yield function and the Mohr-Coulomb yield function. Parameters required for this model is shown in Table 2.3.

Table 2.3: Parameters for the Soft Soil model.

Parameter	Name	Unit
Stiffness:		
Modified compression index	λ	-
Modified swelling index	κ	-
Strength:		
Cohesion	c	kN/m^2
Friction angle	ϕ	°
Dilatancy angle	ψ	°

Modelling of pile groups in Plaxis

When installing piles, vibrations in the surrounding soil are caused due to dynamic processes and hence stresses around the pile increases which induces excess pore pressure (Plaxis, 2017b). However, modelling of the pile installation procedure is complex due to the difficulty in modelling a penetration problem in Plaxis 2D, as large distortions and displacements are inherent to the problem. Therefore, the soil displacement caused by the pile installation has to be modeled by using for example an applied load or a prescribed displacement, to imitate the main effects in the real case.

Existing piles can be modeled by using either a structural object or a soil polygon, for which material model and material properties has to be defined. It is important to model the pile correctly, since sliding of the soil along the pile causes material damping. The interaction between the pile and the soil can be considered by adding interfaces elements along the pile. Interface are elements used for modelling the soil-structure interaction. It can be applied next to a plate, geogrid or between two different soils to take the interactions due to shearing stresses and normal stresses into account (Plaxis, 2017a).

Structural objects available for modelling of pile rows are plate, node to node anchor or the embedded beam row (EBR) elements (Sluis, Besseling, & Stuurwold, 2014). The properties that can be input varies for these elements. Plate elements are beam elements from where bending moment and axial forces can be retrieved in the output window. It considers deflections from shearing and bending (Plaxis, 2017a). For plate elements the correlation between the soil and the pile can be modeled with interface elements, although it comes with restrictions since the interface elements demolish the soil mesh.

The node to node anchor consists of a spring with two nodes that have a constant stiffness which can be exposed to both tensile and compressing forces (Plaxis, 2017a). Using this method to model piles allows for soil to flow unrestrained of the piles, hence there is no correlation between soil and pile, and thus the soil mesh is unaffected by the piles. However, in reality, it is not true that there is no correlation. Nevertheless, the correlation in horizontal direction is neglected, which constrains the use of this method to only fully axially loaded piles.

The EBR element is a sort of combination of the plate and node to node anchor, where the benefits of both been utilized. The properties of the piles in this method are similar to the plate element, while the soil mesh is more similar to the node to node anchor element with a continuous mesh. As for the plate element, it considers deflections from shearing and bending (Plaxis, 2017a). For the EBR, a special interface is applied by default, which connects the beam and soil with each other. The resulting displacement when using this element is the average soil displacement in the out of plane direction. The EBR is only available in the plane strain model and cannot be utilized in the axisymmetrical model.

Another way to model a pile group is to use the soil polygon feature for which a material cluster that has the same properties as a structural element needs to be defined (Plaxis, 2017a). With this method substantial out of balance forces can arise due to differences in unit weight of materials. However, it can be solved later during the staged construction phase. The soil polygon will, as in the case of using the plate element, not allow for modelling of the soil that flows through the pile rows, since it is interpreted as a wall element by Plaxis.

3 Methodology

In this Chapter the methods and assumptions used to perform this investigation are presented. The different steps required to conduct the study are presented in Figure 3.1.

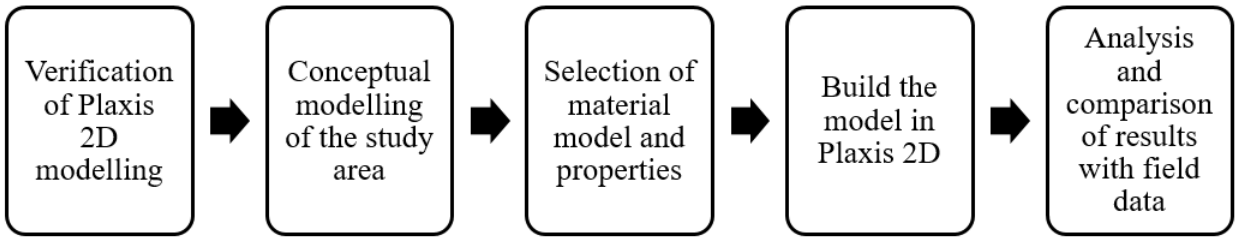


Figure 3.1: The methodology used to conduct the study.

Modelling using Plaxis 2D plane strain was deemed to be a good approach for the following case study, considering available resources. To ensure that Plaxis 2D could provide sufficiently accurate results, a model was setup imitating a previous study, to enable comparison with experimental values and 3D modelling. Thereafter, the modelling of the actual case area was initiated by creating a conceptual model of the area including definition of boundary conditions, soil layers and geometry of the constructions. Next, proper material models and material properties were adopted for both soil and construction material. After that the model was built in Plaxis 2D using plane strain theory, and appropriate phases for staged construction were applied. Finally, the model simulations were performed, and the results were analyzed and compared with field measurements from the database provided by the Traffic Office in Gothenburg, called *Projektnav GG*.

3.1 Verification of Plaxis 2D plane strain modelling

Modelling of pile displacement due to soil displacement in Plaxis 2D was verified by imitating a study conducted by Ghee (2009), in which a single pile was subjected to lateral soil displacement in a shear box test. Ghee and Guo (2010) and Al-Abboodi, Toma-Sabbagh, and Al-Jazaairry (2015) later used this test to calibrate 3D models in the 3D finite difference and finite element programs, Flac 3D and Plaxis 3D, respectively. The model setup in Plaxis 2D is shown in Figure 3.2. Two different models were made in order to see how the choice of structural object to model the pile (either plate element or EBR) would affect the result. The diameter of the plate element was reduced to match the cross-section area of the EBR pile, since the plate element is not tubular.

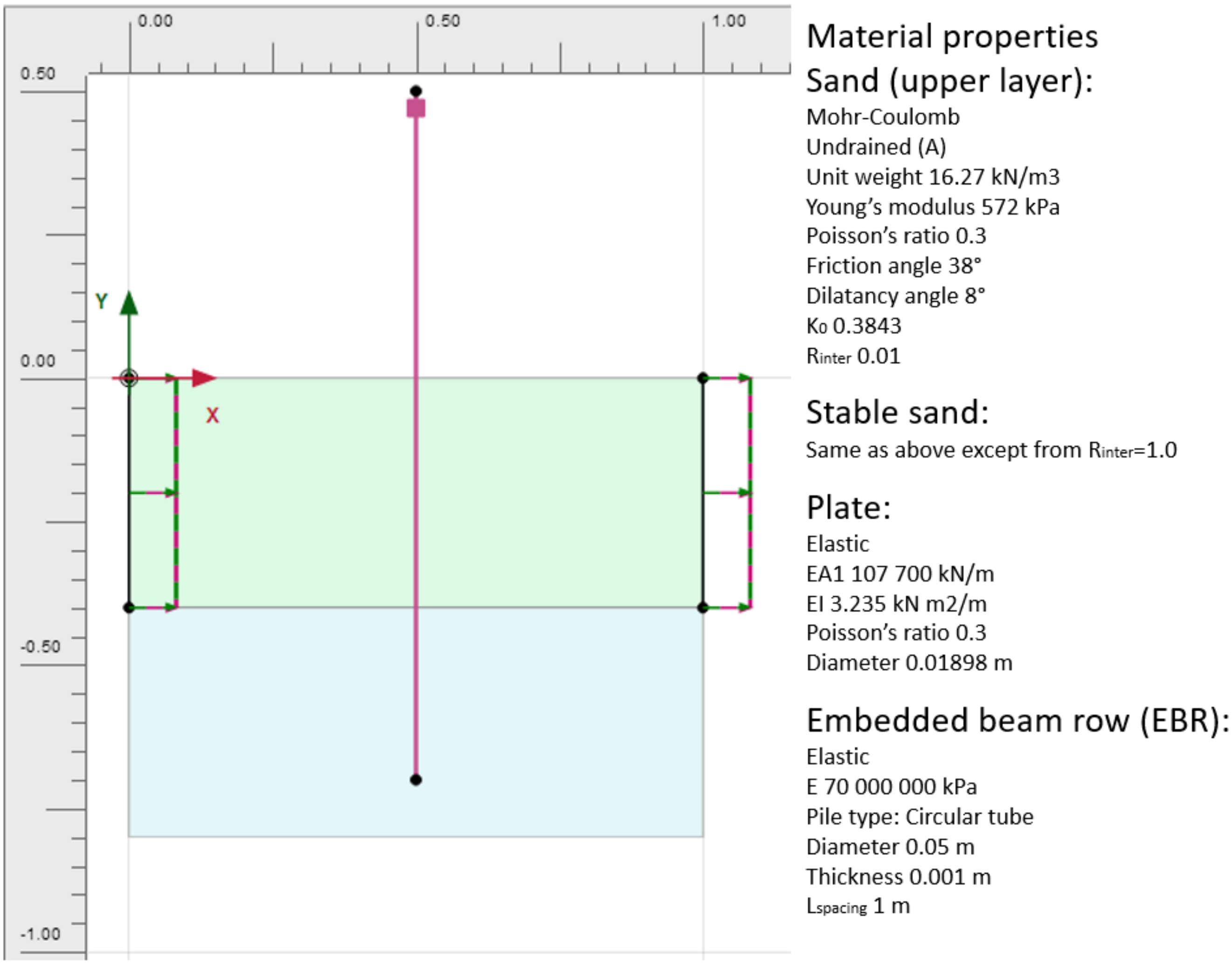


Figure 3.2: Model setup including material properties.

The result of the deflection of the pile in horizontal direction can be seen in Figure 3.3. The plate and EBR element gives rather equal results, where the EBR is slightly closer to the experimentally measured values. The results are not that far from the measured experimental values and the results obtained in Plaxis 3D, the difference is approximately a factor of 1.3. It should be noted that the Plaxis 3D modelling was not performed by the same authors who did the experimental test and Flac3D modelling.

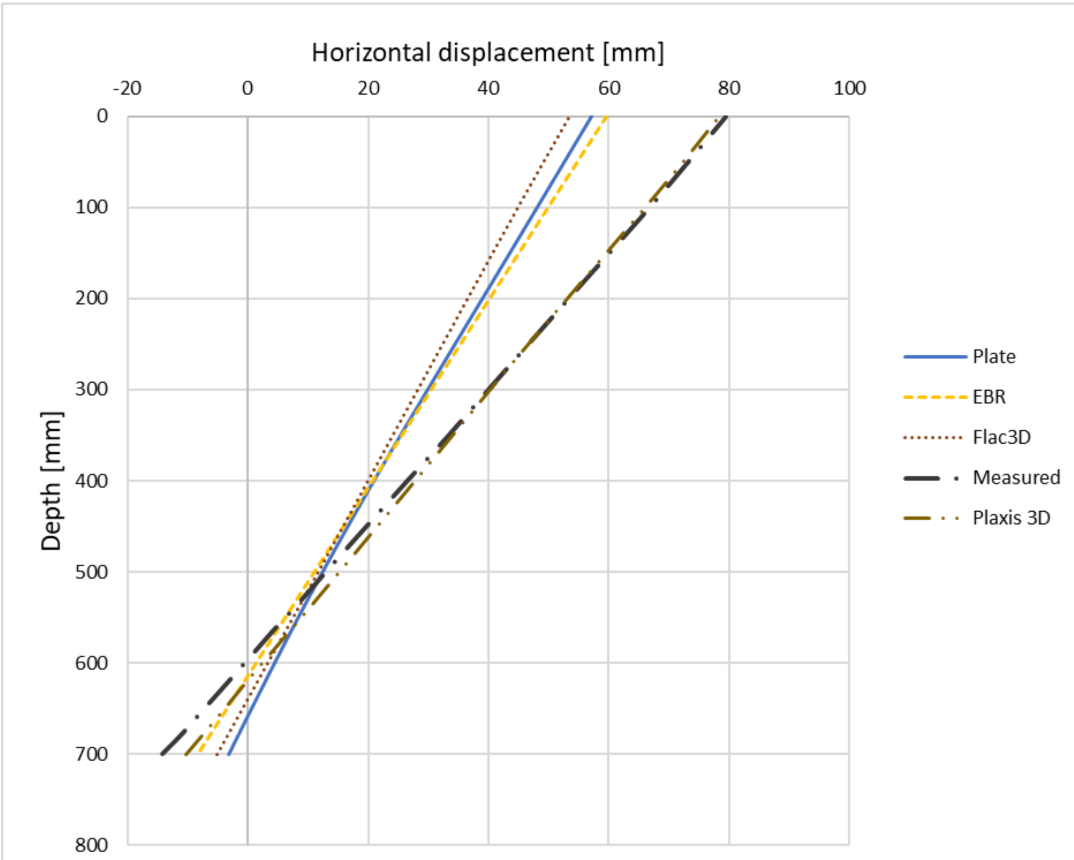


Figure 3.3: Displacement of pile in horizontal direction. Data from Al-Abboodi, Toma-Sabbagh, and Al-Jazaairry (2015) for Plaxis 3D, from Ghee and Guo (2010) for FLac3D and from Ghee (2009) for measurements.

The same method was also conducted to estimate the bending moments and the shear forces in the pile. However, the 2D modelling gave much lower values that what had been experimentally measured and modeled in 3D FEM programs. Thus, using Plaxis 2D appears to be a unreliable approach for assessing the magnitude of forces and moments induced in piles due to soil displacement. The graphs of bending moment and shear forces along the pile can be seen in Appendix A.

Regarding horizontal displacement, the EBR and plate element appears to give results that are accurate enough for this type of study. The EBR element allows for modelling the interface between soil and pile which means that bending moment and shear forces will be obtained from the software without the need of reducing them due to the pile diameter as in the case of the plate element, see Appendix A. This reduces the risk of human error influencing the results and motivates the usage of the EBR element. The usage of a prescribed displacement to model the soil displacement proved to give rather accurate results in the verification study and this type of modelling is therefore used when analyzing the effects of the piling activities for the Hisingsbron.

3.2 Case study, Hisingsbron

This study focused on the ongoing foundation works for the Hisingsbron on the south side of the bridge, i.e. in the district of Gullbergsvass. During the construction of the Hisingsbron, two other projects were also performing piling in the nearby area as stated in Section 1 and seen in Figure 3.4. The presence of the three projects made it hard to assess which foundation works caused which displacement in the ground. In this study the piles beneath bridge support II for the Götaälvbron and support 13 for the Hisingsbron were modeled, see Figure 3.4. These pile groups were selected since they are located close to each other, which implied decreased risk of other foundation works affecting the soil displacements. Thus, the validation through comparison with measurements from *Projektnav GG* was enabled. The measurement points in the field were located on the bridge supports of the Götaälvbron, and not on the piles, and thus the assumption that the bridge support and the piles were displaced in an equal magnitude was made.

Figure 3.4: View of the study area, including the location of the piling areas for Hisingsbron (blue), Platinan (green) and road E45 (red) together with bridge support II and 13 (pink). Retrieved from (Bouzas, 2018). Reprinted with permission.

3.2.1 Soil layering

The soil strata of the area have been assumed by using information from the geotechnical site investigation (Vilumson, 2014), the detail development plan (Siewertz, 2014) and the map viewer from the Geological Survey of Sweden (SGU, 2018). By reviewing this material, the soil layering has been assumed as shown in Figure 3.5. The top layer at level +2.5 consist of a fill material and beneath, at level 0 m, there is a clay layer that is probably deeper than 100 m. The ground water table is assumed to be located between the fill layer and clay layer.

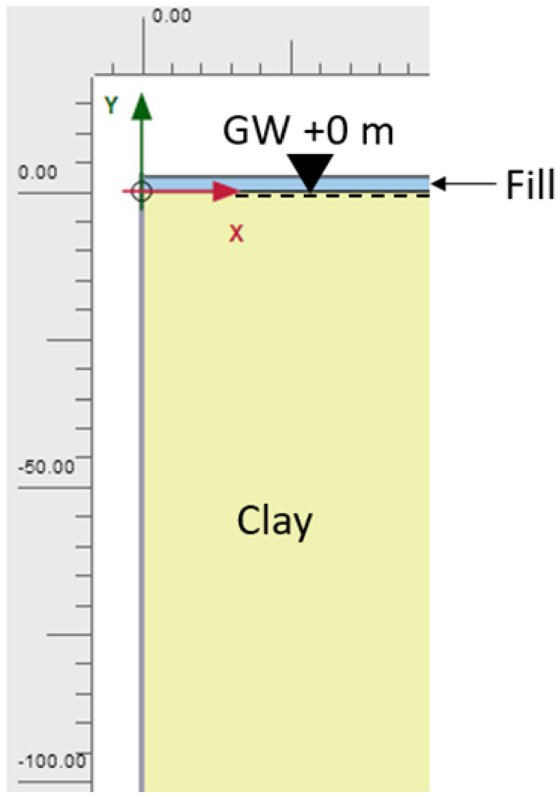


Figure 3.5: Assumed soil layering.

3.2.2 Pile foundation for bridge support II

The existing piles for the Götaälvbron beneath bridge support II are made of jointed cohesion piles of wood and have a total length of 36 m, see Appendix B. The piles are tapered, where the top diameter of the upper pile is 25 cm and for the lower pile 15 cm. Originally 80 piles were installed in 5 rows and 16 columns. Of these piles, 14 are vertical and the rest are inclined with either 1:10 or 1:8 degrees. Above the piles is a reinforced concrete structure. In 1958 the bridge was broadened and additional piles were installed. Blueprints of the extension of piles due to the broadening has not been provided for bridge support II. However, for bridge support X it has been found that 4 vertical piles were added, see Appendix B.

3.2.3 Piling area for bridge support 13

The piles for the Hisingsbron beneath bridge support 13 are made of cylindrical steel piles with a total length of 96 m, which consist of together-spliced steel elements. The dimensions are 400 mm in diameter and totally 52 piles have been installed (Bouzas, 2018). The piles are installed with direction towards the existing Götaälvbron.

3.3 Plaxis 2D model

A Plaxis 2D model was created to analyze the effects on the existing piles for the Götaälvbron due to the soil displacement induced by the installation of the piles for the Hisingsbron. A plane strain model with 15 noded elements was used. The distance between the existing and installed piles was assumed to be around 60 m. This assumption is based on measurements from blueprints of the new bridge, where only the firstly installed piles for bridge support 13 are considered and they are the ones farthest away from the existing Götaälvbron (Göteborgs Stad, no date).

The boundary condition in x-direction was set to 400 m to have a border that was larger than four times the installed pile length. The boundary in y-direction was set to -150 meters, in order to have sufficient space beneath the installed piles. The existing piles for bridge support II were modeled using the embedded beam row element and the soil displacement induced from the installation of the piles beneath bridge support 13 were modeled using the line displacement feature. In the following subsections the material properties used and model setup is described.

3.3.1 Material models and properties

The material properties of the soil layers were defined as seen in Table 3.1. The material data has been assessed by reviewing information from the geotechnical site investigation for the Hisingsbron (Vilumson, 2014). Nevertheless, in this report only a few material parameters have been reported and thus the material properties have been supplemented with information from a site investigation for the upcoming city block Region City which will be located between the Gothenburg central station and road E45 (Wood, 2014). For the top fill layer, a Mohr-Coulomb model was chosen due to limitation of available material data for this soil layer. The clay layer was divided in three layers and modeled with the Soft Soil model to enable modelling of the compression behavior of the soft clay.

Table 3.1: Material properties for the soil models.

Parameter	**Name**	**Unit**	**Fill 2.5 to 0 m**	**Clay 1 0 to -3m**	**Clay 2 -3 to -18 m**	**Clay 3 -18 to -150 m**
General						
Material model	*Model*	-	Mohr-Coulomb	Soft Soil	Soft Soil	Soft Soil
Drainage type	*Type*	-	Undrained (A)	Undrained (A)	Undrained (A)	Undrained (A)
Dry weight	γ_{unsat}	kN/m^3	18	16	16	16
Wet weight	γ_{sat}	kN/m^3	20	16	16	16
Parameters						
Modified compression index	λ	-	-	0.1078	0.1590	0.2335
Modified swelling index	κ	-	-	0.0118	0.0140	0.0145
Young's modulus	*E'*	MPa	10	-	-	-
Poisson's ratio loading/unloading	ν	-	0.3 / 0.15	-	-	-
Cohesion	c'	kPa	0	1.7	1.7	4.35
Friction angle	ϕ	°	35	30	30	30
Dilatancy angle	ψ	°	0	0	0	0
Groundwater						
Permeability in horizontal direction	k_x	m/day	7.65	0.0864*10^{-3}	0.0864*10^{-3}	0.0864*10^{-3}
Permeability in vertical direction	k_y	m/day	7.65	0.0864*10^{-3}	0.0864*10^{-3}	0.0864*10^{-3}
Interfaces						
Interface strength	-	-	Manual	Manual	Manual	Manual
Interface reduction strength	R_{inter}	-	0.67	0.67	0.67	0.67
Initial						
$K_0 determination$	-	-	Automatic	Manual	Manual	Manual
Lateral earth pressure coefficient	$K_{0,X}$	-	0.4264	0.63	0.59	0.59
Over-consolidation ratio	OCR	-	-	1.59	1.37	1.37

The construction of bridge support 13 was modeled by using soil polygons with concrete material and embedded beam rows for the piles. The assumed material properties for the concrete and embedded beam rows can be seen in Table 3.2 respectively Table 3.3. The values for dry unit weight for the concrete material has been taken as the weight for reinforced concrete given in a publication of the Swedish Road Administration (Örtendahl & Holmström, 1994). Young's modulus was chosen in accordance to the values for a concrete type C28/35, since the concrete type on the blueprints of bridge support II was denoted as Btg 350 (Swedish National Board of Housing & Planning, 2004). Poisson's ratio for the concrete material has been assessed in accordance to Eurocode in which 0.2 is the value for uncracked concrete and 0 is the value for cracked concrete (EN-1992-1-1, 1992). Due to lack of information about the interface strengths between structure and soils an assumption of Rinter= 0.67 is made (Plaxis, 2017a).

Table 3.2: Properties for concrete elements.

Parameter	**Name**	**Unit**	**Concrete**
General			
Material model	*Model*	-	Linear elastic
Drainage type	*Type*	-	Non-porous
Dry weight	γ_{unsat}	kN/m^3	24
Parameters			
Young's modulus	*E*	GPa	32
Poisson's ratio	ν	-	0.15
Interfaces			
Interface strength	-	-	Manual
Interface reduction strength	R_{inter}	-	0.67

The Young's modulus and unit weight of the EBR has been assumed using typical values for tree piles given in Olsson and Holm (1993). Since it was not possible to model tapered piles using the EBR-feature the pile diameter was set to the mean value. i.e. 0.2 m. Pile joints were not included in the model, instead the piles were modeled as one continuous element with a total length of 36 m. The axial and lateral skin resistance were assumed to have equal magnitude and were calculated based on the assumption that each pile can take 25 tons (Hachicha & Hjalmarsson, 2013). For the skin resistance linear variation with depth was assumed. It was also assumed that 90 % of the total bearing capacity is at the shaft due to cohesive forces, and 10 % at the base (Abd Elsamee, 2012), see Appendix C for further calculations.

Table 3.3: Material properties for piles beneath bridge support II.

Parameter	**Name**	**Unit**	**Embedded beam row**
Material type	Type	-	Elastic
Properties			
Young's modulus	*E'*	GPa	10
Unit weight	γ	kN/m^3	7
Pile type	-	-	Predefined
Predefined pile type	-	-	Massive circular pile
Diameter	D	m	0.2
Pile spacing	$L_{spacing}$	m	1
Axial/Lateral skin resistance	-	-	Linear
	$T_{start,max}$	kN/m	10
	$T_{end,max}$	kN/m	358
Base resistance	F_{max}	kN	30
Interface stiffness factor	-	-	Default values

3.3.2 Model setup

The model setup can be seen in Figure 3.6. As the global coordinate system shows, the view in the model is the same as when watching the bridges from Hisingen, which enables the line displacement, representing the installed piles, to be putted in x=0. The line displacement is assumed to have a length equal to the pile length, i.e. 96 m. The value of the displacement was assessed by computing the cumulative volume of the installed piles each week, see Appendix D. First the volume displacement caused by the installation of a single pile was calculated for a solid pile with length of 96 m and diameter of 0.4 m. This volume was then reduced by a factor of 0.5 due to the fact that the piles are tubular and thereby displace less soil. The reduction factor (RF) is not equal to the volume of the tubular pile since a soil plug is formed at a certain depth within the pile which leads to a cavity. The RF was determined from test piling in the case area, where the tubular piles were found to give a reduction of either 45 or 55 % compared to the solid pile for a driven and a vibrated pile, respectively (Bouzas, 2018). From these calculations a volume of 6 m^3 displaced soil per pile was obtained. Thereafter, this volume was multiplied with the amount of installed piles to get the total soil displacement per week. The displaced volume for each week was then assumed to form a superpile, and the prescribed displacement in the plane strain model was set as the radius of the superpile. Since the piles in this bridge support has been installed over a period of several weeks, a decision was made to only look at the first five weeks in which 15 of the 52 piles were installed. The distribution of line displacement was assumed to be uniform with depth. A mesh with medium coarseness was used, refined around the structural objects.

Only the middle pile row of bridge support II was modelled and thus the other pile rows are assumed to have the same setup, although, this is not the case in reality, see Appendix B. The piles beneath the extension part of the bridge could not be modeled as vertical, since the lack of a third dimension in Plaxis 2D and thus these were modeled with an inclination at 1:8.

A self-weight of the overlaying bridge was calculated by using defined unit weights from Örtendahl and Holmström (1994) and estimating the volumes of steel, timber and coating for the road, railings, sidewalk and the supporting columns, see Appendix E.

To see the influence of the bridge stiffness in the out of plane direction, two different models were created. The difference between these two models were that in one of the models the vertical concrete borders were fixed using the line displacement tool, and in the other model the borders were free to move. In the second case an interface element was applied on the concrete borders of the bridge support foundation to allow for a slip between the soil and the structure.

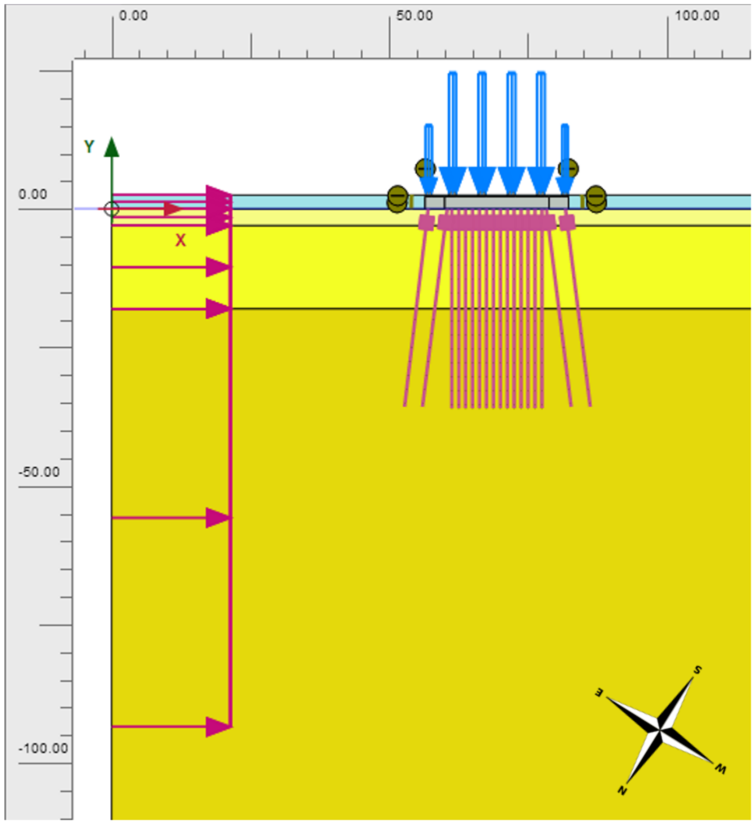


Figure 3.6: Model setup in Plaxis.

3.3.3 Plaxis calculation

In total, 15 phases were defined in the staged construction mode, see Table 3.4. The loading type for each phase were set to staged construction. This was the case for all phases except the last one, final consolidation, in which minimum excess pore pressures was chosen as calculation type. In every phase temperature was ignored, and thus no thermal calculations were performed. For the phases that had plastic calculation type, the phreatic level was chosen for pore pressure calculation. Whilst when the calculation type was consolidation, pressures were instead used from the previous phase.

The initial phase was set to K0 procedure and all the elements except for the line displacement at x=0 were activated. Since it was not possible to activate the load from the overlaying bridge in this scenario a plastic phase, bridge loading, was added. Since the model is not symmetrical around the bridge support this caused the bridge foundation to be more displaced in the positive x-direction. Thus, a consolidation period at 2000 days were added, to get the horizontal displacement in the bridge foundation back to zero as well as to include the stress conditions in the ground in the calculations.

In the following phases the line displacement, representing the soil displacement of installed piles, were activated with varying values for each week depending on the number of installed piles per week. In reality, more piles were installed after week 44, however, in this model a theoretical long-term consolidation period of 2000 days followed by a final consolidation period were added to get a sense of the long-term effects.

Table 3.4: Calculation phases in Plaxis.

Phase	Calculation type	Days	Comments
Initial phase	K0 procedure	0	
Bridge loading	Plastic	0	The self-weight of the overlaying bridge is activated
Cons post bridge loading	Consolidation	2000	Consolidation after activation of bridge loading
W40 disp	Plastic	0	Activation of line displacement of 0.14 m
W40 cons	Consolidation	7	Consolidation period after pile installation
W41 disp	Plastic	0	Activation of line displacement of 0.24 m
W41 cons	Consolidation	7	Consolidation period after pile installation
W42 disp	Plastic	0	Activation of line displacement of 0.28 m
W42 cons	Consolidation	7	Consolidation period after pile installation
W43 disp	Plastic	0	Activation of line displacement of 0.24 m
W43 cons	Consolidation	7	Consolidation period after pile installation
W44 disp	Plastic	0	Activation of line displacement of 0.28 m
W44 cons	Consolidation	7	Consolidation period after pile installation
Long-term cons	Consolidation	2000	Line displacement deactivated
Final cons	Consolidation		

Finally, in the output window the horizontal and vertical displacement for the bridge support were plotted and the displacement occurring at the top of the support in point A and B, see Figure 3.7, were compared with the measured displacement of the Götaälvbron from the database *Projektnav GG*.

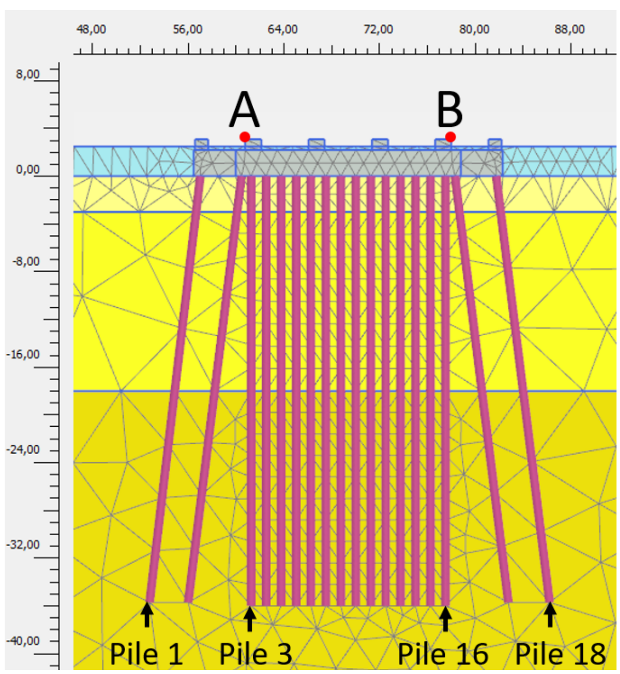


Figure 3.7: Location of point A and B in Plaxis model including numbering of the piles.

4 Results and Discussion

In this Chapter the calculated result in Plaxis 2D is presented and compared with the field measurements retrieved from *Projektnav GG*. The results are presented in form of displacements in the soil and the structure, together with charts over shear forces and bending moments in the piles. The Chapter also includes a sensitivity analysis, where factors that were believed to have noticeable impact on the result are further investigated. In the end of the Chapter unsolved modelling issues are described and discussed.

4.1 Displacement in bridge with free and stiff bridge support

In Figure 4.1 to Figure 4.4 the displacement occurring in points A and B (see Figure 3.7) of the bridge foundation are shown for a free construction and a fixed construction, respectively, compared to the field measures for the equivalent points in reality. The presented field measurements show displacements in the east-west direction, compare with Figure 3.6. Field measurements show displacements between +3 mm and -1 mm in horizontal and vertical direction during this time period according to data from *Projektnav GG*, for more detailed figures see Appendix F. This implies that the result is affected by which stiffness the bridge has. It can be seen that for the free alternative the displacements are quite high, about ten times higher than reality, meanwhile the fixed alternative gives fairly small displacements. If comparing with the real case, the fixed alternative is closer, hence it can be concluded that the concrete structure should have an applied stiffness, but perhaps not be totally fixed.

It is reasonable that the displacements get bigger with a setup of free concrete structure, since there is nothing holding the structure back, so the soil can simply be pushed in the easiest direction. The displacements are big but even, which suggest that as long as everything can move evenly in the same magnitude and direction no undesired stresses are believed to occur. For the displacements in the fixed structure, point B moves less than point A, which is due to that the fixed structure prevents the soil to displace in the same amount further away due to that displacements decreases with distance from the source. The unevenly movement may result in a turning movement of the structure which could lead to development of undesired stresses. However, comparing to the free case, the predicted displacements are very small.

In the vertical direction both the free and fixed cases show the same tendency of displacing by means of heave. The magnitude of the heave does not appear to be particularly dependent on whether the bridge is free or fixed in the horizontal direction. The initial values begin at -0.1 m which can be explained by the settlements from the bridge load which the program interprets as an applied load. The more piles installed, the more heave occurs. Point B heaves less than point A, which is reasonable since it is further away from the lateral soil movement and the displacements decreases with distance from the source. The variations in vertical displacement during the loading steps are bigger in the modeled cases than in field measurements from *Projektnav GG*. This could be due to the fact that the structure is not at steady state in the beginning of the modelling stages, since the overlaying bridge load cannot be defined in the initial phase. If longer initial consolidation period was assigned to account for the 80 years the bridge has been standing, perhaps better results could have been achieved. Nevertheless, to fully be able to achieve accurate stress conditions in the ground, the changes in the soil properties due to previous construction work should also be included. Though, this is considered to be difficult to model, since a lot of construction has been performed in the area of concern throughout the years.

In both the vertical and horizontal direction displacements increase with amount of piles installed, which can be explained by the amount of soil being pushed aside towards the existing structure. When assigning phases with lateral soil displacements it was known how many piles that were installed per week, but it was not known at which days of the week that these were installed, and neither the rate of which piles were installed in the nearby area. Thus, it was assumed in the model that all of the piles in bridge support 13 were installed on the first day of each week at a time frame that was equal to zero, and then the line displacement were kept during the week while consolidation occurred. Thus, the curves are shaped as staircases. This sort of modelling contributes to an overestimation of the displacement in the time between the installations of piles. However, it is hard to estimate how long time the lateral displacement, caused by pile installation, affects the existing constructions nearby. This is the reason for keeping the line displacement activated during the whole weeks, to get a solution on the conservative side.

Overall it has been found that to achieve correct horizontal displacement, the bridge should have an applied stiffness. Heave occurs when the soil displacement is activated. Using the proposed model overestimates the magnitude of the heave. Furthermore, it is believed that the initial stress conditions in the ground must be properly modeled to achieve correct vertical deformations.

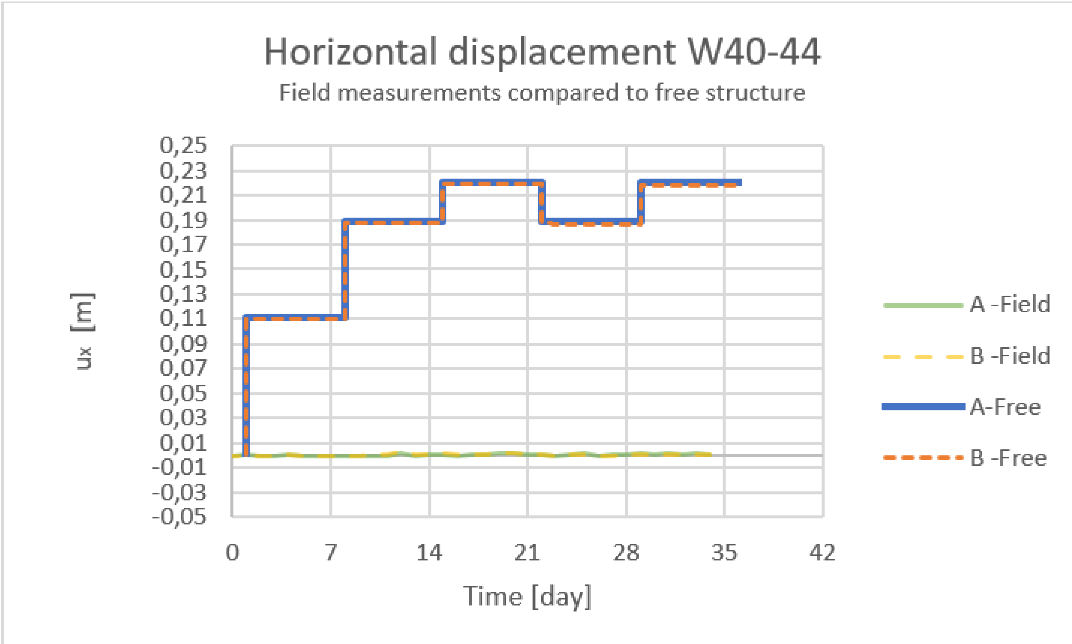


Figure 4.1: Horizontal displacement for the concrete structure when the concrete borders are free to move in the horizontal direction. The result is compared to field measurements from *Projektnav GG*.

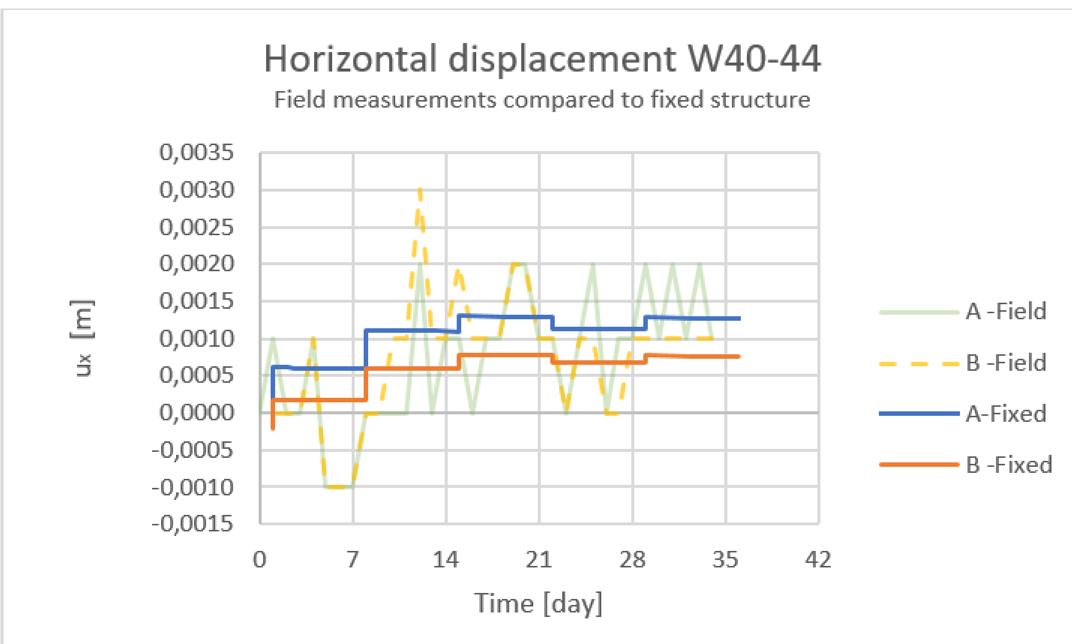


Figure 4.2: Horizontal displacement for the concrete structure when the concrete borders are fixed in the horizontal direction. The result is compared to field measurements from *Projektnav GG*.

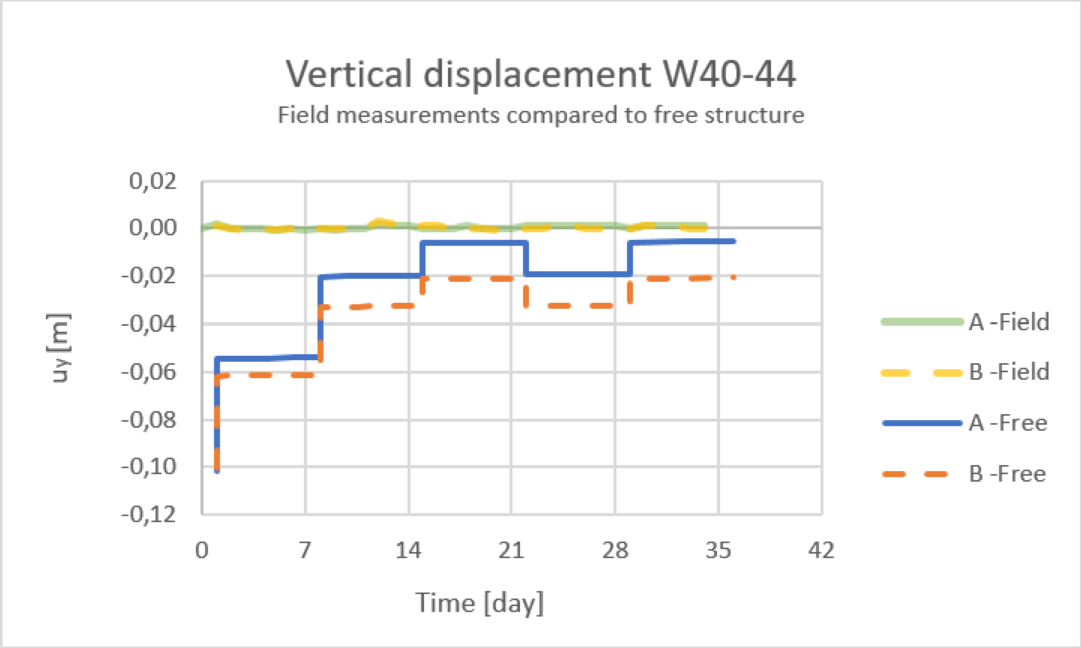


Figure 4.3: Vertical displacement for the concrete structure when the concrete borders are free to move in the horizontal direction. The result is compared to field measurements from *Projektnav GG*.

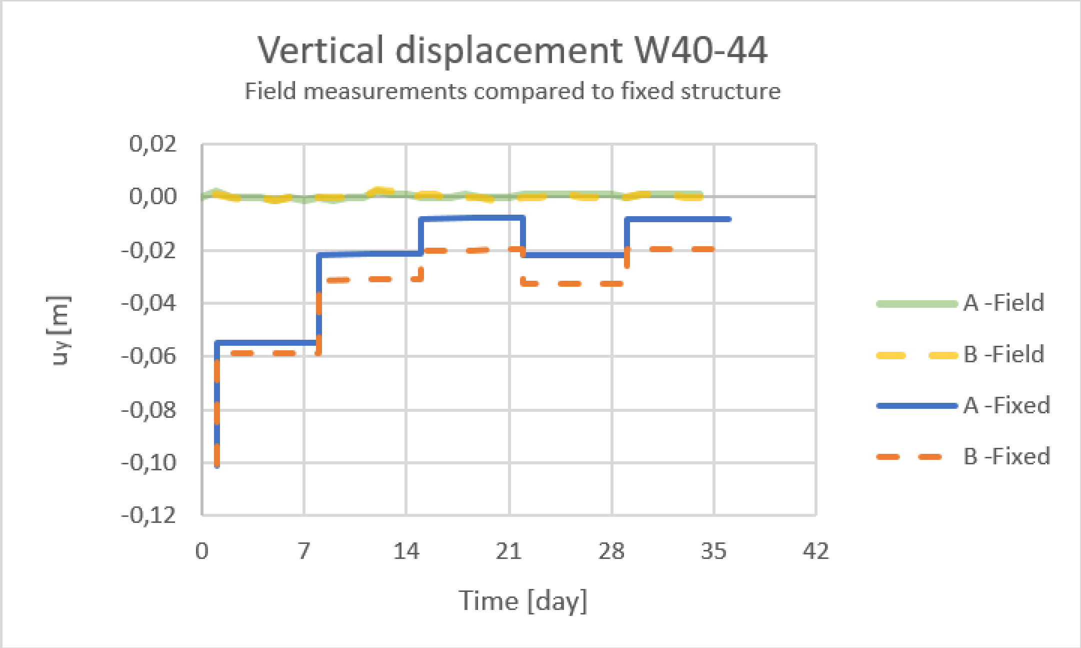


Figure 4.4: Vertical displacement for the concrete structure when the concrete borders are fixed in the horizontal direction. The result is compared to field measurements from *Projektnav GG*.

4.1.1 Soil displacement

The Figures in this section shows some of the characteristics or expected results based on the performed literature study. Figures for vertical and horizontal displacements for the entire model during different phases of interest are presented. In Figure 4.5 and Figure 4.6 the deformed mesh is shown for both the free and fixed alternative.

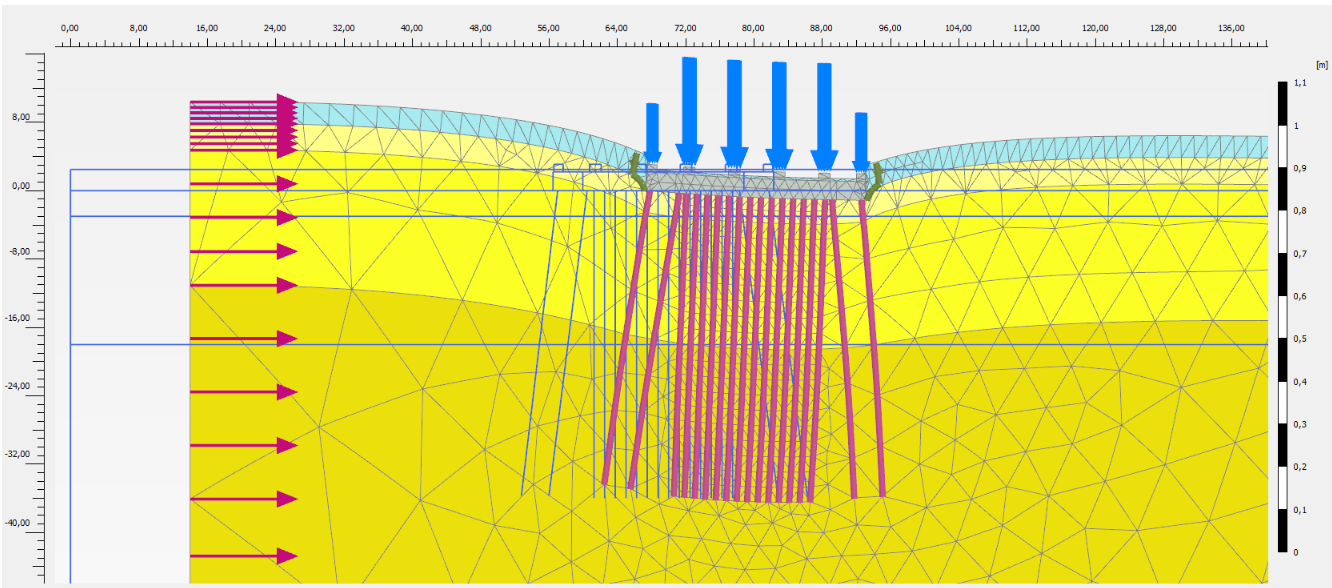


Figure 4.5: Deformed mesh after installation of new piles when the concrete structure is free in horizontal direction. The mesh is scaled up 50 times.

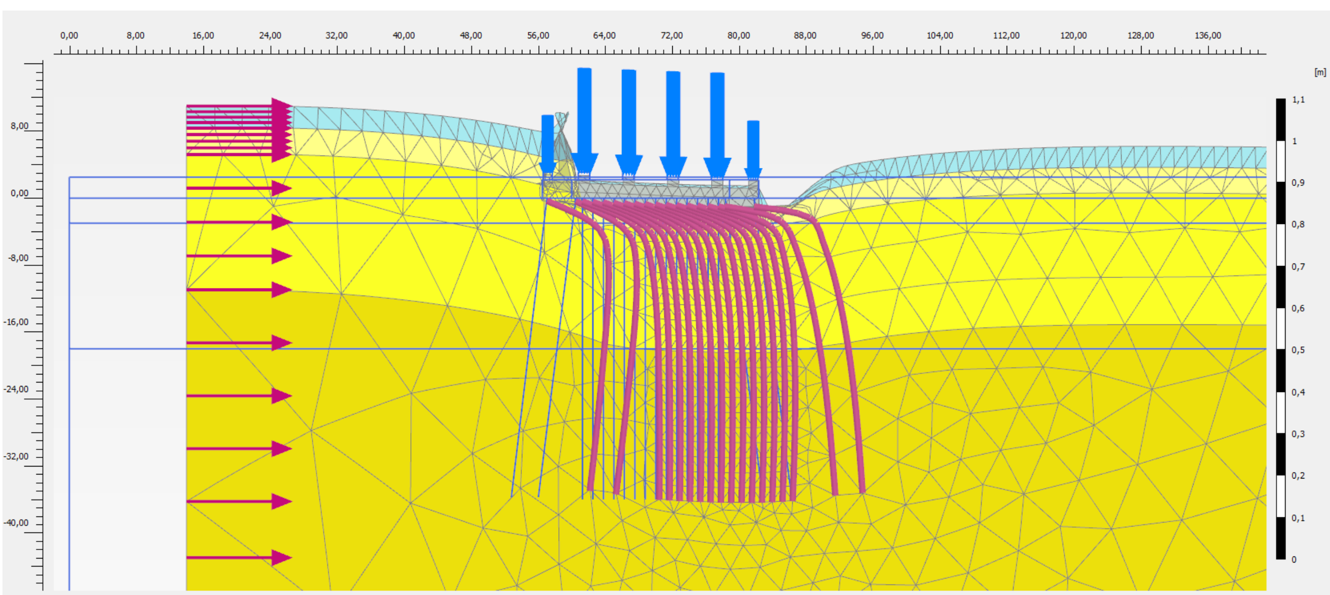


Figure 4.6: Deformed mesh after installation of new piles when the concrete structure is fixed in horizontal direction. The mesh is scaled up 50 times.

The difference of how the existing piles are affected when the load from installing new piles are applied, can clearly be seen in these figures. In Figure 4.5 the piles are almost equally displaced with depth, away from the new piles. In the fixed alternative, Figure 4.6, the piles bend and the pile heads stays fixed in the concrete structure while the pile tips move away from the source of soil displacement. As mentioned before, the difference between the free and fixed mode is that the free alternative moves the easiest way, meanwhile the fixed mode is restrained in horizontal direction making the piles subjected to larger lateral loads.

The soil response adjacent to the concrete structure differs, depending on if it is free or fixed. In the free mode, the soil moves smoothly together with the foundation while in the fixed mode gaps are created between the soil and the concrete foundation, due to that the soil moves separately from the structure. For both cases heave occurs both before and after the bridge support, but mostly before the bridge which is reasonable, since most soil is displaced before the bridge, and upwards direction is the easiest way for the soil to move.

In Figure 4.7 to Figure 4.8 it is showed how the bridge load is treated, since Plaxis do not interpret this load as an existing load but as an applied load. Figure 4.7 shows the displacements retrieved after activating the bridge load. The displacements have a tendency to move in the positive x-direction which is due to the non-symmetry in the boundary conditions. The boundaries had to be asymmetric since the prescribed displacement had to be applied on a boundary to make sense in Plaxis. To handle the settlements from the bridge load and not letting it affect the horizontal displacements due to the new installed piles, a consolidation phase was added which can be seen in Figure 4.8. The horizontal displacement moves back and a more bulb shaped symmetric displacement under the bridge is formed.

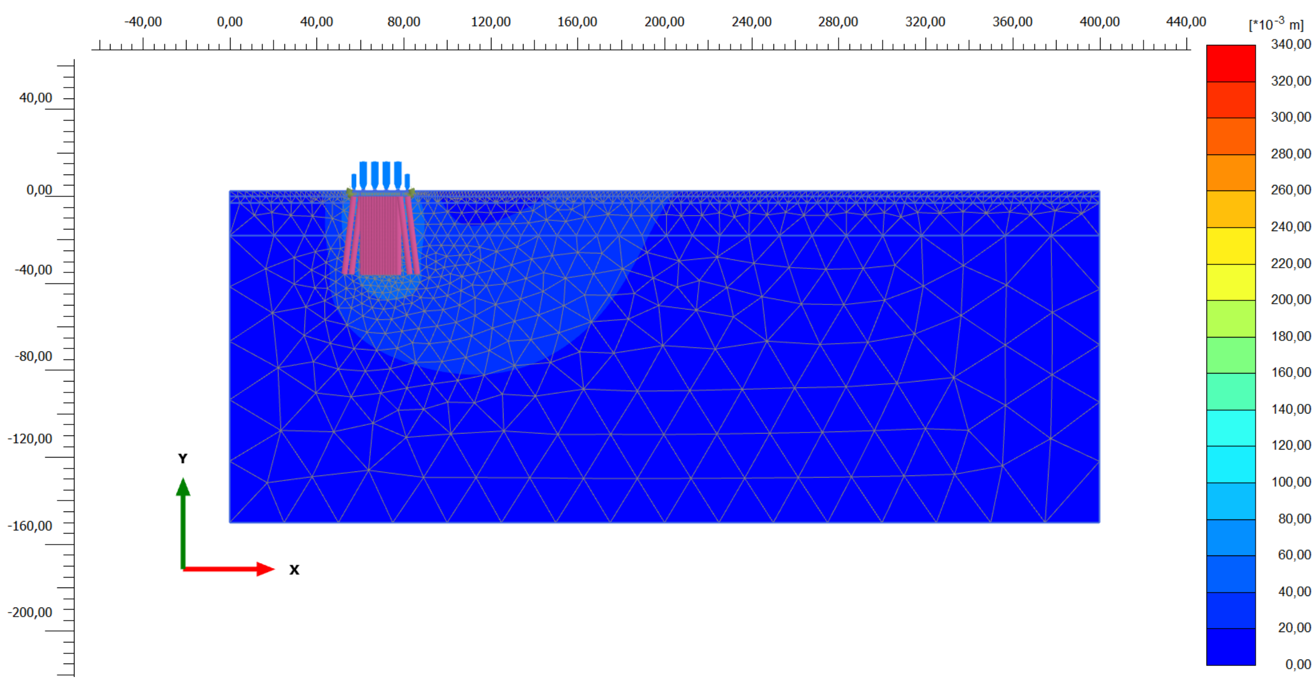


Figure 4.7: Total displacement after applying the bridge load when the concrete structure is free in horizontal direction.

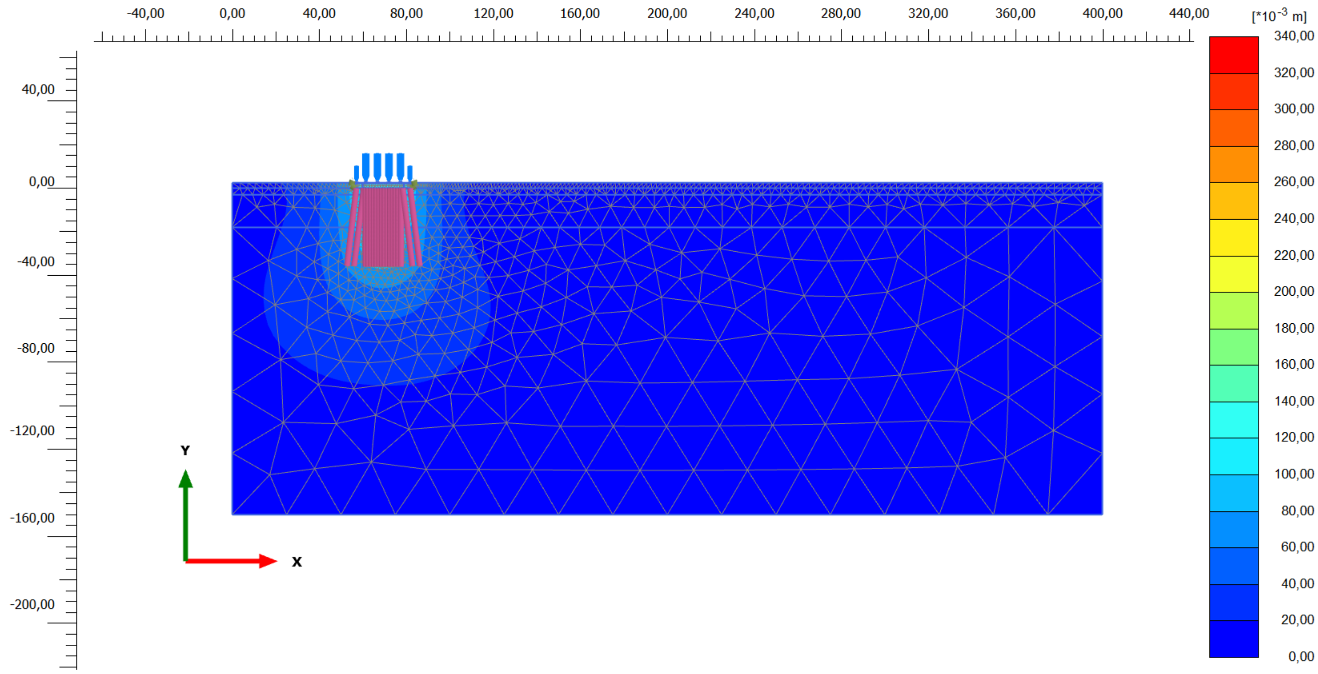


Figure 4.8: Total displacement after applying the bridge load and letting it consolidate for 2000 days, when the concrete structure is free in horizontal direction.

As described in the literature study, most of the predicted displacements will be close to the newly installed piles and they will then decrease with distance from the source. This can be seen in Figure 4.9 and Figure 4.10. In Figure 4.10 a good example of heave, that occurs when installing piles, is shown. At the top close to the surface and mostly close to the newly installed piles the soil moves upwards, meanwhile it goes downwards deeper down in the profile. This was expected from the literature study.

In summary, the expected soil kinematics due to pile installation observed in the literature could be reproduced by simulations with Plaxis 2D. Thus, this authenticates this type of study to see the effects on existing structures due to soil displacements from pile installation.

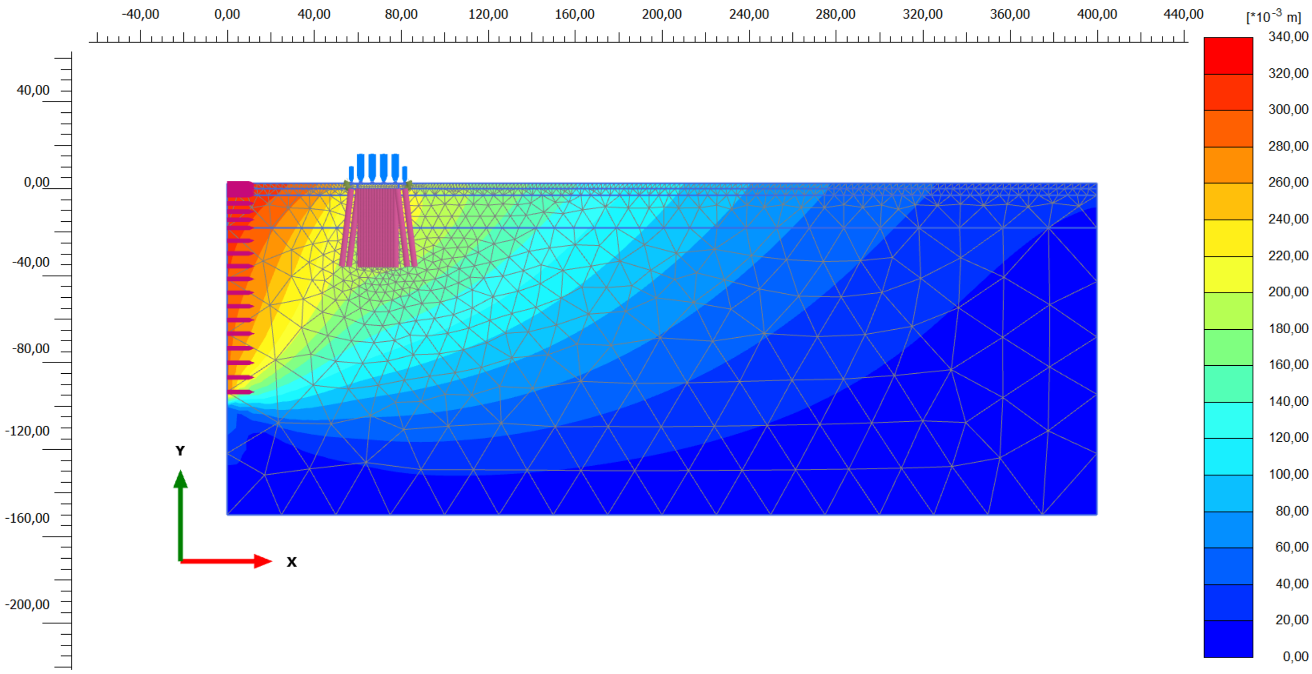


Figure 4.9: Total displacement in the fifth week of pile installation, when the concrete structure is free in horizontal direction.

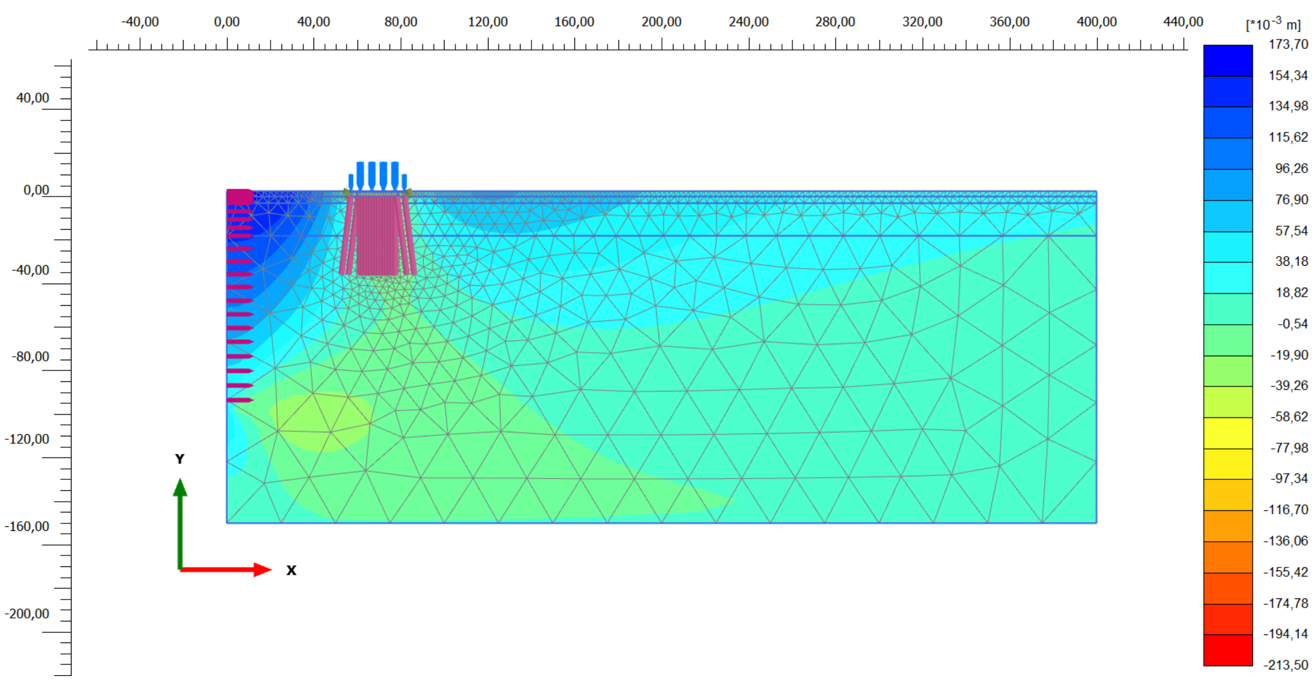


Figure 4.10: Total displacement in the fifth week of pile installation, when the concrete structure is free in horizontal direction.

4.1.2 Displacements in piles

The horizontal displacements in pile 3, which is the first vertical pile in the direction of the soil displacements (see Figure 3.7 for definition of pile numbering) during different phases, are shown in Figure 4.11 and Figure 4.12. The displacements during the consolidation phases in week 40-45 are not shown, since these are approximately the same as during the displacement phases for each week. In both the cases, whether the concrete structure is fixed or free, some horizontal displacements happens when the bridge load is applied, and then the displacements move back to almost being zero during the consolidation period. The displacements in the pile in the free structure are similar to the one showed with the verification model, see Section 3.1, where the pile is displaced linearly with maximum displacement occurring at the top of the pile. The magnitude of the displacement is in direct correlation to the applied line displacement, which is a reasonable result. In the long run it appears that the piles will move back towards their original position, and perhaps will be displaced a little bit closer to the Hisingsbron than they originally were, provided the consolidation can proceed without further activities happening in the area.

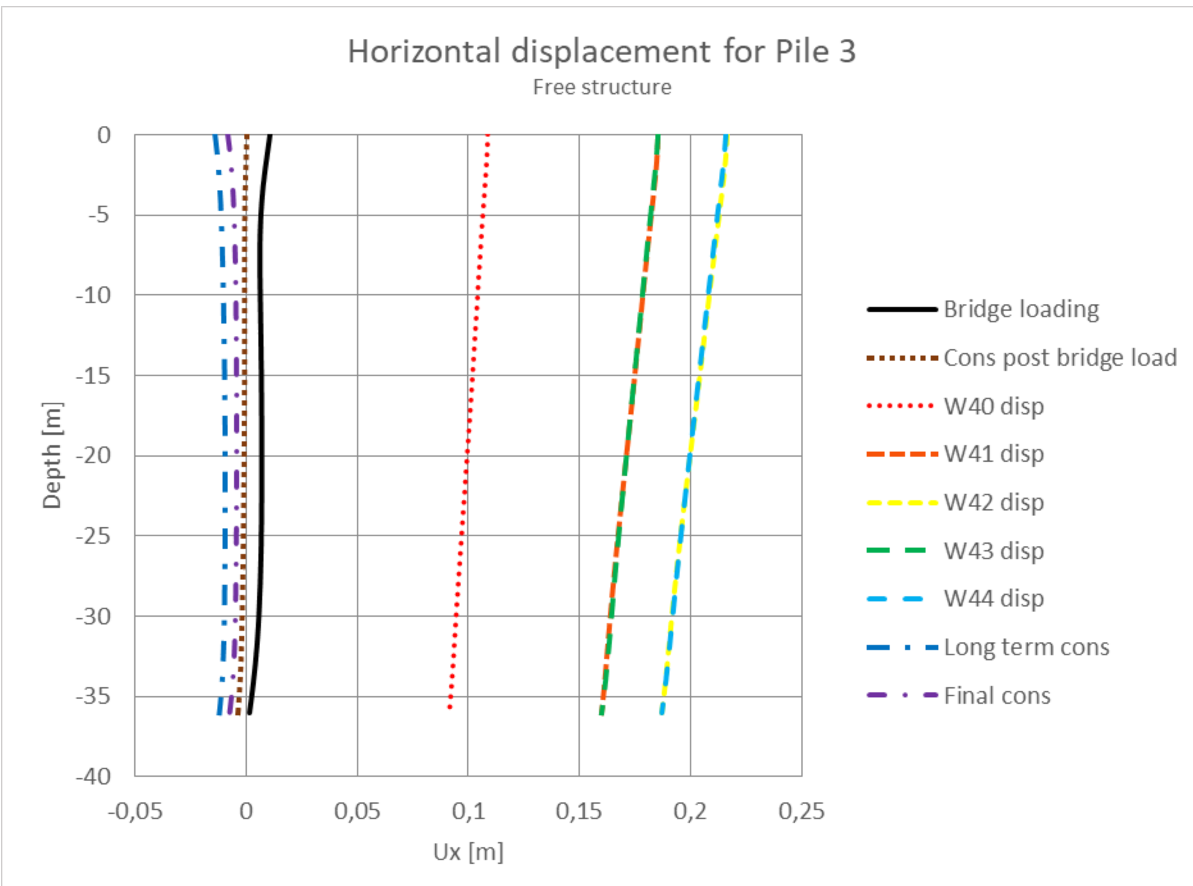


Figure 4.11: Horizontal displacements in pile 3 at different phases.

In the fixed structure the pile head is locked in the concrete, hence no displacements occur there. However, the pile is then bent in the upper part of the pile, and the bottom of the pile is displaced approximately as much as the pile tip for the free structure. This implies that the displacements at the bottom of the pile are pretty much independent of whether the concrete structure is fixed or free in this case. Thus, it could be of interest to setup a model where the piles are fixed in the pile tip.

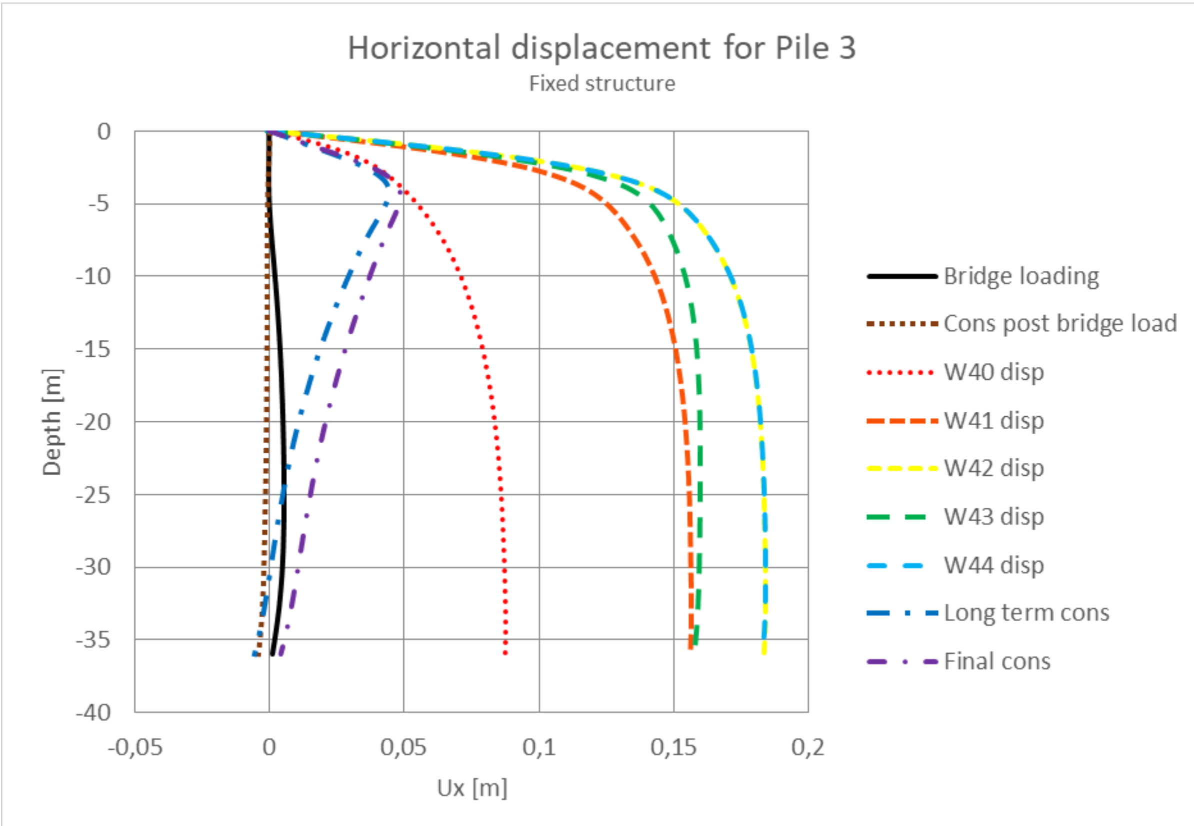


Figure 4.12: Horizontal displacement in pile 3 at different phases.

The difference between piles in the free and fixed structure, respectively, are shown in Figure 4.13 and Figure 4.14, where the horizontal displacements for different piles have been plotted for the first phase of horizontal soil displacement, i.e. phase W40 disp. On the x-axis the ratio of the displacement in the pile and the lateral displacement at x=0 is plotted. In the free structure, pile 3 shows a linear displacement with depth while the other vertical pile, 16, is a bit curved and only shows a tendency to have linear displacement with depth. The inclined piles, 1 and 18, have a bent displacement curve at the top of the pile, which with increasing depth becomes more of a linear curve. The piles closest (1 and 3) to the newly installed piles are less displaced than those further away, which implies that the existing pile group in some way increases the magnitude of the displacement, causing the piles further away to displace more, which may also be viewed in Figure 4.6. This is the opposite effect to the displacement occurring in point A and B, see Figure 1 and 3 in Appendix F. However, the difference in displacement is rather small, less than one centimeter. In the fixed structure all the piles, both vertical and inclined, are bent in the same manner, and the relationship where the piles closer to the source of the displacement are displaced less than those further away applies.

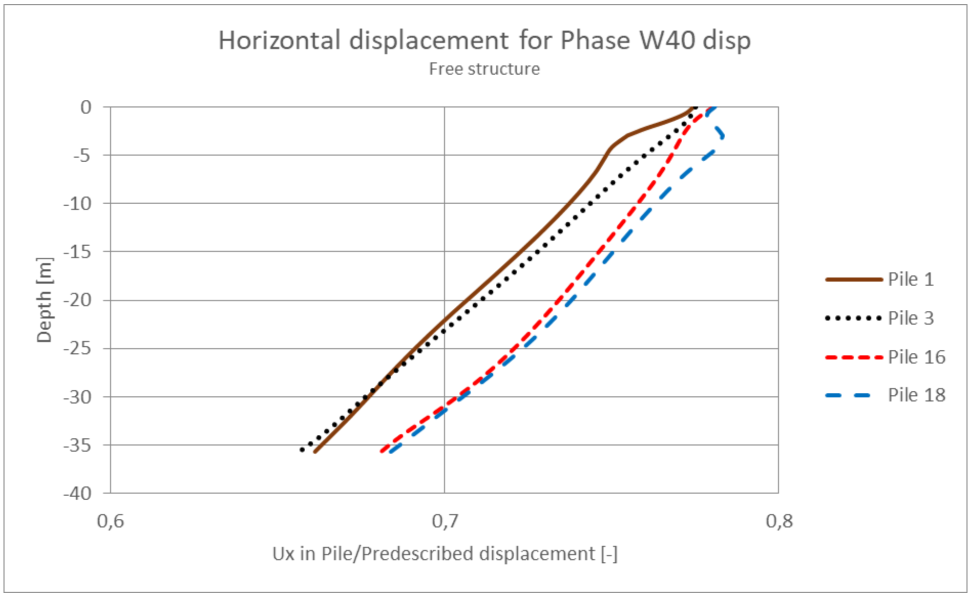


Figure 4.13: Horizontal displacement in pile 1, 3, 16 and 18 for phase W40 disp when the concrete structure is free to move in horizontal direction.

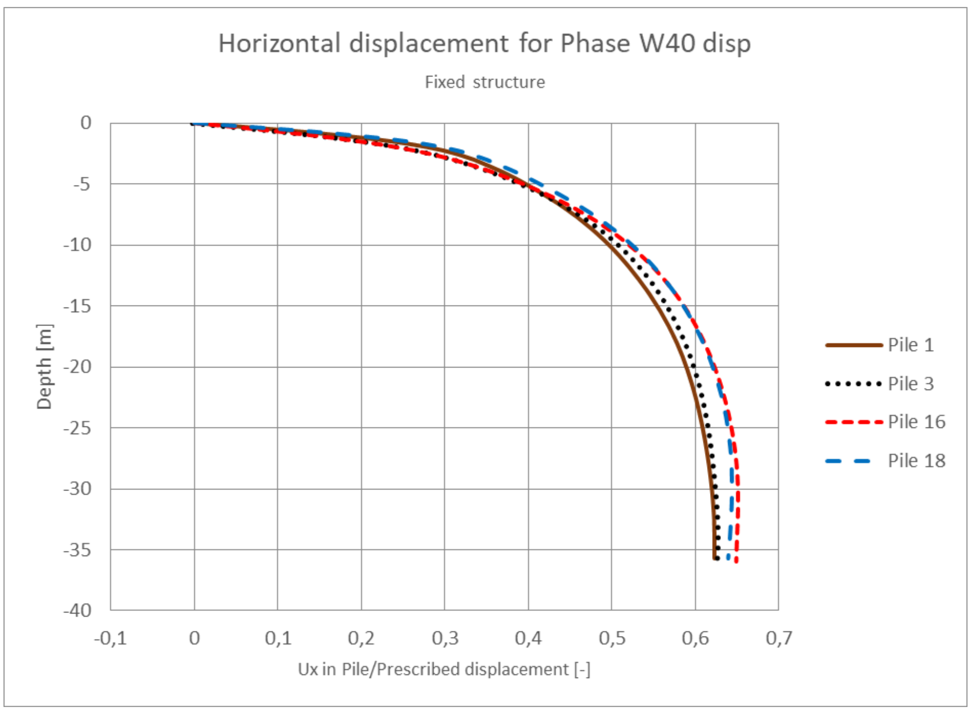


Figure 4.14: Horizontal displacement in pile 1, 3, 16 and 18 for phase W40 disp when the concrete structure is fixed to move in horizontal direction.

4.1.3 Forces and moments in piles

According to the verification of modelling pile response due to lateral soil movements, Plaxis 2D underestimated the values of bending moments and shear forces in the piles compared to 3D modelling and experimental tests. Nevertheless, the shape of the bending moment and shear forces curves were rather similar. In the following charts the bending moment and shear forces distribution for pile 3 are shown for both the case where the concrete structure is fixed and free to move in the horizontal direction. Regarding moment distribution, see Figure 4.15, the shape of the curves of the free and fixed structure are similar, however, the bending moments in the fixed structure are much bigger than in the free structure. This behavior is expected since the fixed structure has to carry more load due to its inability to move away with the soil. It is also in accordance with the large bending curve that could be viewed in the horizontal displacement, see Figure 4.14. The bending moments are most occurring at the top and bottom of the pile and in between the resulting moment is almost equal to zero. This could be a response to that the piles moves away freely with the soil at larger depth, and thus the bending moments get smaller. It should be noted that the moments are given in the unit kNm/m and therefore represents an average of the moment distribution in the pile and the surrounding soil.

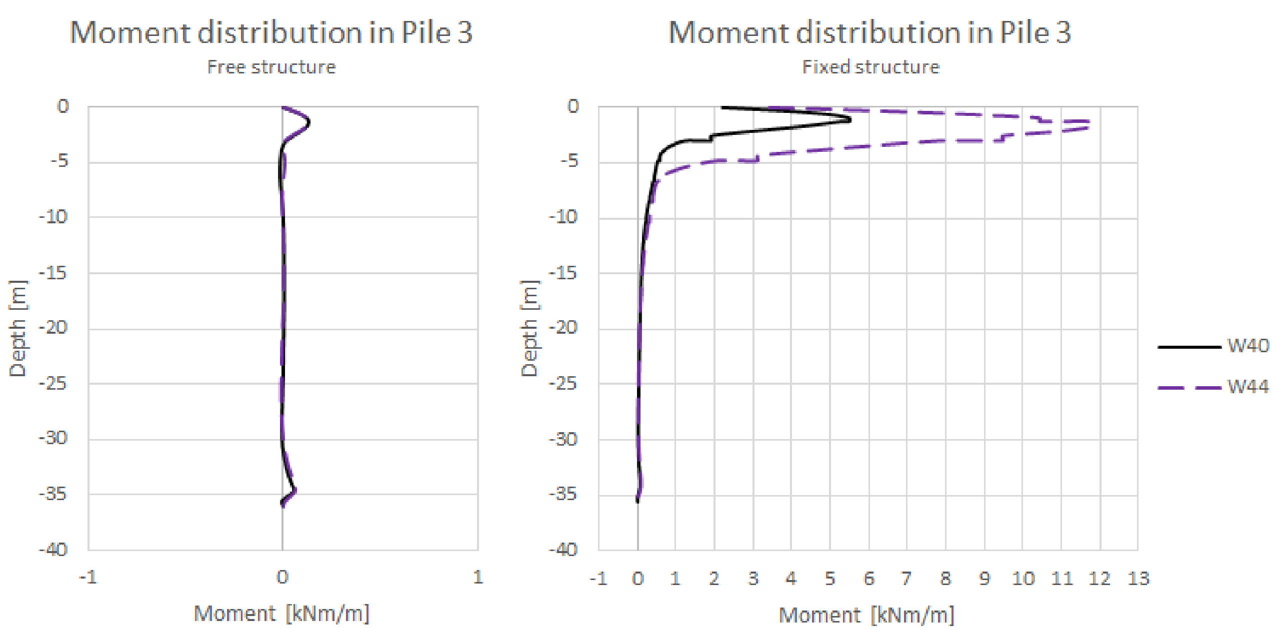


Figure 4.15: Moment distribution in pile 3 for free respectively fixed concrete structure.

As for the bending moments, the shape of the shear forces curves for the fixed and free structure are similar, while the value of the forces are much larger in the fixed case, see Figure 4.16.

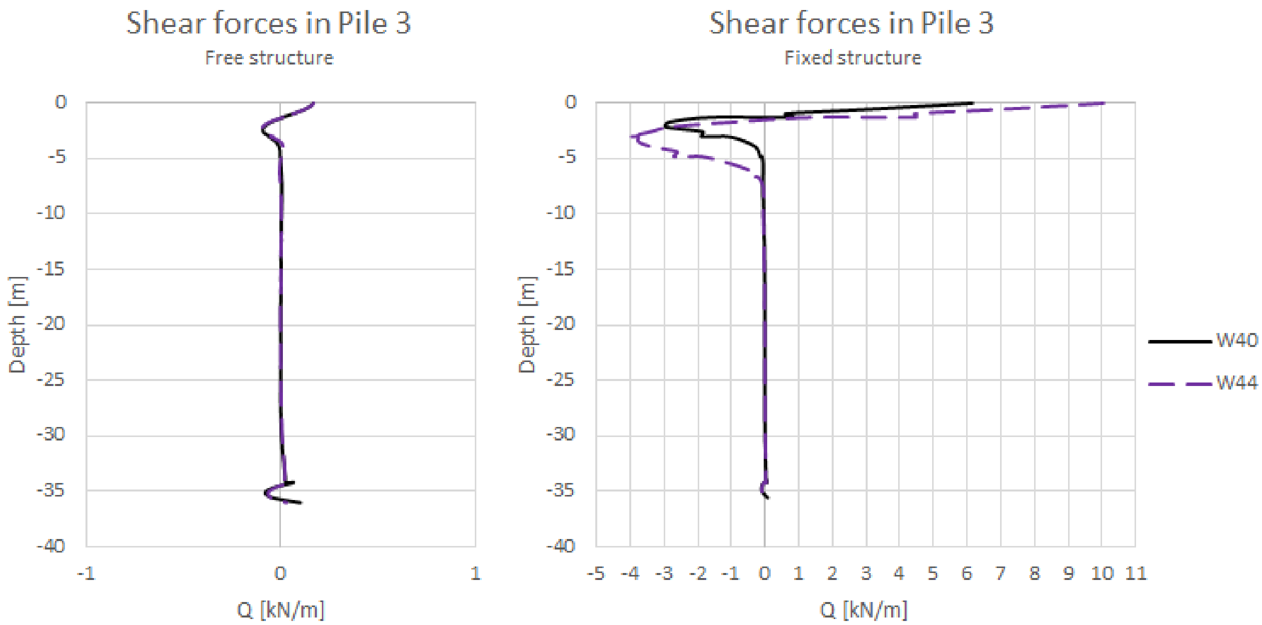


Figure 4.16: Shear forces distribution in pile 3 for free respectively fixed concrete structure.

4.2 Sensitivity analysis of input parameters

During the analysis of the results, some factors that are believed to have considerable effect on the outputs have been detected and are listed below. Sensitivity analysis for each of the factors are presented in the sections below.

- Assign a stiffness to the bridge by using the anchor feature to create a concrete structure that is in between free and fixed.
- Use linear prescribed displacement in the free and fixed case to see the influence of the soil displacement volume and distribution.
- Increase the consolidation period after the bridge loading phase to see the effect on the vertical displacements when the stress conditions are closer to the ones in the real case.
- Fixating the piles in the bottom to account for that the pile tip is stable and stuck in the ground.

4.2.1 Bridge with applied stiffness

A major factor that influences the displacements at the top of the concrete structure turned out to be whether the structure is fixed or free to move in the horizontal direction. The truth was deemed to be somewhere in between the two cases, and therefore a trial was made where the concrete structure was assigned a stiffness by using the anchor feature in Plaxis. The anchors were placed in the middle of the left and right borders of the concrete structure and assigned an EA of 200 GN. The spacing was set to one meter. The displacement in point A and B can be seen in Figure 4.17 and Figure 4.18 and the displacement in pile 3 during phase W40 disp can be viewed in Figure 4.19. The applied stiffness provides rather equal results compared to the fixed case, in particular when viewing the displacement in pile 3. This is reasonable since the applied stiffness is rather high and gives similar displacement in the concrete structure as in the fixed case. The horizontal displacements for the stiff structure are slightly above those measured in field and in the fixed alternative. In the vertical direction, the predicted displacements do not reflect the field measurements that well.

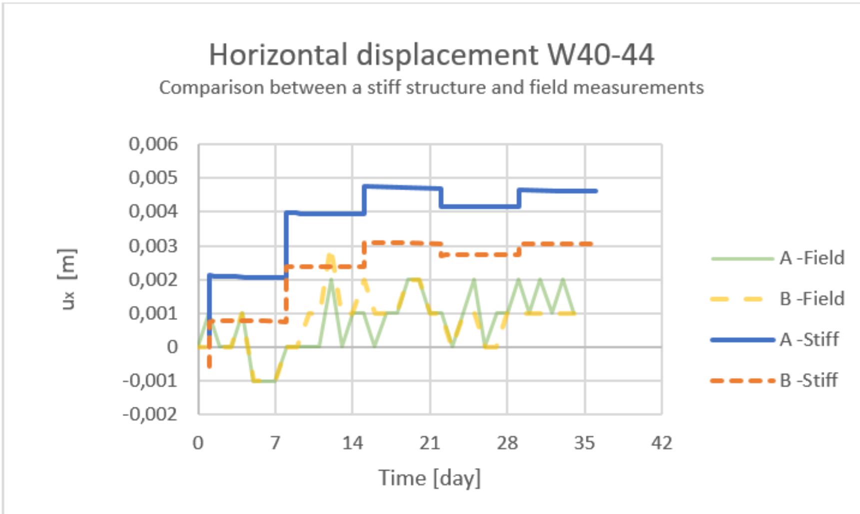


Figure 4.17: Horizontal displacements for the concrete structure when the concrete structure has an applied stiffens of 200 GN.

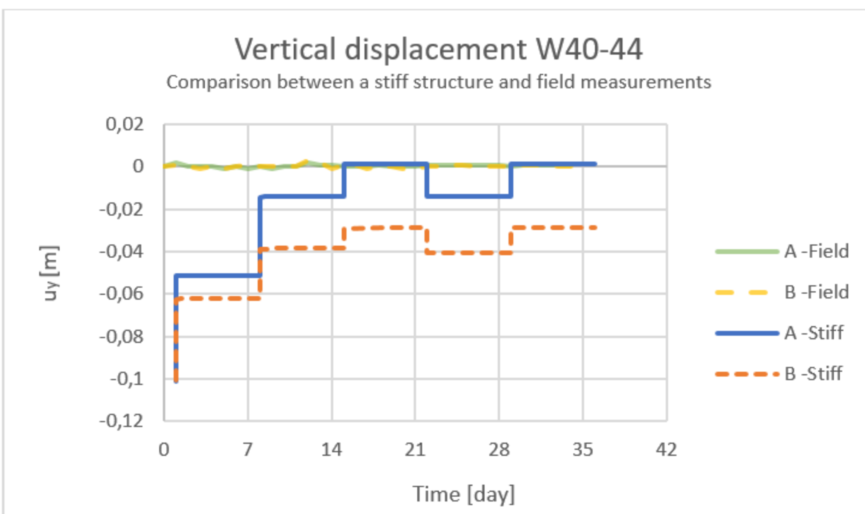


Figure 4.18: Vertical displacements for the concrete structure when the concrete structure has an applied stiffness of 200 GN.

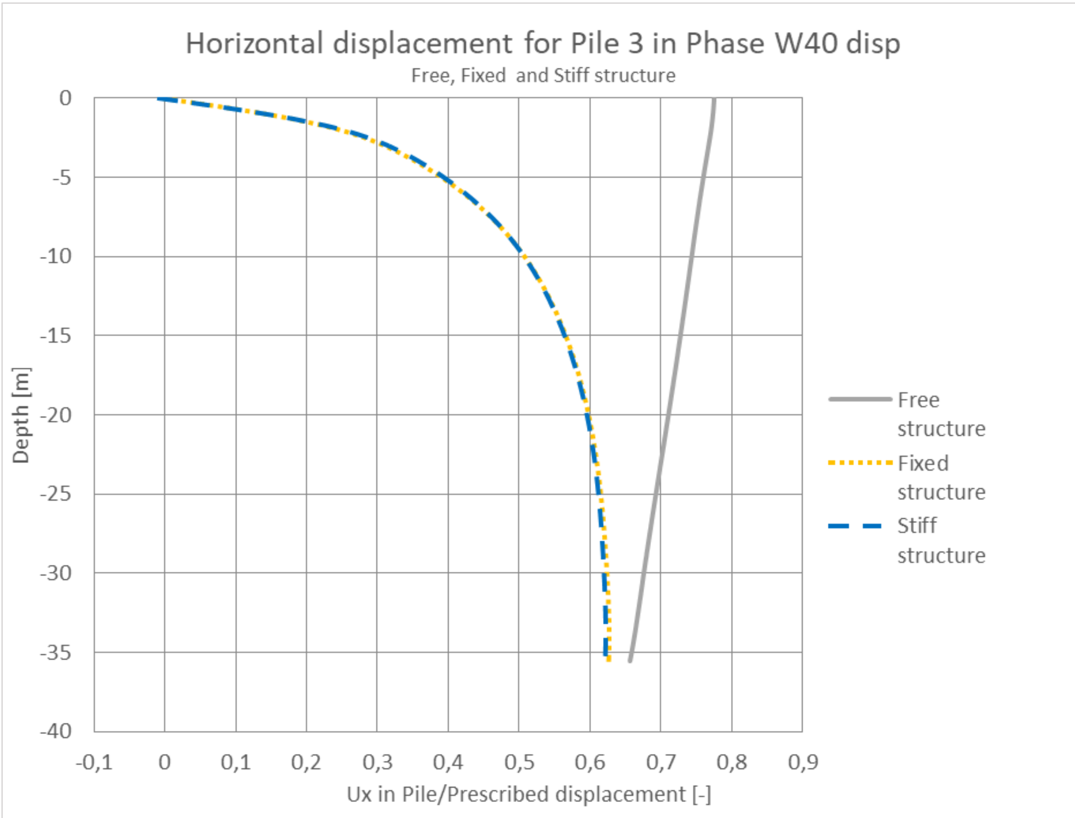


Figure 4.19: Horizontal displacements in pile 3 when using anchors to model a stiff bridge structure.

4.2.2 Linear line displacement distribution

The line displacement was changed from being uniform to decrease linearly with depth. This case was performed to see how dependent the model is on the type of soil displacement assigned. Furthermore, the linear displacement distribution is similar to the one assumed in the Hellman/Rhenman method, see Section 2.3.1. The horizontal pile displacement for free and fixed concrete structures can be seen in Figure 4.20. The linear line displacement gives less soil displacement, and thereby smaller horizontal displacements in the piles, than in the case of a uniform distribution. The shape of the curves for both the fixed and free structure are preserved from the previous case with the uniform distribution. This suggests that the switch from uniform to linear line displacement only affects the magnitude of the displacements and not the direction in which the structure displaces. It is confirmed by the vertical and horizontal displacements for point A and B in which the case of a linear distribution obtains smaller displacements. The proportions between the points compared with previous obtained results are kept, see Figure 4.21 (for vertical and free cases see Appendix H). This means that the model is highly dependent on the value of the applied prescribed line displacement, whether the concrete structure is fixed or free. Therefore, the assumed soil displacement that happens due to the pile installation is a crucial parameter that must be estimated properly in order to obtain accurate results.

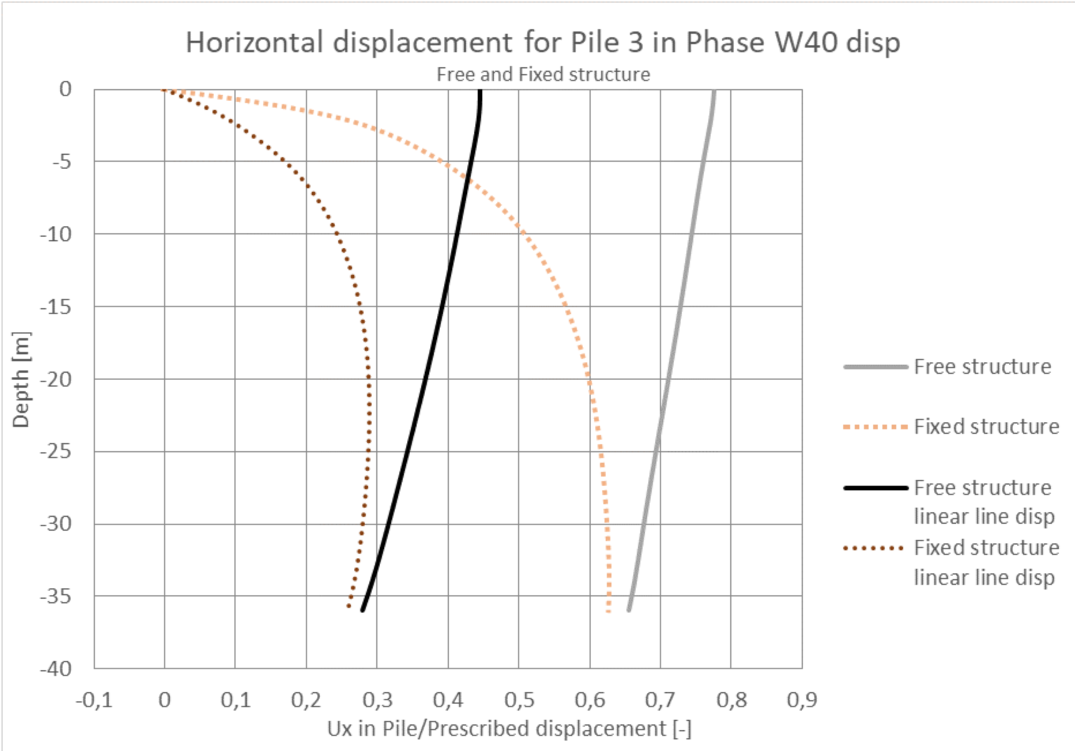


Figure 4.20: Horizontal displacement in pile 3 with linear line displacement distribution.

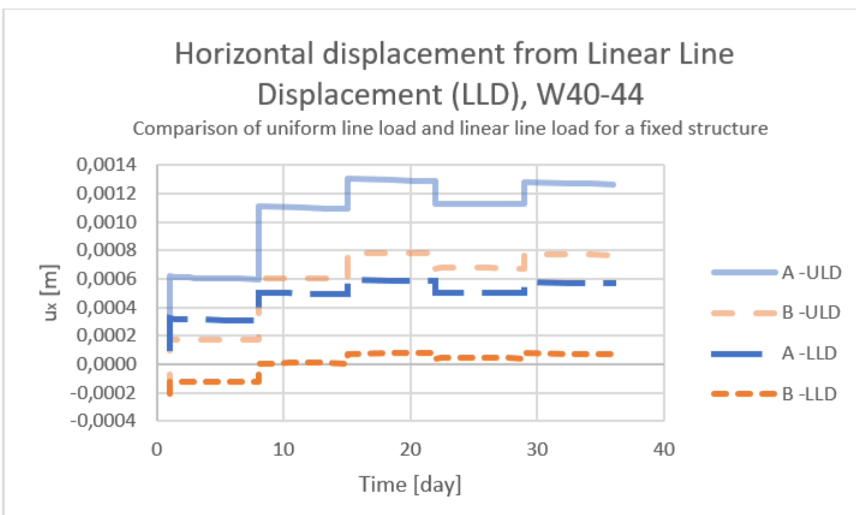


Figure 4.21: Horizontal displacements from applied linear line displacement (LLD) for the concrete structure when the concrete borders are fixed in the horizontal direction. The result is compared with the previous data with prescribed displacements for a uniform line displacement (ULD).

4.2.3 Increased consolidation period for post bridge loading

The consolidation period after the bridge loading were increased from 2000 to 30 000 days to see if this could affect the magnitude of the vertical displacements, as a larger consolidation time would change the stress conditions in the ground. By increasing the consolidation period, the structure is allowed to settle further before the lateral soil displacement is applied. This result in that the vertical displacement are at lower levels when the piles are installed, see Figure 4.22. However, the amount of heave, due to horizontal soil displacement, is still of the same magnitude as in the case of 2000 days of consolidation, and thus increasing the consolidation period does not give more accurate prediction of the vertical displacements.

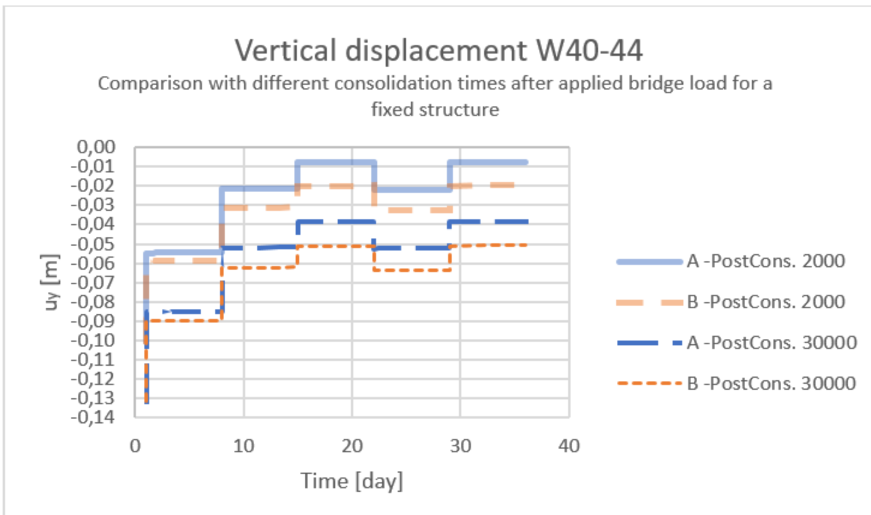


Figure 4.22: Comparison of vertical displacement for a fixed structure when having 2000 days consolidation, respectively 30 000 days consolidation.

4.2.4 Fixed pile tip

The pile tips were fixed to be unmovable in x-direction while the y-direction was set to be free using the point displacement tool in Plaxis. If the y-direction was set to fixed as well, the calculation did not work due to the error "soil body seams to collapse". The horizontal pile displacement for free and fixed concrete structures with fixed pile tips can be seen in Figure 4.23. The predicted displacements in the piles are less, however, the displacements in both vertical and horizontal direction for the measured points, A and B, increases, see Appendix G. This could be the result of that, when the piles do not deflect as much as the overlaying concrete structure, the displacements are no longer even, and therefore the concrete structures gets overturned and the part of the structure that is further away from the source of the displacement (point B) settles more than the one closer to the source (point A).

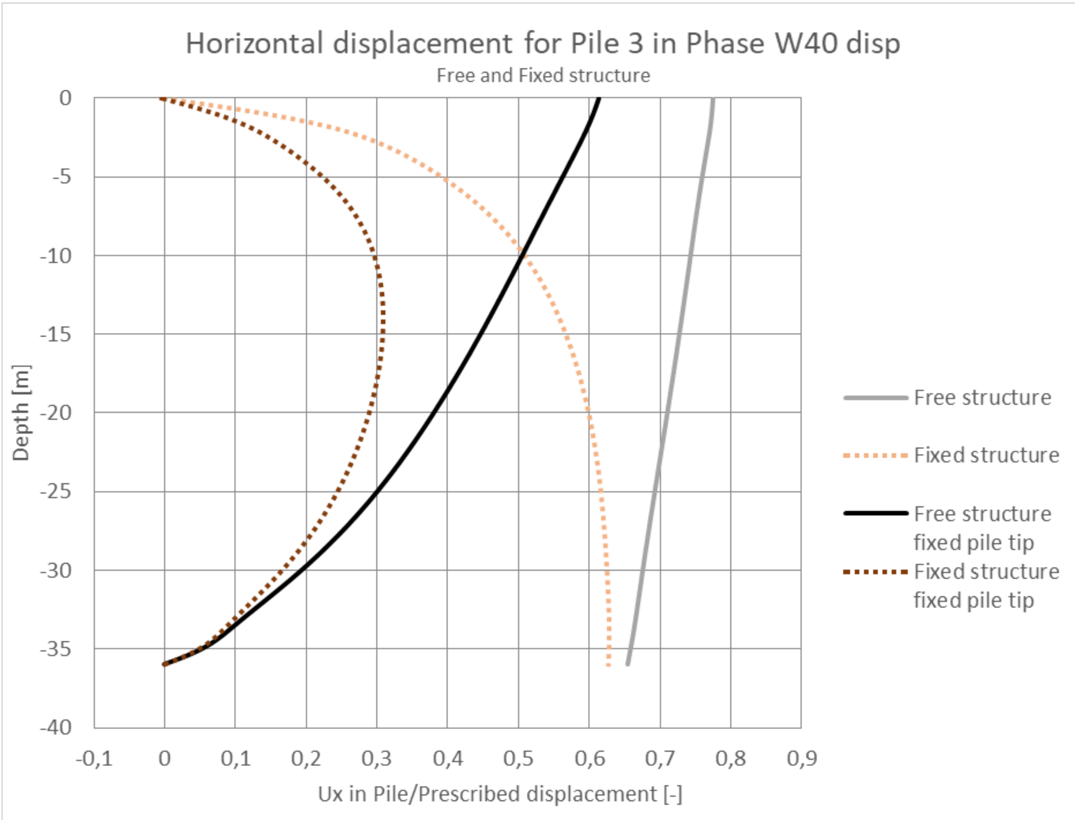


Figure 4.23: Horizontal displacement in pile 3 when the pile tips are fixed.

In conclusion, assigning a stiffness to the bridge gives slightly larger displacements than the fixed case, and thus provides a more conservative solution. However, it can be difficult to assess what values to insert on the parameter EA for the anchor, therefore, it might be easier to use a fixed structure and compensate in the magnitude of the volume displacement to get a conservative solution. The magnitude and distribution of the prescribed line displacement are factors that have a big impact on the results, and thus these parameters must be assessed carefully. A consolidation period is needed to ensure that horizontal displacements are not affected by asymmetrical boundary conditions. However, increased consolidation does not contribute to more realistic prediction of vertical displacements and further investigations are needed to assess these correctly. By fixing the pile tips, smaller horizontal movements are obtained in the piles, whilst the deformation in the superstructure becomes more uneven.

4.3 Modelling issues

One of the biggest constrains with this type of modelling is that the model is done in 2D, which does not allow for modelling the deflections in every possible direction. How the soil moves and interacts with the piles is a real 3D problem. The soil displaces radially and these triggered displacements decreases with distance, and also the soils takes the easiest way around obstacles. In 3D it could have been possible to see how much of the soil from the pile installation that hits existing piles. In 2D an estimation of how much of the displacement of the soil that displace the old piles in a specific spot was done and this is an uncertainty that needs to be considered. When using Plaxis 2D, two different modes of interpreting the third dimension is given, axisymmetric and plane strain. In this study the plane strain model was used which enabled the selection to use the EBR for modelling the existing piles, which was desirable to get the interaction behavior between soil and pile. However, when using a plane strain model, the soil displacement applied using the line displacement tool might have been overestimated since this displacement is assumed to happen around the border, x=0, for all eternity out of the plane.

Another big constrain is that there were several foundation works done at the same time in the area of interest. Thus, the measured values for bridge support II in *Projektnav GG* were probably affected by other activities than just the piles installed in bridge support 13. This limitation was reduced by choosing a time frame in which as little other foundation works were occurring. However, when viewing the results from *Projektnav GG* for horizontal and vertical displacement, it is obvious that the displacements has been affected by other activities as well: Both by other foundations works, but also from measures taken to reduce the soil displacements in the area by performing pre-augering and other preventative measures.

Regarding the measurements obtained in *Projektnav GG*, it is uncertain on how accurate those measurement of the ongoing soil movements are. The exact location on the bridge support which the measuring equipment are installed on are not specified in *Projektnav GG*, and thus it is not certain that the location of point A and B is correctly defined on a local scale in the model. Nevertheless, the obtained results for point A and B do not differ that much in magnitude from each other throughout the different models. Hence, this limitation is deemed to not affect the results as much, compared to other assumptions and constrains that exist in the model.

A limitation of the study is that in reality the piles are tapered and using plate and EBR element did not allow for modelling this geometry. This could affect the strength of the piles, as the piles were assumed to be too thick or too thin at some places. Also, in reality the piles are jointed together, these joints could be the weakest points on the piles. However, due to limitations in the program but also in time this could not be modeled. Thus, in the model the weakest spots on the piles are not included.

An uncertainty is that there could be unknown objects in the ground around the modelled area, which could affect the way the soil moves. In the model it is assumed that there is only soil around the installed piles and the old bridge. If there would be old piles, conduits, pipes and other structures in the ground, these could affect the direction of the soil displacements.

The applied bridge load is estimated by looking at pictures, blueprints and Eurocodes. The load seems reasonable when comparing with expected loads for the new Hisingsbron and the bearing capacity of the tree piles. How this load then is applied and interpreted by Plaxis matters. Since plane strain was used, the load was adapted as a line load with unit kN/m/m, such that the load is applied throughout eternity in the out of plane direction. This implies that the amount of applied load in Plaxis has to be normalized to be accounted as load per meter-width, having a spacing of one meter in the out of plane direction. It is important to perform this normalization of load correctly, in order to obtain the proper weight of the overlaying bridge. If the load is too large or small or applied in such a way that Plaxis interpreters it wrong, it could affect the final result of the displacements.

When modelling soil-structure interaction, interfaces are important. They need to be applied correct and be assigned with proper values to reflect the reality of how the structure and soil moves in relation to each other. In this model a general assumption of R_{inter} at 0.67 was done due to lack of information. The different materials should probably have some variations in the interface reduction strength, although, due to lack of information and due to the instructions in the Plaxis manual, 0.67 was reasonable to use. When observing how the soil and concrete structure moved with and without the interface applied, the applied case was considered to mirror the reality most accurate. For the piles the embedded beam row provided default values for the interface parameters, based on input data for the material, was assumed to be reasonable.

The soil parameters were assumed by using overall data for the entire project and nearby projects which were chosen due to partly the unavailability of site-specific data, and also to avoid the time-consuming process of interpreting field data. Nevertheless, if more site-specific field data could be obtained this could limit the errors of the result.

As always when using a FE software, it is important to reflect over what to put in in the program, if wrong data are inserted the result becomes wrong. Hence, care must be taken with what to put in the model. The program only calculates based on the input and cannot decide which data that is reasonable or not. Engineering judgment are needed to analyze the result and reflect if it is reasonable or not.

5 Further investigations

To enable more accurate calculations of the lateral soil displacements in the area, it would be preferable to create a 3D model in order to include more of the site-specific criterion than those allowed in a 2D software. By using this type of modelling, perhaps the source of the soil displacement could be modeled as a point source instead of a plane/line source as it becomes in the 2D case. The 3D model could either be performed in a FEM program or as a physical model.

The model could be further improved by collecting more detailed information about which foundation works that has been conducted at a more detailed time frame. This would enable modelling of the soil displacements as an average per day, which is the same time frame as the measurements are reported in *Projektnav GG*.

Vertical displacements were not properly assessed by using the modelling procedure presented in this report, since the heave was overestimated. It could therefore in a further investigation be worth to consider modifying the model to account for the vertical displacement due to pile installation in a more accurate manner.

The modeled area is just a tiny part of a bigger area in which several projects are performing activities that affects the soil displacements. It could be interesting to change to a macro perspective to see how the entire area is affected by all the ongoing foundation works. However, such an analysis is most likely time-consuming and perhaps to complex too model in a FEM program.

6 Conclusions

In this project the effects of the installation of a pile group on existing neighbouring piles was investigated, in terms of horizontal and vertical displacements, shear forces and bending moments. The piling work for the new Hisingsbron was used as a case study. The prediction of horizontal displacements was most accurate, whereas the prediction of vertical displacements, bending moments and shear forces still need to be improved.

The modelled study area is a very complex case which is not fully documented. As a result the numerical model required some well-judged assumptions that impacted the reliability of the output results. Therefore, rather than performing calculations closest to the largely unknown real case limiting cases were studied instead, i.e. both fixed and free moving concrete pile cap. In the current case with a stiff superstructure a fixed or stiff structure provides the most reasonable results.

The magnitude of the applied horizontal soil displacements from a pile group were calibrated against experimental data and 3D modelling. A uniform distribution with depth is recommended as a conservative optimum. The proposed method, which best resembles cavity expansion provided rather accurate results for the horizontal displacement. Nevertheless, to obtain more realistic soil displacement predictions in the vertical direction some modifications of the method need to be implemented, e.g. by adding a vertical component to the prescribed displacements.

Finally, some of the soil kinematics due to pile installation observed in the literature study was reproduced in the current analyses. Hence, this supports the presented modelling approach for calculating the effects on existing structures from soil displacements.

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A Verification model, Moment and shear forces along pile

The following charts shows moment (Figure 1) and shear forces (Figure 2) along the pile in the verification test. The value of the moment and shear forces of the plate element has been reduced with a factor equal to the diameter of the pile (0.01898) since the plate element is perceived as a wall element in Plaxis 2D plane strain.

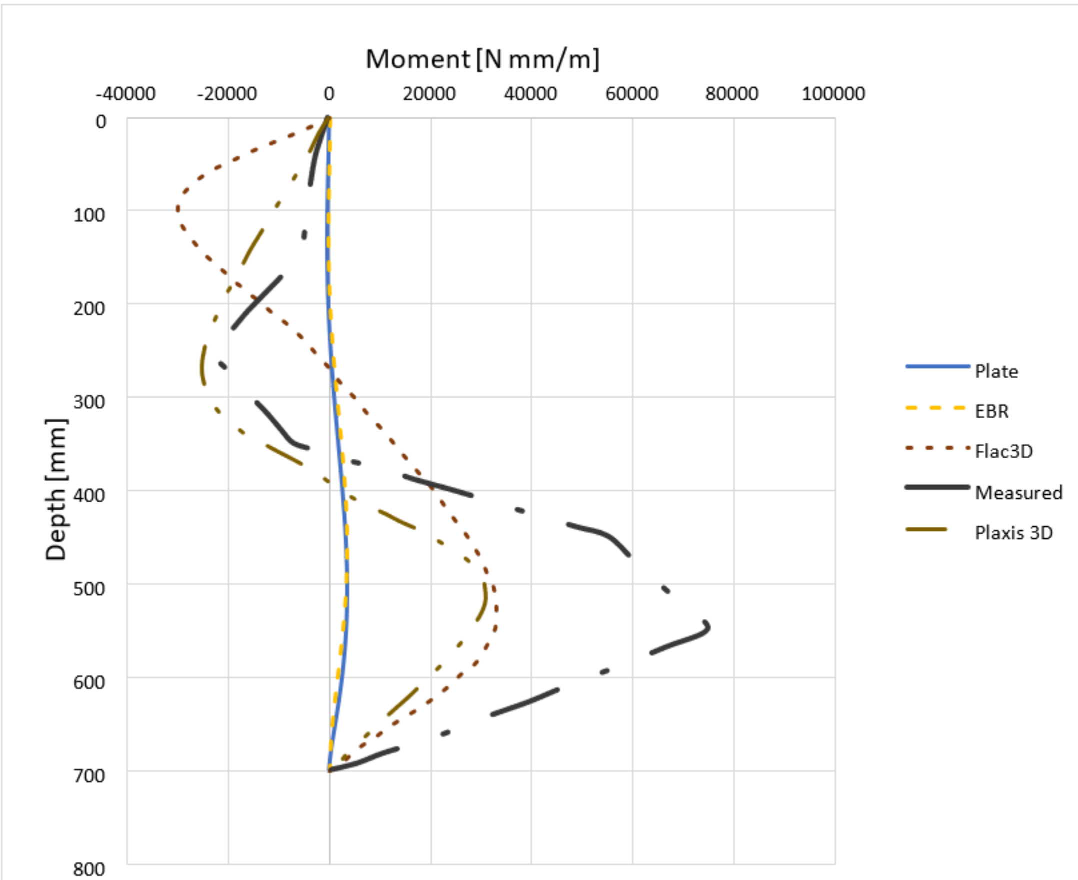


Figure 1: Bending moment in pile. Data from (Al-Abboodi, Toma-Sabbagh, & Al-Jazaairry, 2015) for Plaxis 3D, from (Ghee & Guo, 2010) for FLac3D and from (Ghee, 2009) for measurements.

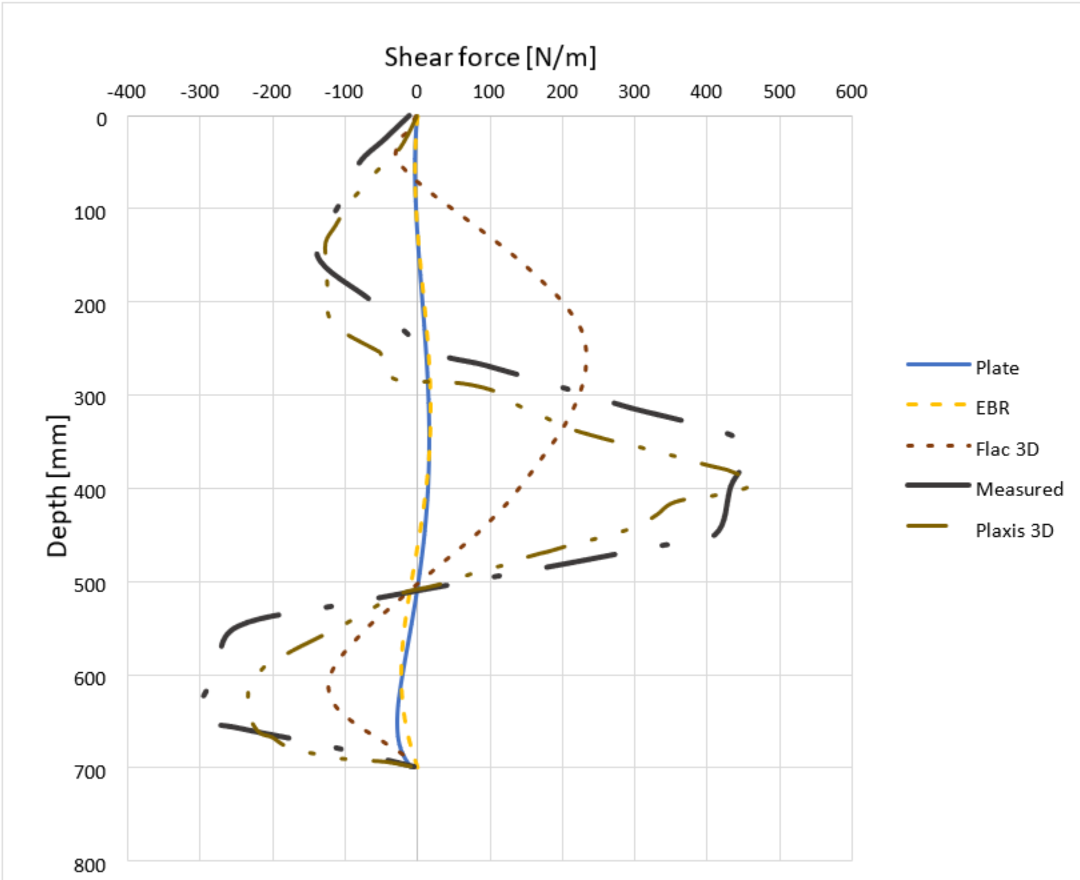
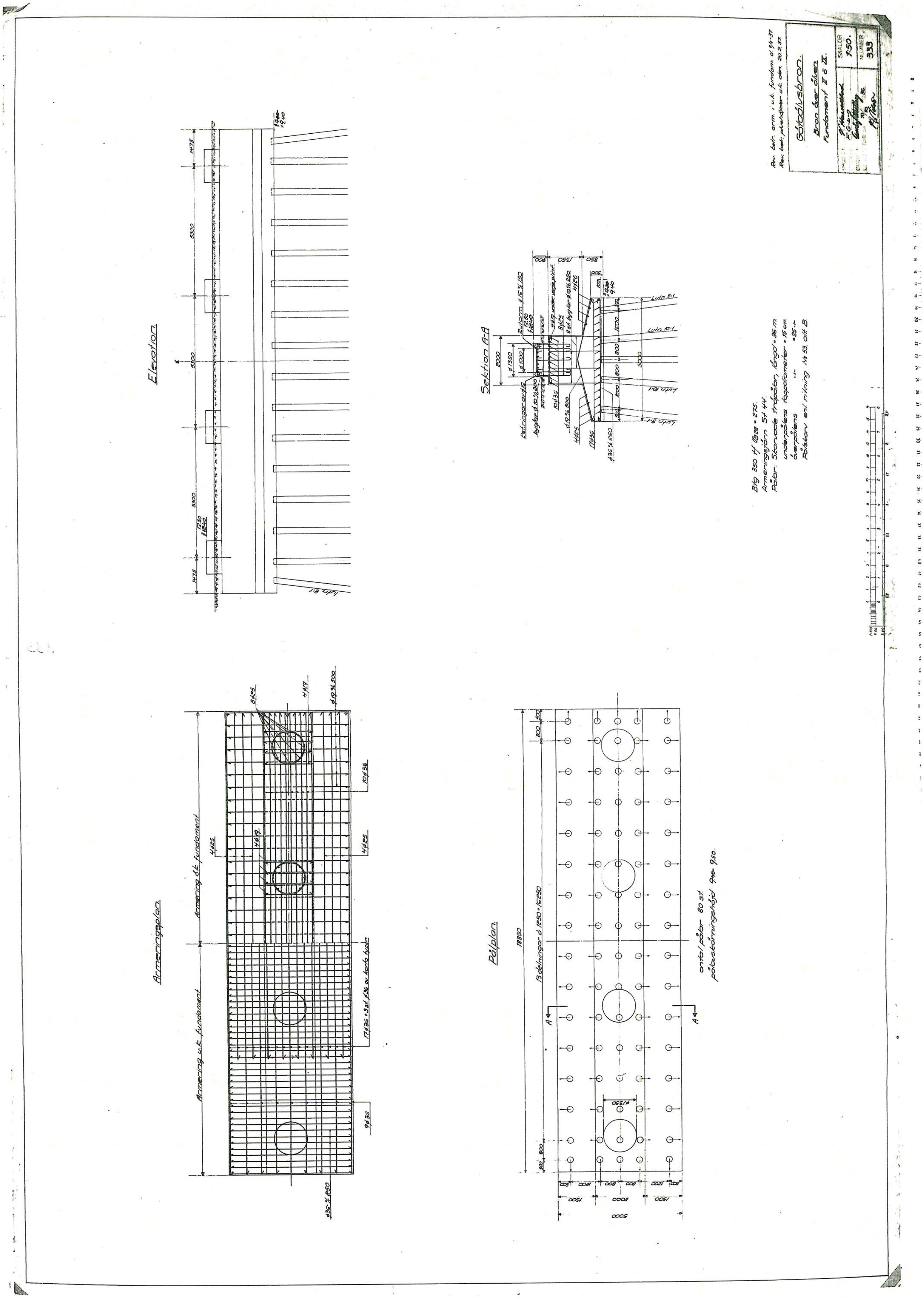


Figure 2: Shear force in pile. Data from (Al-Abboodi, Toma-Sabbagh, & Al-Jazaairry, 2015) for Plaxis 3D, from (Ghee & Guo, 2010) for FLac3D and from (Ghee, 2009) for measurements.

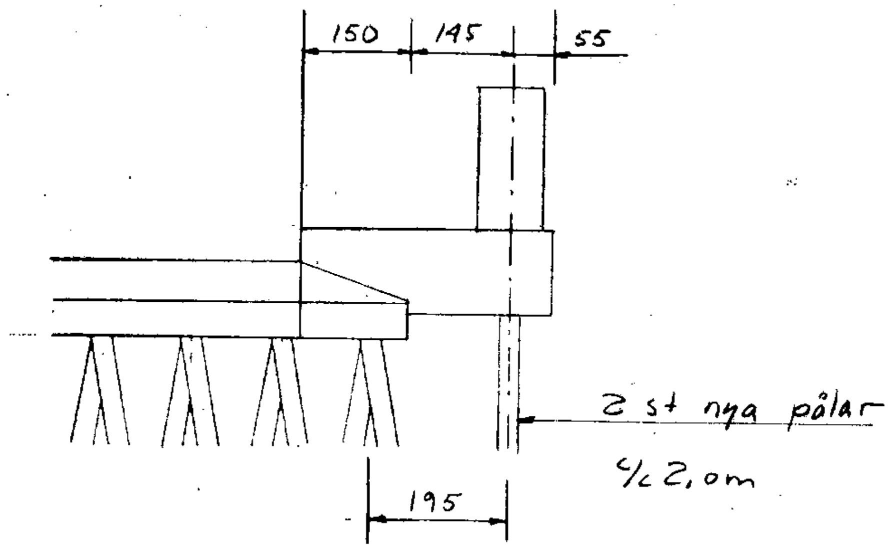
B Blueprints of the Götaälvbron

B.1 Blueprint of piles in bridges support II and IX


Elevation
Sektion A-A
Armeringsplan
Pålplan
Götaälvsbron
Bron över älven

B.2 Sketch of the pricipal extension of the Götaälvbron

Tillbyggnad av fundamentet



Befintliga pålar 114 st i lutn 6:1 $\cos v = 6/\sqrt{37}$

1 st vertikal $= 0,9864$

Nya pålar 4 st vertikala

$\Sigma \cos^2 v = 114 \cdot 0,973 + 5 \cdot 1,00 = 116$

Beräkning av pållaster

Pålgruppens utseende enl. Göteborgs Hamns ritning nr 339

Pålbelastningar av en vertikalkraft V i pålcentrum

Vertikala pålar $P = V/116 = 0,00862\ V$

Sneda pålar $P = V/116 \cdot 6/\sqrt{37} = 0,00850\ V$

C Calculation of shaft and base resistance

Calculation of skin and base resistance

Geometries

Pile diameter	0,2	m
Pile length	36	m
Maximum force per pile	0,250	kN

Amount of pile rows

Road	5
Sidewalk	2

Amount of piles per row

Road	16
Sidewalk	2
Combined row	18

Total force for the element

Total force road	20,000	MN
Total force sidewalk	1,000	MN

Total force for one pile row

Road	4,000	MN
Sidewalk	0,500	MN
Combined row	4,500	MN

Skin resistance

The skin takes 90 percentage of the load	0,900	
Total skin resistance entire pile row	4,050	MN
Skin resistance for one pile	0,225	MN
Skin resistance for one pile per m2	0,010	MN/m2
Skin resistance for one pile at 1m	0,010	MN/m
Skin resistance for one pile at 36m	0,358	MN/m

Base resistance

The base take 10 percentage of the load	0,100	
Total base resistance entire pile row	0,450	MN
Base resistance for one pile	0,025	MN

D Calculation of effective pile volume

Effective pile volume of installed piles

Table 1: Pile properties.

#Piles	52	
#Pile rows	4	
#Piles columns	13	
L	96	m
D	0,4	m
RF, cylindrical piles	0,5	
V disp soil/pile	6,03	m^3

Table 2: Calculation of predescribed displacement per week.

Week	#installed piles	V displaced soil [m^3]	Equivalent Disp in x-direction in Plaxis 2D [m]
40	1	6,03	0,14
41	3	18,10	0,24
42	4	24,13	0,28
43	3	18,10	0,24
44	4	24,13	0,28

E Calculation of the bridges self-weight

Calculation of weight on support II

Scale	7	cm	5,3	m	0,76	m/cm
Distance south	40,5	m				
Distance north	42,0	m				
Length of bridge element	41,25	m				

Road			Main beams			Other beams		
Quantity Road	1		Quantity	4		Quantity	3	
Road Width	27	m	Distance to next	5	m	Distance to next	5	m
			Height	3	m	Height	1	m
			Width	0,1	m	Width	0,04	m
			Total volume	41	m3	Total volume	6	m3
Crossmembers			Timber reinforcement			Coating		
Quantity	6		Quantity	1		Quantity	1	
Distance to next	7	m	Distance to next -			Height	0,2	m
Height	1	m	Height	0,01	m	Width	20	m
Width	0,05	m	Width	27	m	Total volume	165	m3
Total volume	15	m3	Total volume	11	m3			
Cylindrical columns								
Quantity	4							
Length	10	m						
Radius	0,2	m						
Thickness	0,2	m						
Total volume	10	m3						

Sidewalk

			Main beams			Coating		
Quantity	2		Quantity	2		Quantity	2	
Side walk width	3	m	Distance to next	1	m	Height	0,05	m
			Height	1	m	Width	3	m
			Width	0,05	m	Total volume	12	m3
			Total volume	10	m3			

Railing			Cylindrical columns		
Quantity	4		Quantity	2	
Length	41	m	Length	10	m
Total lenght	165	m	Radius	0,1	m
			Thickness	0,2	m
			Total volume	1	m3

Total volumes for the road

Total volume timber	11	m3
Total volume coating	165	m3
Total volume steel	72	m3
Total railing lenght steel	0	m

Total volumes and lengths for the sidewalk

Total volume timber	0	m3
Total volume coating	12	m3
Total volume steel	12	m3
Total railing lenght steel	165	m

Densities

Density timber	6000	N/m3
Density coating	24000	N/m3
Density steel	77000	N/m3
Force from railing	500	N/m

Traffic load

4435200	N

Total weight road

For the entire element	14026962	N
	14	MN
Force for one plinth	3506741	N
	4	MN
Force per m2	2449888	N/m2
	2450	kN/m2
Diamter of plinth	1,35	m
Line load	3307	kN/m
Reduction due to rows	661	kN/m

Total weight sidewalk

For the entire element	1270324	N
	1	MN
Force for one plinth	635162	N
	1	MN
Force per m2	668358	N/m2
	668	kN/m2
Diamter of plinth	1,1	m
Line load	735	kN/m
Reduction due to rows	368	kN/m

F Displacements charts for free, fixed and field alternatives

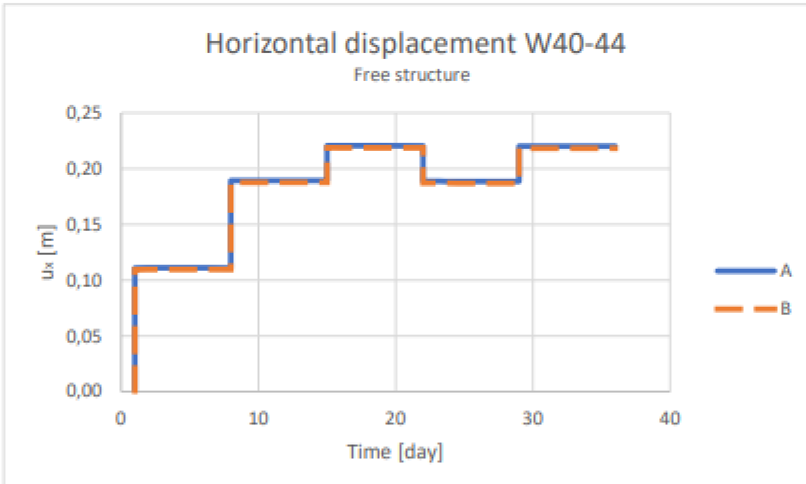


Figure 1: Horizontal displacement for the concrete structure when the concrete borders are free to move in the horizontal direction.

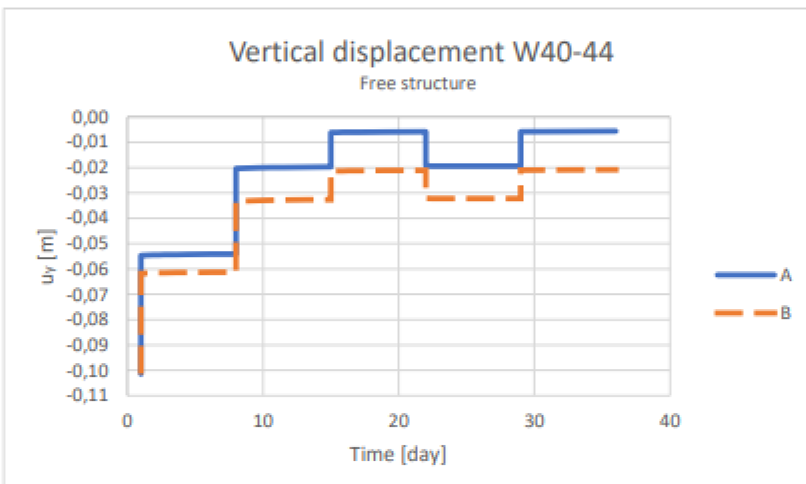


Figure 2: Horizontal displacement for the concrete structure when the concrete borders are fixed in the horizontal direction.

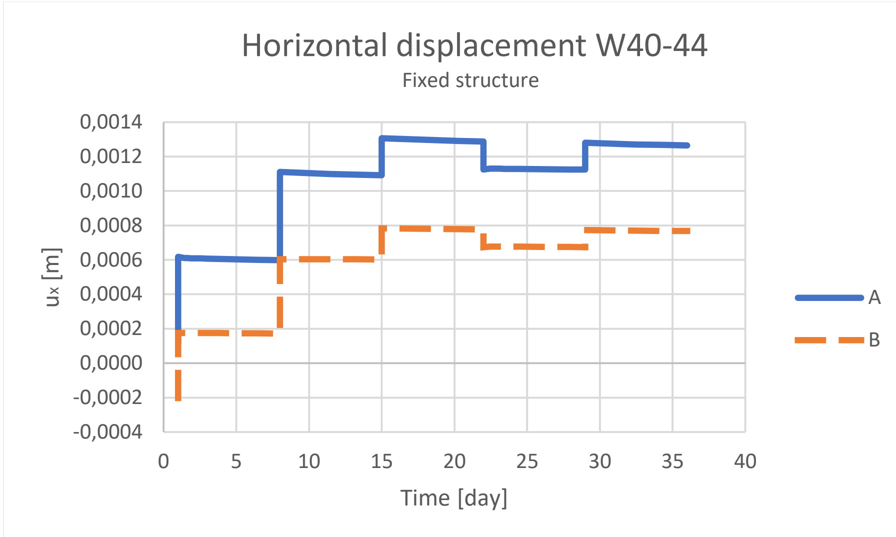


Figure 3: Vertical displacement for the concrete structure when the concrete borders are free to move in the horizontal direction.

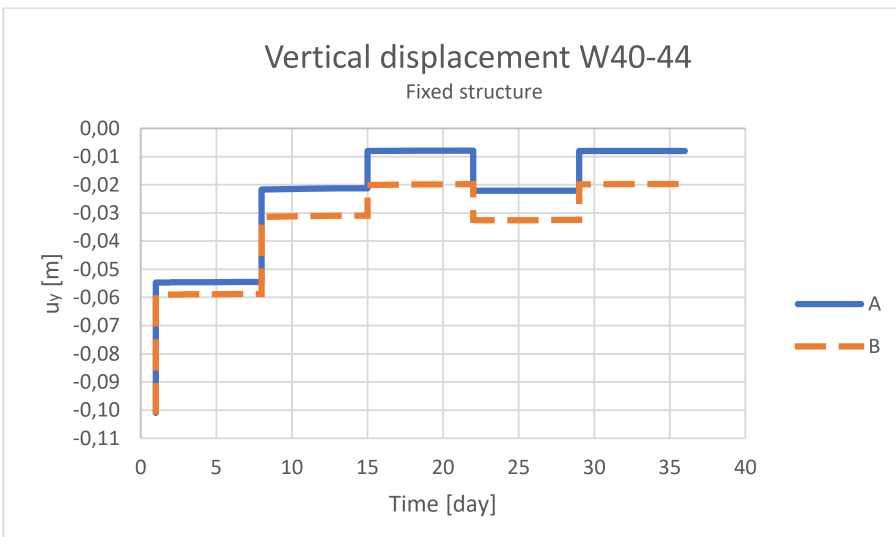


Figure 4: Vertical displacement for the concrete structure when the concrete borders are fixed in the horizontal direction.

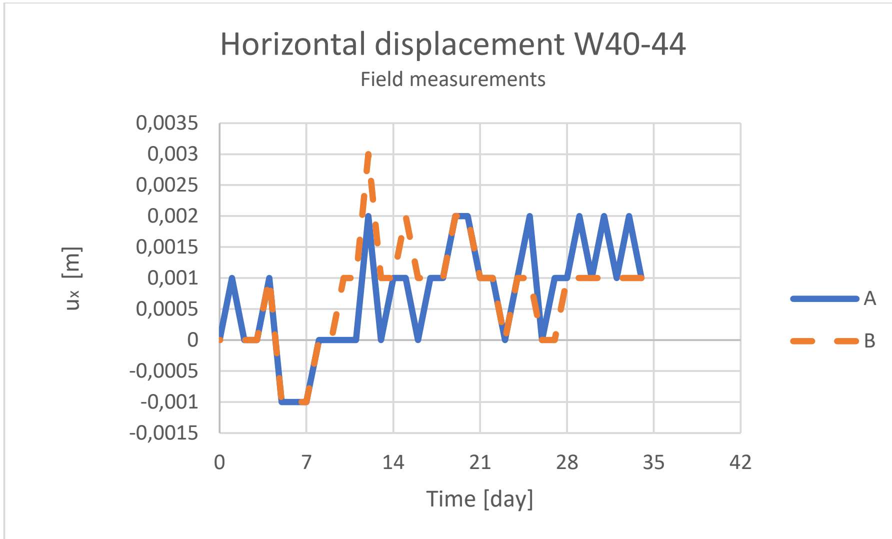


Figure 5: Measured horizontal displacement, from the field data, for the concrete structure. Data taken from Projektnav GG.

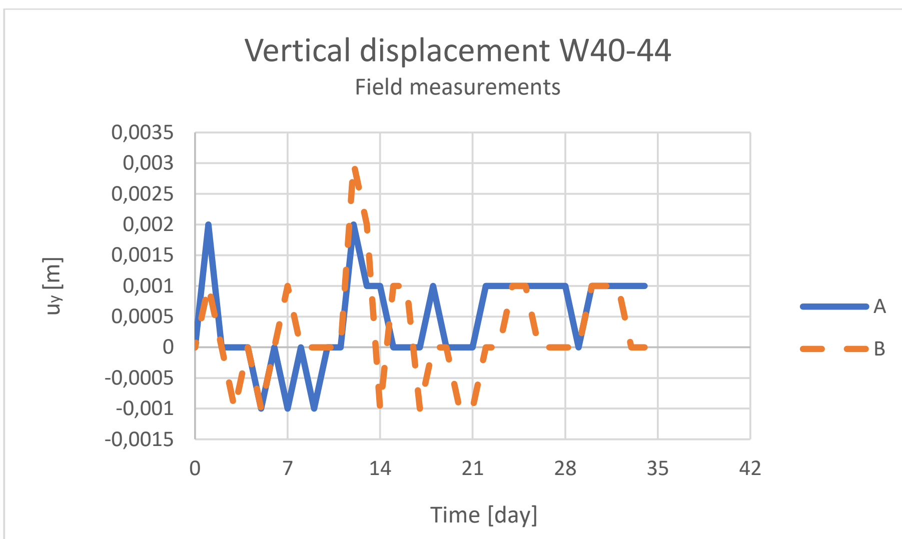


Figure 6: Measured vertical displacement, from the field data, for the concrete structure. Data taken from Projektnav GG.

G Difference in displacements between free pile tips and fixed pile tips

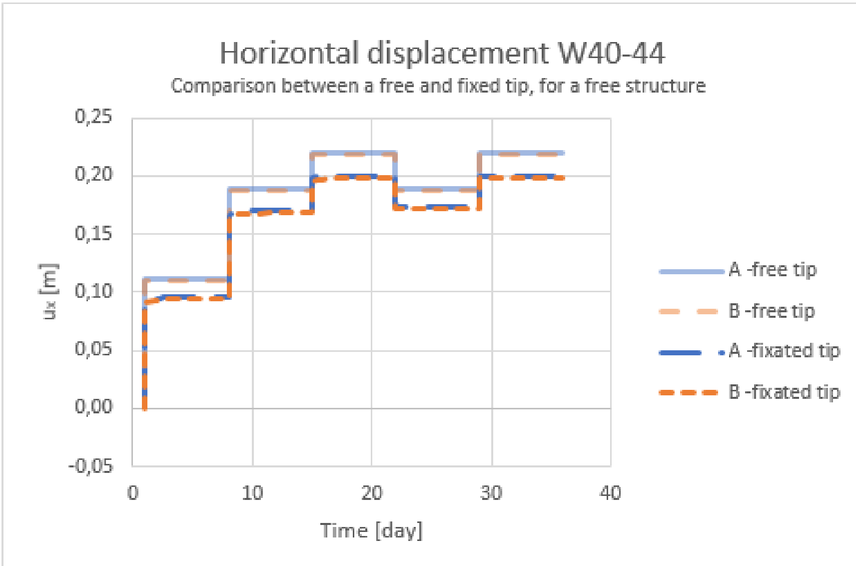


Figure 1: Horizontal displacement for the concrete structure when the concrete borders are free to move in the horizontal direction and the pile tips are fixed in horizontal direction at the bottom. The result is compared with the previous data when the tips were free.

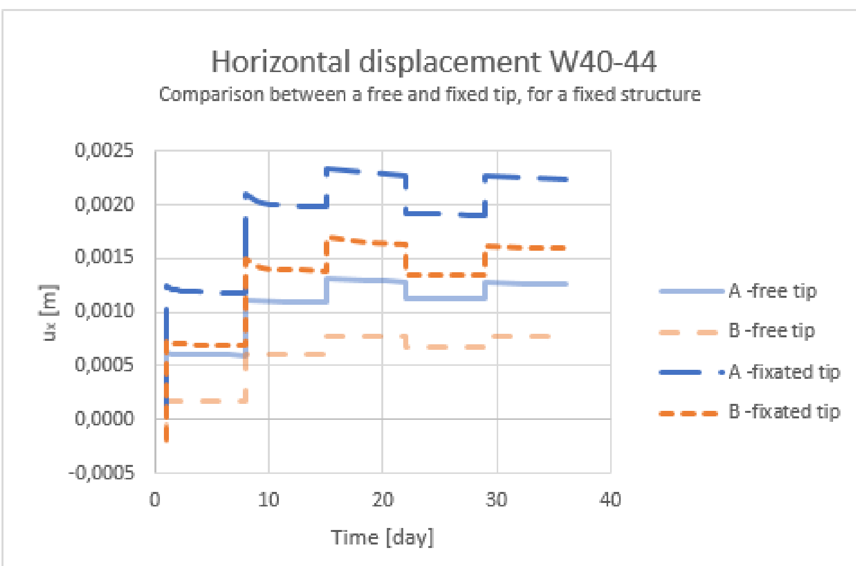


Figure 2: Horizontal displacement for the concrete structure when the concrete borders are fixed in the horizontal direction and the pile tips are fixed in horizontal direction at the bottom. The result is compared with the previous data when the tips were free.

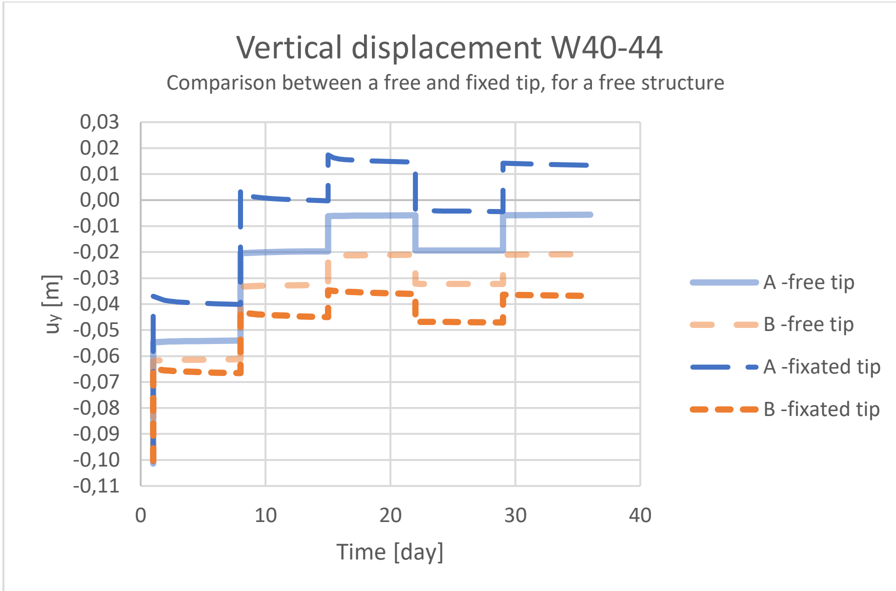


Figure 3: Vertical displacement for the concrete structure when the concrete borders are free to move in the horizontal direction and the pile tips are fixed in horizontal direction at the bottom. The result is compared with the previous data when the tips were free.

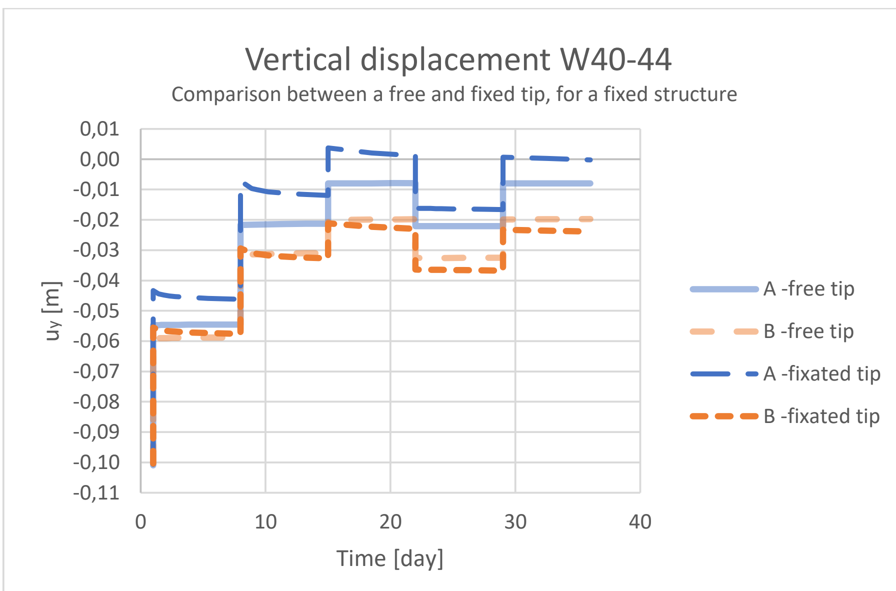


Figure 4: Vertical displacement for the concrete structure when the concrete borders are fixed in the horizontal direction and the pile tips are fixed in horizontal direction at the bottom. The result is compared with the previous data when the tips were free.

H Difference in displacements when using uniform line displacement and linear line displacement

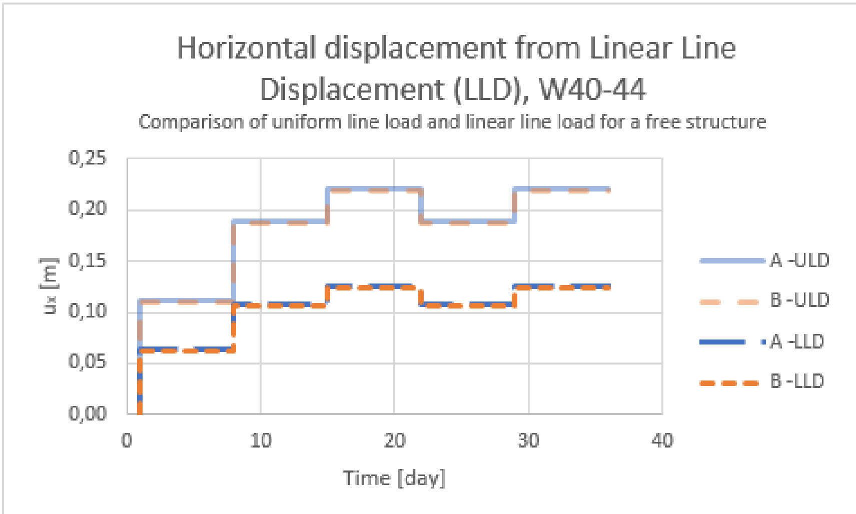


Figure 1: Horizontal displacement from applied linear line displacement, for the concrete structure when the concrete borders are free to move in the horizontal direction. The result is compared with the previous data when the displacement came from a uniform line displacement instead.

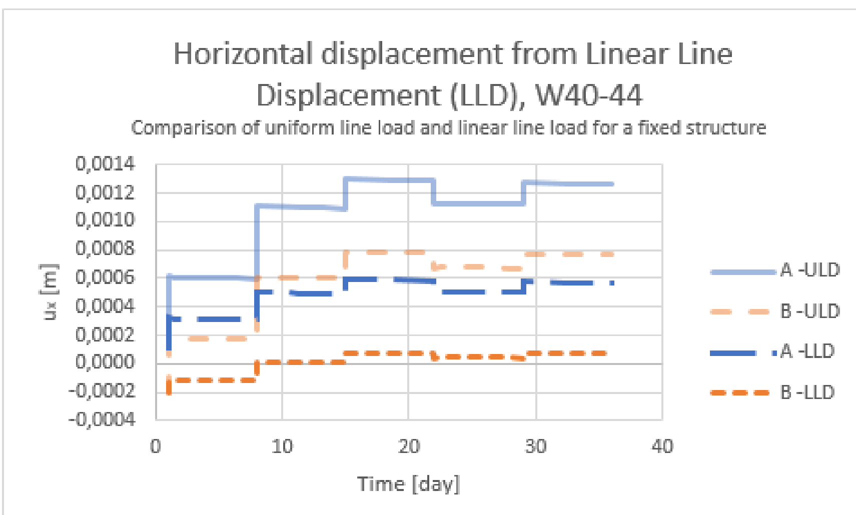


Figure 2: Horizontal displacement from applied linear line displacement, for the concrete structure when the concrete borders are fixed in the horizontal direction. The result is compared with the previous data when the displacement came from a uniform line displacement instead.

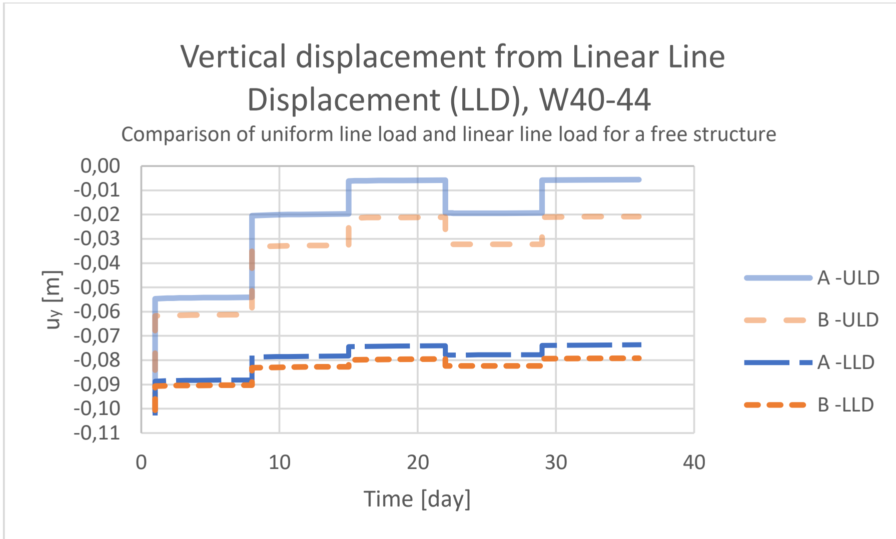


Figure 3: Vertical displacement from applied linear line displacement, for the concrete structure when the concrete borders are free to move in the horizontal direction. The result is compared with the previous data when the displacement came from a uniform line displacement instead.

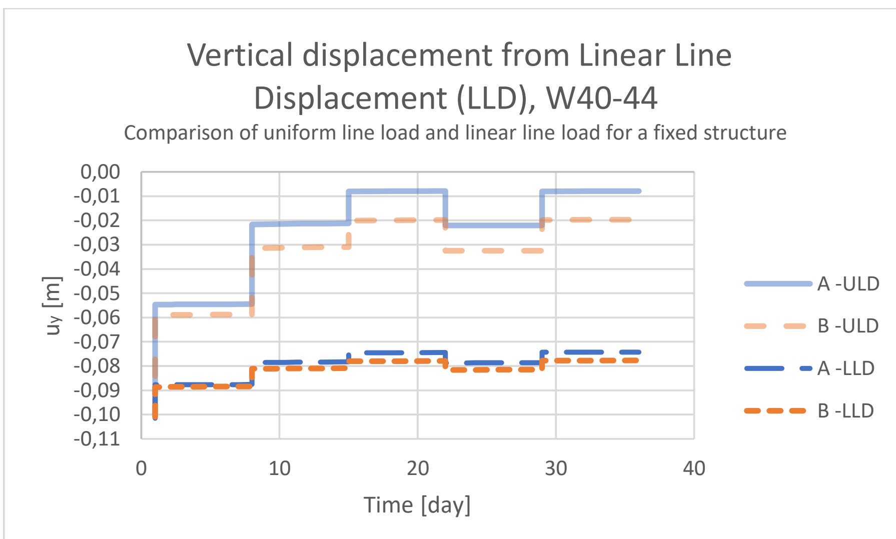


Figure 4: Vertical displacement from applied linear line displacement, for the concrete structure when the concrete borders are fixed in the horizontal direction. The result is compared with the previous data when the displacement came from a uniform line displacement instead.