A Case Study of Heave of Pile-Supported Structures Due to Pile Driving in Heavily Overconsolidated Very High Plasticity Palaeogene Clay

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ABSTRACT
The process of pile driving in high plasticity clays is commonly known to result in full displacement of the soil thereby causing vertical and lateral movements in the ground surrounding the pile. These movements may potentially lead to significant heave and damage of adjacent structures and foundations even when these are supported on piles. This was observed to be an issue during construction of Aarhus Story, an extension to the existing open-air museum Den Gamle By in Aarhus. In this paper the detailed case is presented.

The case involves pile driving for a new 3-story building with a basement structure, which is to be erected in-between and in close proximity to two existing buildings. Pile driving is carried out from the base of a deep basement excavation. Both existing buildings are recent, and both comprise basement structures with pile-supported basement slabs. Hence, all three buildings are supported on piles, and in all cases the piles are driven into heavily overconsolidated very high plasticity clay.

This case study presents a detailed account of the observed gradual heave of the adjacent buildings as pile driving proceeds for the new building. On this basis different parameters are identified which influence the heave of the adjacent buildings. Finally, the results are compared with an analytical model from literature, and it is discussed whether it can be used to predict heave of pile-supported structures.

Keywords: Case study, high plasticity Palaeogene clay, deep excavation, pile driving, heave of pile-supported structures.

1 INTRODUCTION

1.1 Background

The use of driven piles for heavily loaded structures has for long been the favoured foundation solution in many construction projects in Denmark, when permitted by the ground conditions. The speed of construction and hence lower costs as compared to the installation of bored piles is often the main reason for the selection of a driven pile solution.

The process of pile driving in high plasticity clays is commonly known to result in full displacement of the soil. The soil displacement causes vertical and lateral movements in the ground surrounding the pile. These movements may potentially lead to significant heave and damage of adjacent structures and foundations even when these are supported on piles. This was observed to be an issue during construction of Aarhus Story, an extension to the existing open-air museum Den Gamle By in Aarhus. In this paper the detailed case is presented.

The influence of pile driving on existing pile-supported structures is a complex matter, which has only to a limited extend been investigated in past studies. Hence, the presented case study will help to shed light on the issue and may provide further in-sight into the complex mechanism, which occur in high plasticity clays in connection to pile driving.

1.2 Ground movement in connection to pile driving

When prefabricated reinforced concrete piles or closed ended tubular steel piles are driven into very high plasticity clay the short-term soil displacement will be equal to the volume of the piles, since the clay behaves as incompressible under the fast driving process and due to the very low permeability of the saturated clays.

There are different theories on how the pile driving affects the soil. Early theories derived from field-testing concluded that the displacements where mainly vertical (Hagerty and Peck, 1971). Further analysis has been carried out by Massarsch (1976) using model- and field-tests with pile groups. Wersäll and Massarsch (2013) concluded based on these results and Finite Element Analysis made by Edstam (2011) that pile driving causes mainly lateral movements and that vertical movements can be neglected close to the driven pile. The soil displacement pattern around a driven pile is illustrated in Figure 1.

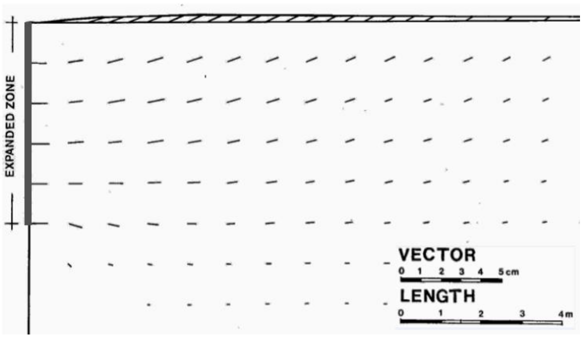

Figure 1 Soil displacement pattern around a driven pile, showing displacement vectors (Wersäll and Massarsch (2013)).

The ground movements in connection to a single pile are equal in all directions assuming uniform ground conditions. When several piles are driven in a pattern (e.g. pile rows or groups), the driving direction has an influence on the heave. Ground heave is greater in front of the pile group in the direction of pile driving, and is reduced adjacent to the location of the piles first driven (Dugan and Freed, 1984 and Wersäll and Massarsch 2013).

Wersäll and Massarsch (2013) have proposed an analytical model to estimate the heave of the ground surface in front of a pile row driven into soft clay. They suggest that the magnitude of heave is controlled by the cross sectional areas of the piles, the pile spacing and the distance from the pile row. These parameters are taken into account by an equivalent soil displacement factor, u_{eq} that corresponds to the cross section area of one-quarter pile divided by the pile spacing.

$$u_{eq} = \frac{\frac{1}{4}a}{c} \qquad (1)$$

Where a is the cross section area of one pile and c is the pile spacing.

The pile length on the other hand is suggested to control the zone of influence; defined as the distance beyond which heave is negligible, and also the distance to where maximum heave occurs.

1.3 Heave of pile-supported structures due to pile driving

Existing pile-supported structures located adjacent to an area of pile driving are likely to have a great impact on the vertical movement of the ground, and visa versa the ground movement from pile driving will have an impact on the vertical movement of the pile-supported structure. The heave of pile-supported structures is complex and is expected to be influenced by several factors including the weight of the structure, the length of existing piles and the ground properties. These factors are, in addition to the factors mentioned previously, controlling the ground movement around driven piles. All these factors will influence the impact that pile driving has on existing pile-supported structures.

A series of case studies made by Dugan and Freed (1984) have highlighted the complexity of this problem. Survey points were placed both on the ground and on buildings. The measurements show as expected that the heave of pile-supported buildings is significantly smaller than the heave of the unrestrained ground surface. The restraining effect of adjacent pile-supported buildings on heave movements is therefore relevant to consider.

At present there exist no models, which can accurately predict the heave of pile-supported structures located adjacent to pile groups driven into clays.

2 CASE STUDY – AARHUS STORY

2.1 Project description

The Aarhus Story project involves pile driving for a new 3-story building with a basement structure, which is to be erected in-between and in close proximity to two existing buildings; Plakatmuseet (Building A) and Den Moderne By (Building B), as shown on the site plan in Figure 2.

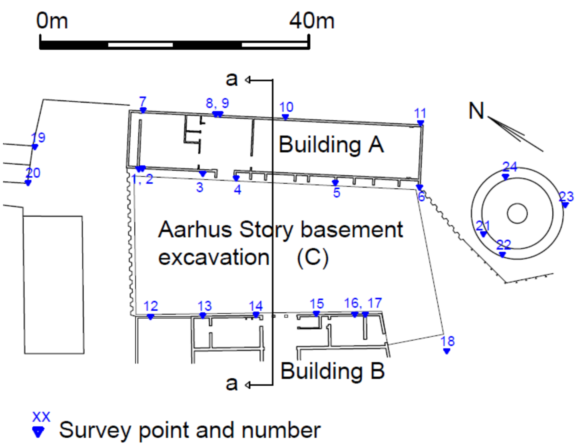

Figure 2 Site plan showing the excavation of Aarhus Story and the location of survey points.

Pile driving is carried out from the base of a deep basement excavation. Both existing buildings are recent, and both comprise basement structures with pile-supported basement slabs. Hence, all three buildings are supported on piles, and in all cases the piles are driven into heavily overconsolidated very high plasticity clay, as illustrated in Figure 3. The figure shows cross section a-a (marked in Figure 2) through the centre of the excavation with average pile lengths of the buildings.

The top of the Palaeogene clay is found at approximately level -10 m in the cross section. All levels given in the paper refer to mean sea level (DVR90).

Building A to the east is supported on a pile-supported concrete slab (steel piles type HE180A) with base level at +5.0 m. The toe level of the steel piles is from level -12 m to -22 m. Building B is also supported on a pile-supported concrete slab but with concrete piles (size 30x30 cm).

The base level of the slab varies since there is not a basement below the entire building. The basement is deepest in the central part, with floor level +1.7 m and base level +0.7 m. The toe level of the concrete piles is approximately -18 m.

The project Aarhus Story includes a basement and lowest excavation level is +3.6 m. The new building is to be pile-supported like the two adjacent buildings. The concrete slap is supported on concrete piles with increasing pile length to the north.

In connection to the excavation a sheet pile wall is established along the north-western side and partially along the southeast side as indicated in Figure 2. All sheet piles were driven before the first survey and therefore do not contribute to the measured soil displacement and where not expected to affect the ground movement during subsequent pile driving. The deepest sheet pile toe is at -8.5 m.

2.2 Site conditions

The ground and water conditions at the site have been obtained from the site investigation carried out by Geo (2013). The ground level before excavation was at level +7.0 m to +9.3 m, rising in the northern direction. Below ground level are found typical glacial deposits consisting of alternating layers of clay till, meltwater sand and embedded glacial floes of high plasticity clays. There is no systematic stratification of these deposits.

Palaeogene clay is found below the glacial layers. In the south-eastern end of the site the top level of the Palaeogene clay is found at -6.0 m to -7.0 m. From here it dives to the northwest, where it is found at level -15.9 m. The Palaeogene clay consists primarily of Søvind Marl and in some areas by thin layers

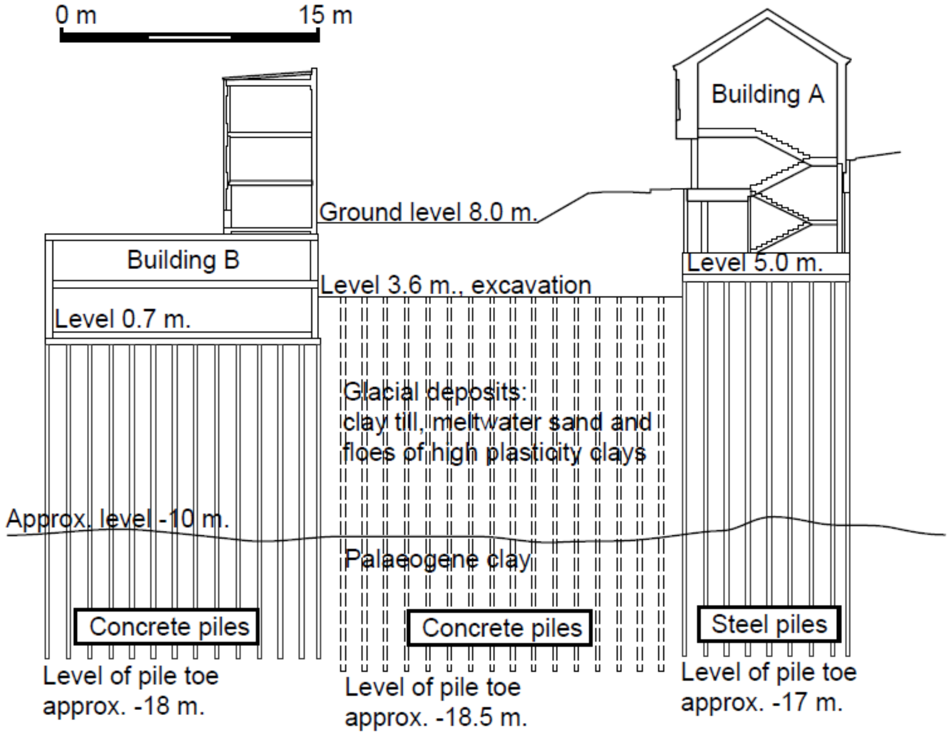

Figure 3 Cross section of the basement excavation for Aarhus Story and the adjacent buildings (Southeast to North-western direction).

of Septarian Clay. Søvind Marl is a marine sedimentary clay. It is heavily overconsolidated and it can be characterized as a extremely high plasticity clay (the liquid limit is typically reported in the range 100-240% (Sorensen and Okkels, 2015)). It is fissured in its natural condition.

The upper part of the formation is very calcareous (25-56%) and Søvind Marl is therefore significantly different from the other high plasticity Palaeogene clays found in Denmark. The plasticity index is between 51-115% and the field vane shear strength, c_{fv} is between 400 kPa – 700 kPa.

The water table in the area varies from level +5.3 m to +8.7 m increasing to the north.

2.3 Monitoring program

A total of 34 survey points were linked to the project. 24 of these were relatively close to the site and the remaining 10 points were located at a distance of up to 100 meters from the site. These 10 points were used as reference points.

All of the survey points were placed on the adjacent buildings from the ground floor to just below the roof structure, between level +7.3 m to +17.5 m. The internal movements in the building are expected to be small with minimal influence on the heave measurements. Figure 2 shows the 24 points located on the adjacent structures. 11 of these points are placed on Building A and 7 points are placed on Building B.

The points were continuously surveyed in 203 days between February 17th and September 8th 2014, corresponding to the beginning of the pile driving until two months after.

Originally, there were only 9 points on the adjacent buildings, but as the foundation project progressed, heave was registered and therefore more points were added. Survey points 1, 3 and 6-11 were added to Building A and 12, 13 and 15 to Building B. Furthermore the frequency of measurements was more concentrated at the second half of the process. Due to the more infrequent measurements at the beginning, the data set was inadequate for analysis in this period.

A surveyor monitored the survey points with a TST (total station theodolite) located

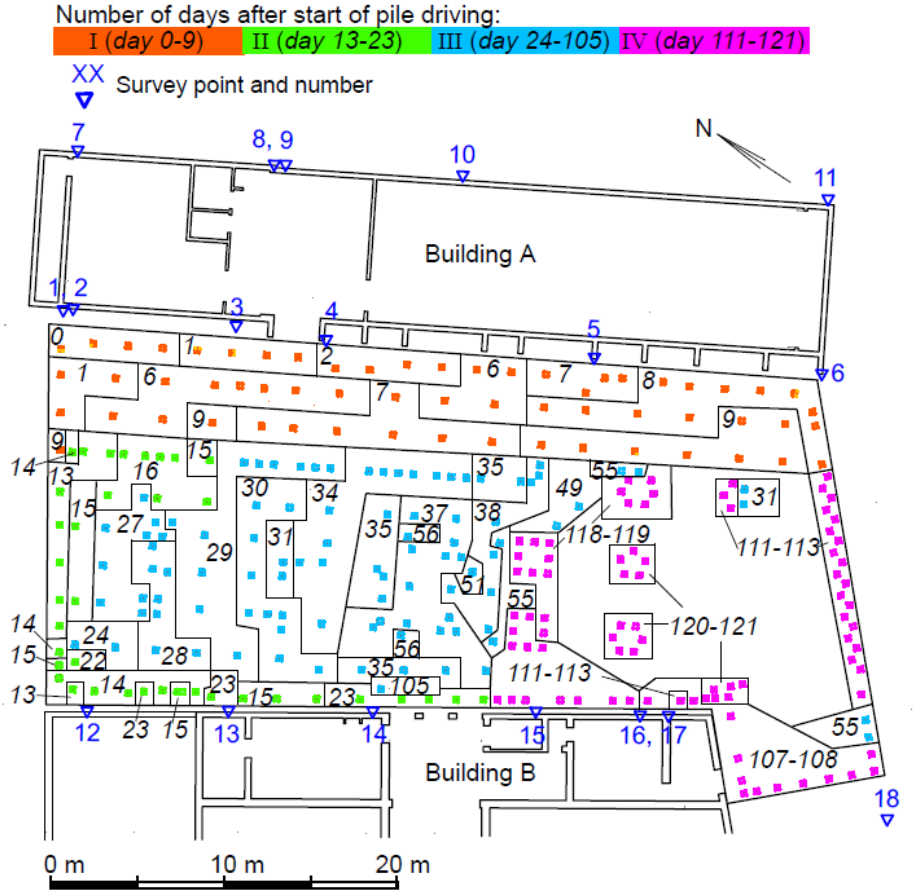

Figure 4 The progress of pile driving at Aarhus Story.

within the construction site. The surveyor reported an uncertainty of measurements of less than 2 mm.

2.4 Pile driving

The project has a total of 280 driven concrete piles and 59 permanent bored in-situ cast micro-piles (GEWI®). The driven concrete piles has square cross section with side length b = 0.25 m, but with different penetration depths from 12 to 25 m. The pile lengths are dependent on the depth of the top of the Palaeogene clay, hence the pile lengths increases from south to north.

The pile spacing varies between c = 0.8 - 2.3 m, which gives a spacing ratio (c/b) of 3-9. Approximately 65% of the piles have a spacing c = 1.5 - 2 m, which gives a narrower spacing ratio of 6-8. Some of the piles have been installed using pre-augering (fully or partial) to minimize further heave. Figure 4 illustrates the location and progress of the driven piles divided into four periods. The bored micropiles are not considered to result in any soil displacement, hence these are not considered in the further analysis and are not shown on the figure. A general specification of the differences in the periods is shown in table 1.

Table 1 A general specification of the driven piles in each period.

Periods	I	II	III	IV
Number of piles	60	39	98	83
Penetration depth [m]	21-25	20-25	19-25	12-17
Pre-augering depth [m]	8-9	9	12	14-16
Displaced soil per pile [m^3]	0,8-1,1	0,8-1,2	0,5-0,8	0,1-0,3

The pile driving took place from March 4th (day 0) to July 3rd (day 121) 2014 and went from north to south, starting closest to the adjacent buildings, as shown in Figure 4.

3 OBSERVED HEAVE OF PILE-SUPPORTED BUILDINGS

In connection to the pile driving, heave of the two adjacent buildings were registered as shown in Figures 5 and 6. The shown heave is the accumulated heave, which is represented by the relative change in vertical movement from the first survey (the reference measurement).

The timeline on the horizontal axis indicate all days on which measurements are made, represented by days after start of pile driving (notice that the timescale is not constant). In the periods between each measurement the numbers of piles driven vary between 1 and 33, however over the full period of driving the number of driven piles was more or less evenly distributed.

The survey points at Building A (point 2, 4 and 5) show a very significant heave of the building in the beginning of the pile driving, followed by a very small increase in the rest of the process (cf. Figure 5). In contrast, the observed heave of Building B shows a gradual heave that develops as the pile driving progresses. As more piles are driven the greater the heave becomes (cf. Figure 6). This is a likely result of the differences in piling driving patterns next to the two buildings, as shown in Figure 4.

It should be noted that not all survey points have the same reference date, due to the fact that some of the points, as mentioned, were added after the start of pile driving.

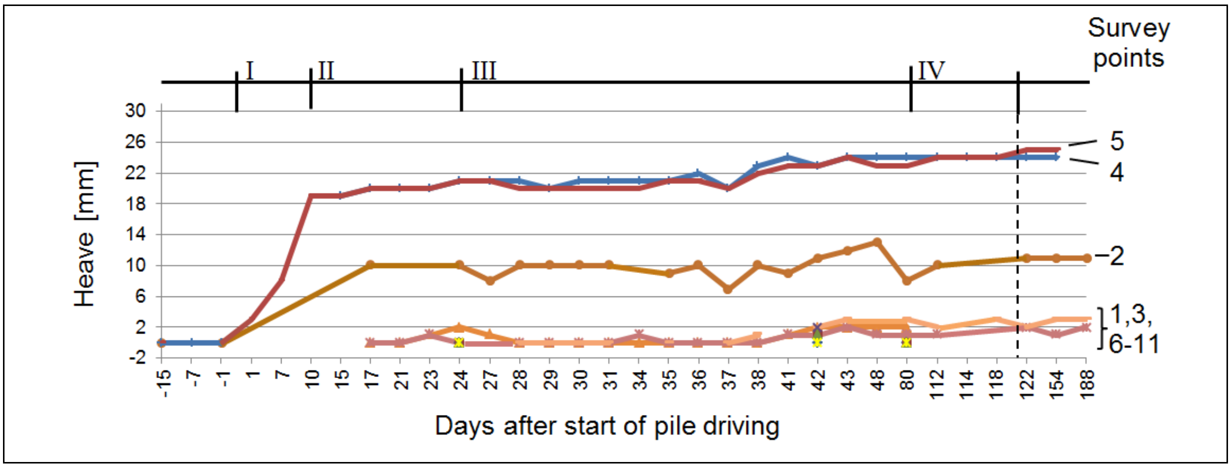

Figure 5 Accumulated relative heave of Building A with an indication of the pile driving periods. The timeline indicates all days on which measurements are made, represented by days after start of pile driving. End of pile driving is on day 121.

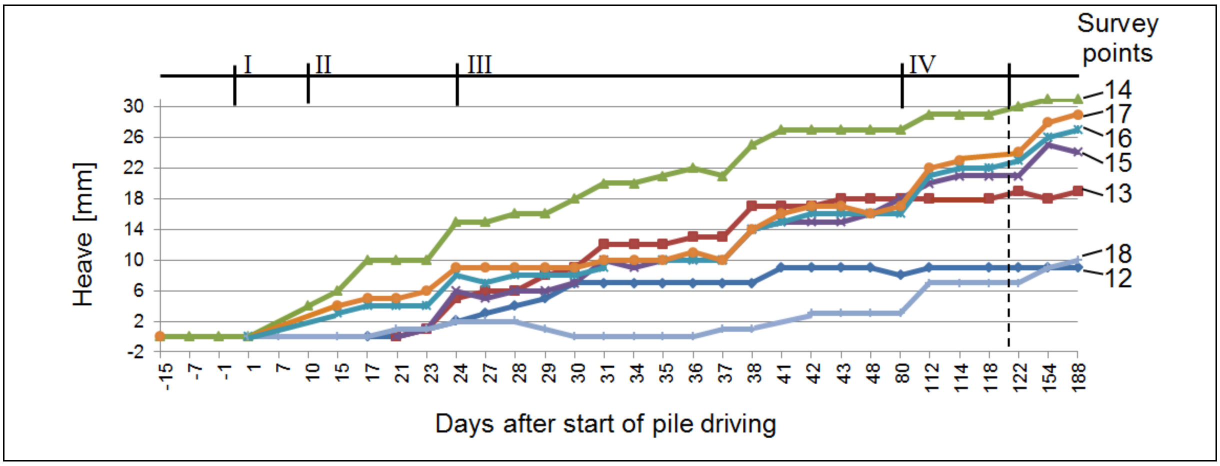

Figure 6 Accumulated relative heave of Building B with an indication of the pile driving periods. The timeline indicates all days on which measurements are made, represented by days after start of pile driving. End of pile driving is on day 121.

As seen in Figure 5 this means that the first survey of several points (1, 3, 6-11) were undertaken after the initial observation of very significant heave for Building A (that occurred in period I, day 0-9). Hence it is likely that the other parts of the facade of Building A facing the area of piling also have experienced similar movement to those shown by survey points 2, 4 and 5, but no data can verify this.

The points 12, 13 and 15 on building B were also added later (day 17-21), which may be the reason why point 13 and 15 have experienced lesser heave compared to point 16 and 14 respectively. The points 13, 16 and 15, 14 are comparable because of their location in relation to the central part of the foundation area.

The maximum accumulated heave of both buildings was observed from survey points facing the central part of the foundation area. Building A experienced 24-25 mm heave observed by survey points 4 and 5, and building B experienced 27-31 mm heave observed by survey points 14, 16 and 17.

Driving of piles in close proximity to the buildings causes significant heave for the survey points closest compared to the points further away. For example measurements on day 23 show that survey points 13-17 experience significant heave (3-5 mm), whereas survey points 12 and 18 on building B and points 1-11 on building A have minimal (-1 to 1 mm) or no displacement.

On day 37, 14 piles were driven in the central part of the foundation area, which resulted in heave (3-4 mm) of survey points 13-17, 4 and 5 that were also facing the central part of the foundation area. An interesting observation is found for the same points on survey day 31-36, where insignificant heave (0-2 mm) is observed although 25 piles were driven in close proximity. This observation is interesting since no larger variation is registered.

The last pile was driven on day 121, yet measurements from day 122-188 show an additional heave of 3-5 mm (points 15-18), which may indicate a delayed response time in the displacements of the clay. These points are located adjacent to the area where the last piles were driven.

3.1 Factors influencing observed heave

The purpose of this analysis is to determine which parameters influence heave of pile-supported structures. The basis of the analysis is formed by data obtained by focusing on significant changes in the vertical movement of the structures (e.g. Figure 6, between day 23 and 24). The increase of heave between two survey days is assumed to be caused only by the displaced volume between these two days. The data listed in Figure 7 and 8 are all obtained by these datasets, which is why the heave is smaller than the accumulated heave in Figure 5 and 6.

In Figure 7 a linear correlation is seen when heave (h_s) is compared with displaced volume (V), which is also suggested in the literature (Dugan and Freed, 1984). The calculation of displaced volume is for all deposits, thus displaced volume in Palaeogene clay only is not investigated. Only heave measurements for distances from 1 to 11 m from the survey point to the centre of the pile group has been included in the figure to minimize the influence of distance. However, some scatter still remains as a result of difference in pile lengths and layout of pile groups.

The data depicted is within the relative distance, s/L = 0.05 - 0.5, where s is the horizontal distance from the centre of the driven pile group to the survey point, and L is the average pile length within the pile group (16.5 m - 23 m).

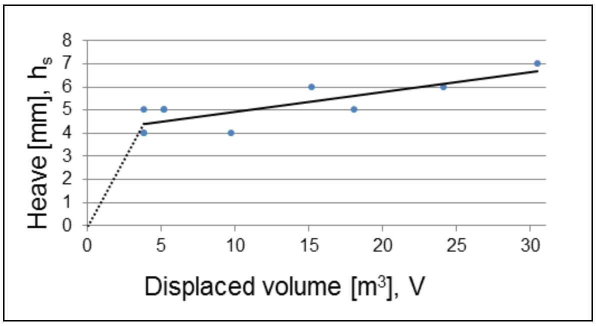

Figure 7 A linear correlation between heave and displaced volume for distances up to 11 m, with a relative distance s/L=0.05-0.5. The trend line is given by h_s=0.085·V+4 for V=4m^3–30m^3.

For this case study the total heave and the inclination of the trend line is relatively small compared to the expected movement of the unrestrained ground surface, since the load from the existing buildings and their pile foundations help to limit the vertical movements.

The trend line from Figure 7 is non-existent for values below $V = 4m^3$ because of limited data. It is assumed that no heave occur with a displaced volume of 0 m^3. The dashed line indicates a greater ratio of heave per displaced volume for $V < 4m^3$, which may be due to tensioning of the piles from compression to tension. This could possibly correspond to the heave of a non-pile-supported structure.

The distance to maximum heave is expected to be related to the pile length. This is also indicated from the observations, as seen in Table 2.

Table 2 The distance to where maximum heave is observed for different pile lengths.

Pile length [m]	Distance to maximum heave [m]
16 – 16.5	5.8 – 7.4
21 – 21.5	8.2 – 13.2
22 – 22.5	9.1 – 15.7

The table shows a correlation between these two parameters. The longer the piles the further away maximum heave will occur.

4 COMPARISON OF OBSERVED HEAVE WITH PREDICTED HEAVE BASED ON ANALYTICAL SOLUTION FROM LITERATURE

In the following the data from this case study is compared to the simplified model proposed by Wersäll and Massarsch (2013) for estimation of ground surface heave in front of a driven pile row. This is done with the aim to evaluate if the model can be used to predict the heave of pile-supported structures in front of a pile group driven into high plasticity stiff clay. Differences between the model and observed behaviour can help to highlight the effects of the existing piles below the pile-supported structures and the spatial difference between pile row and pile groups.

The data from this case study is shown in Figure 8 as heave, h_s normalized by equivalent soil displacement, u_{eq} (1). A value of u_{eq} = 8 - 10 mm was determined.

The red line describes the model by Wersäll and Massarsch (2013), and shows maximum heave of the unrestrained ground surface to be equal to $0.4{\cdot}u_{eq}$ in a relative distance 0.3 *s/L* - 1.0 *s/L* from the pile row. According to the model ground heave can be neglected in distances larger than 4 times the pile length. This assumption is based on 2D Finite Element Analysis.

Generally, a large spread is seen in the data in Figure 8, since several factors have not been considered in the plot, amongst others; the effect of pre-augering, the effect of pile-group size and layout and the effect of previously driven piles in front of the pile group.

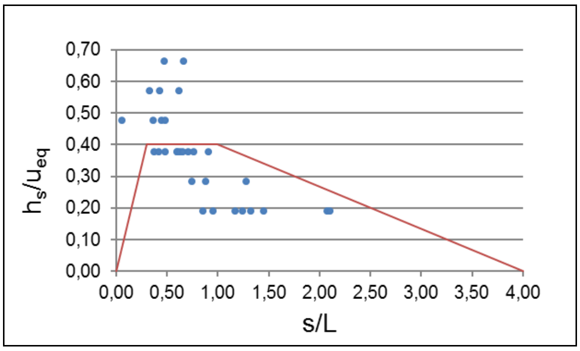

Figure 8 The data from this case study (blue) compared with the model suggested by Wersäll and Massarsch (2013) (red). The data is for displaced volume V=4 m^3–30 m^3.

For a relative distance shorter than 0.7 *s/L* the data shows significantly greater heave than the model, while with increasing distance beyond 0.7 *s/L* a more rapid decay in vertical movement is observed than predicted. The maximum observed heave is nearly 70% greater than predicted by the model.

The greater heave observed at short distances from the driven piles could be expected, as the pile groups are not directly comparable with a pile row, as used in the model. As shown in Figure 4 the groups consist of piles in different patterns (seldom a single row), which is why the influence of additional “rows” has to be taken into account. The additional “rows” in a pile group can be expected to have greatest effect on the heave at short distances when compared to the single row assumed in the model.

At greater distances from the pile groups the model is found to overpredict the heave. This may be expected due to the spatial differences between the pile groups and the pile row. The limited extend of the pile group compared to the pile row will result in less heave at greater distances.

Furthermore, if no other factors are considered, the model may generally be expected to overpredict the actual heave of a piled structure, since the effect of the resistance of existing piles below the piled structure is not considered.

Additionally, the effect of pre-augering is not included in the model. Hence, if the pile is pre-augered this would lead to lowering of the measured heave compared to the heave predicted by the model.

Generally, the data is connected with large uncertainties due to many variables, which is why the observed dispersion is significant.

5 DISCUSSION

Since the considerations in this article are based only on one case study it is important to consider the results with care.

The survey points are concentrated around the excavation, i.e. placed on the adjacent buildings. Since there are no survey points inside the excavation, and very few outside the construction area, this makes the data very grouped around a limited interval of distances.

Only the heave of structures was registered. If the heave of the ground surface were registered both in and outside the excavation, a more accurate distribution of the heave could be constructed. With such data the displaced volume could be estimated more precisely and more accurate correlations of parameters could be determined.

Generally, the case involves many variables, limited data and uncertainties hence the effect of several important factors is difficult to assess, amongst others; the influences on the results of pre-augering, previously driven piles, pile group layout and driving direction.

It is assessed that the soil’s upward movement causes the heave of the pile-supported structures. As the upward moving soil mobilises shaft resistance on the existing piles, the piles will gradually be moving upwards. The combined weight of the building and the mobilised downward shaft friction below the zone of upward movement will help to limit the heave of the piled structure. Hence, if the driven piles are longer than the existing piles and driven close to existing piles, then the driving might result in mobilisation of an upward shaft resistance along most of the pile length of the existing piles, or make the entire soil volume around the existing piles move upward. This could potentially cause significant heave of the structure.

The high plasticity clay has swelling properties, which has not been considered above. With a reduction in stresses, because of the 4-6 meter deep excavation, the long-term heave of the ground might be significant. However, the swelling process is very slow compared to the pile driving period of 4 months. Furthermore it is expected that pile driving to some extend may reduce the negative excess pore pressures caused by excavation and hence lead to a reduction in subsequent swelling (Simonsen and Sørensen, 2016).

6 CONCLUSION

Based on this case study it can be concluded that pile-supported structures are affected by heave when piles are driven into very high plasticity Palaeogene clays. A maximum accumulated heave of 25 and 31 mm was registered for the central parts of Building A and B respectively.

In general it is observed that the survey points near the central part of the foundation area have experienced a greater heave than the survey points at the north-western and south-eastern edge.

After the last pile was driven heave was still observed. From day 122-188 a heave of 3-5 mm was registered, which indicates a delayed response time in the displacements of the clay. Whether the buildings continued to heave or possibly settled in the following months is unfortunately unknown.

The results show that heave depends on the displaced volume and that the distance to where maximum heave occurs depend on the pile length; the longer the pile the further away maximum heave will occur. This confirms previous findings.

In order to make a more thorough analysis of heave of pile-supported structures more studies are needed. But the case study have highlighted the complexity involved if a reliable model is to be developed which can be used to accurately predict the heave of pile-supported structures.

A comparison has been undertaken between data from this case study and the model suggested by Wersäll and Massarsch (2013), which considers the case of vertical ground movement in front of a pile row. Since the actual case in this study is much more complex than considered in the model, the predictions of the model are not directly comparable with the observations. The comparison indicates that the model is likely to overestimate the heave for relative distances larger than approximately 0.7 *s/L* and under predict the heave for relative distances shorter than 0.7 *s/L*. It can be concluded that the model is not applicable in this context.

A further study of the issue has recently been conducted in an experimental project, where soil displacements around a single pile and around pile groups are examined in model tests. The effect of pre-augering is also investigated. The results from the model tests are to be processed and compared with literature as well as the data from this case study. This study will be presented in a future paper.

7 ACKNOWLEDGEMENTS

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