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Influence of pre-augering on ground surface displacements around driven piles in clay

Influence de la pré-tarage sur les déplacements de la surface du sol autour des pieux battus en argile

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ABSTRACT: When precast displacement piles are driven into saturated medium to high plasticity clays, constant volume soil displacements will occur both horizontally and vertically in the ground surrounding the piles. The displacements can have undesirable consequences for surrounding structures, which is why the displacements are often sought reduced. Pre-augering is commonly used in connection to pile driving to achieve this. In this study the issue of soil displacements are studied through model tests. An experimental setup is designed in which soil displacements around single piles, pile rows and around a pile group, are examined. Wooden model-piles are driven into remoulded medium plasticity clay, and movements of the ground surface are registered both horizontally and vertically after installation of each pile. To investigate the influence of pre-augering, model tests both with and without pre-augering are carried out. The results from the model tests are analyzed in order to describe the mechanisms, which occur during pile driving in clay, and to determine the patterns and magnitude of soil displacements as well as the reducing effect of pre-augering. A detailed description of the results is presented and compared with literature.

RÉSUMÉ: Lorsque les pieux de déplacement préfabriqués sont enfoncés dans des argiles saturées de plasticité moyenne à élevée, des déplacements de volume constant du sol auront lieu à la fois horizontalement et verticalement dans le sol entourant les pieux. Les déplacements peuvent avoir des conséquences indésirables sur les structures environnantes, raison pour laquelle les déplacements sont souvent recherchés réduits. La pré-tarage est couramment utilisée pour le battage de pieux. Dans cette étude, la question des déplacements de sol est étudiée à l'aide de tests sur modèles. Une installation expérimentale est conçue pour examiner les déplacements de sol autour d'un pieux unique, de rangées de pieux et d'un groupe de pieux. Les modèles de pieux en bois sont enfoncés dans de l'argile à plasticité moyenne remoulée et les mouvements de la surface du sol sont enregistrés à la fois horizontalement et verticalement après l'installation de chaque pieu. Pour étudier l'influence de la pré-tarage, des tests sur modèle avec et sans pré-tarification sont effectués. Les résultats des essais sur modèle sont analysés afin de décrire les mécanismes qui se produisent lors du battage de pieux dans l'argile et de déterminer les schémas et l'ampleur des déplacements du sol ainsi que l'effet réducteur de la pré-auge. Une description détaillée des résultats est présentée et comparée à la littérature.

Keywords: Model tests; soil displacements; driven piles; clay; pre-augering

1 INTRODUCTION

An increasing number of high-rise buildings are erected in Denmark at locations with high plasticity clay. To limit settlements these buildings are often supported by piled foundation. Traditionally, in Denmark precast concrete piles are favoured over bored piles due to lower cost and ease of installation.

However, as precast piles are driven into saturated low permeability clay the surrounding soil will experience volume constant displacements. The soil displacements cause both horizontal and vertical movements, often of significant magnitude, which may result in complications for adjacent structures. Several reported case studies in the literature illustrate and quantify the significant impact that pile driving may impose on adjacent structures. Hoerlykke et al. (2016) presented a case where pile driving in high plasticity clay not only lead to heave of the ground surface but also resulted in significant heave and damage of nearby pile supported buildings.

The issue has been investigated by several reseachers through both field tests and case studies with the focus to determine the pattern of the displacements and the extent to which it occur, as well as which parameters are of influence (Hagerty and Peck, 1971 and Dugan and Freed, 1984). Massarch and Wersäll (2013) investigated the issue through FEM-analysis of a single pile and by analyzing model tests previously made by Massarch (1976). It was concluded that the pile driving causes mainly lateral movements and that vertical movements could be neglected close to the driven pile as well as the magnitude of the displacements are controlled by the cross sectional areas of the pile and the pile spacing and not the pile length.

Sagaseta proposed the shallow strain path method (SSPM) in 1987, which can predict the vertical movement of the ground surface during the installation of single driven piles. It assumes the soil to be linear-elastic and simulates undrained pile penetration from a stress-free ground surface. The vertical movement S_z given by SSPM is shown in Equation 1 (Sagaseta and Whittle, 2001).

$$S_z(x) = \frac{1}{8}\left(\frac{d^2}{x} - \frac{d^2}{\sqrt{L^2+x^2}}\right) \quad (1)$$

Where x (m) is the distance from pile axis, d (m) is the pile diameter and L (m) is the pile length. In the SSPM equation the pile length is of influence, in contrast to the conclusion made by Massarch and Wersäll (2013).

The general knowledge of soil displacements due to pile driving in clay in connection to installation of pile groups and especially the effect of pre-augering is limited. This paper investigates the issue through model tests with the focus to determine the patterns and size of the displaced soil at the ground surface, the impact on and of existing piles, and the effect of pre-augering.

2 MODEL TESTS

2.1 Test setup

The model tests were carried out in a squared box where model piles were driven into soft clay.

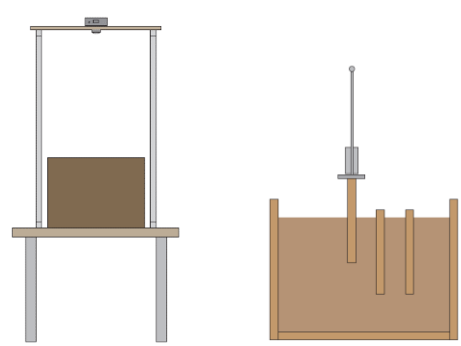

Figure 1. Illustration of the model test setup. Sideview (left) and cross-section of the model (right).

The exterior dimensions of the squared model box were 500x500 mm with a height of 370 mm. The box was made of plywood with a thickness of 21 mm. The clay had a depth of 300 mm in the box.

Wooden piles were used. To imitate the rough surface of concrete piles, fine sand was glued on the piles. The piles had a dimension of 21x21 mm and a length of 200 mm.

Small white plastic spheres with a diameter of 5 mm were laid out on top of the clay in a pattern as shown in Figure 2. The balls worked as measurement points for both horizontal and vertical movements.

2.1.1 Soil description

The soft clay used in the model tests was a commercial remoulded marine tertiary clay of medium plasticity. The natural stiff clay was remoulded with added water, vacuum treated and roll-pressed to obtain a homogenised and fully saturated soft clay. The classification parameters are shown in Table 1.

The clay was built into the modelbox in layers and each layer was compressed to make sure air did not get stuck in between. Along the sides of the model box the friction between clay and box was sought minimized by greasing the inside of the box.

Table 1. Classification parameters of the clay used in the model tests

Water/moisture content (W)	23.6%
Degree of saturation (S_r)	1.00
Liquid limit (W_L)	40%
Plastic limit (W_P)	18%
Plasticity index ($I_P = W_L - W_P$)	22%
Shear vane strength (C_v)	24-36 kPa

2.2 Method

A total of four tests were carried out. Two repeated tests without pre-augering (T1-NP and T2-NP) and two repeated tests with pre-augering (T3-P and T4-P). The pre-augering was done with an 20 mm auger, and for each pile 100 mm was pre-augered, corresponding to half of the pile length. The pile driving was done with a small drop hammer with a weight of 750 grams and a height of fall of 20 cm. To minimize the boundary effects a minimum distance of 118 mm from the pile center to the sides of the box was kept, and the piles were driven to 100 mm from the bottom of the box.

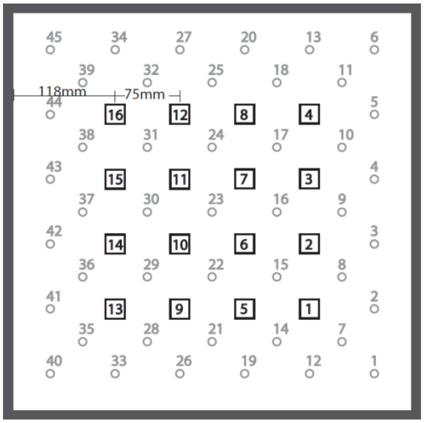

Figure 2. Surface of model test with marking of piles (squares) and measurement points (circles). The pile driving direction follow the numbers on the piles.

The piles were driven in a pattern of 4x4 piles as shown in Figure 2. The direction of the pile driving follow the numbers marked on the piles. The numbered circles marks the measurement points.

2.3 Measurement of horizontal and vertical displacements

The vertical movements were measured manually with a digital vernier caliper with a precision of approximately 0.1 mm. Movements were measured after the driving of each pile.

Horizontal movements were recorded by digital imaging and subsequently analysed using a pixel tracking software (Tracker Video Analysis and Modelling Tool v4.90). Images were taken after driving of each pile with a digital camera (Canon EOS 500D with 15.1 megapixels) placed 1.0 m above the clay surface, as illustrated in Figure 1.

3 RESULTS

3.1 Vertical movements

The summation of the vertical displacement of the soil surface should ideally be equal to the pile volume driven into the soil. Figure 3 shows that the theoretically displaced soil volume was found to be approximately 10% greater than the total increase in soil volume calculated from the vertical displacement of the clay surface. The deviation is small and likely to result from a lack of ridigity in the box and/or slight compaction of the clay in the box.

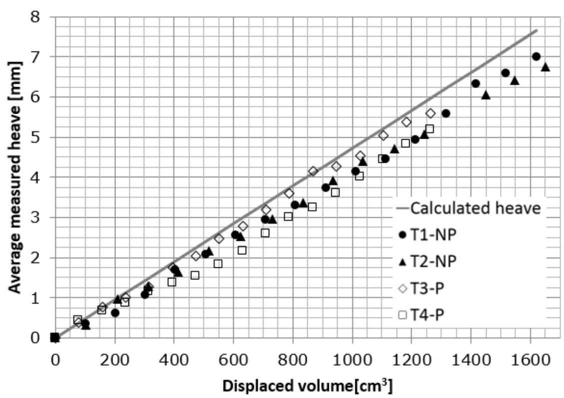

Figure 3. Theoretically calculated displaced soil volume compared to average measured vertical displacement.

3.1.1 Soil movements due to driving of single piles

To asses the vertical movements around a single pile the recorded movement after driving of each pile in sequence was used. This method does not take the cumulative effect from several piles into account and furthermore assumes that the effect of already driven piles is insignificant.

The vertical movements of the soil surface after the installation of piles without pre-augering is shown in Figure 4. Significant reduction in the vertical movements is seen close to the pile with increasing normalised distance *x/L* to the pile, where *x* is the distance and *L* is the pile length. It is found that the vertical movements are approaching zero/negligible at a distance of approximately 350 mm, corresponding to 1.75 times the pile length. No measurements have been made within a distance of 50 mm from the individual piles. However, the pile friction is visually observed to reduce the heave close to the pile.

In Figure 4 the measured movement is compared to the theoretical movement calculated based on the Shallow Strain Path Method (SSPM), cf. Equation 1. It is clear from the plot that SSPM underpredicts the observed vertical surface movements in the model test (at distances $x/L > 0.25$), as could also be expected according to Sagaseta and Whittle (2001). It is found that the theoretical values need to be increased by roughly 8/3 to obtain a better match with the measured values.

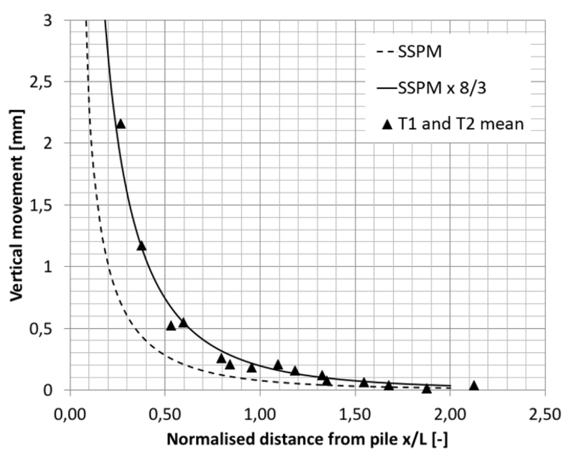

Figure 4. Vertical movements after driving of single piles. Comparison with SSPM prediction.

3.1.2 Soil movements around pile groups/rows

The cumulative effect when driving several piles is illustrated in Figure 5. The figure shows the vertical movements of the soil surface after installation of 1 to 4 pile rows. The contours are drawn by interpolation between the 45 measurement points and indicates the vertical movements per 1 mm.

The greatest vertical movements of the soil surface occur in the centre and just outside the

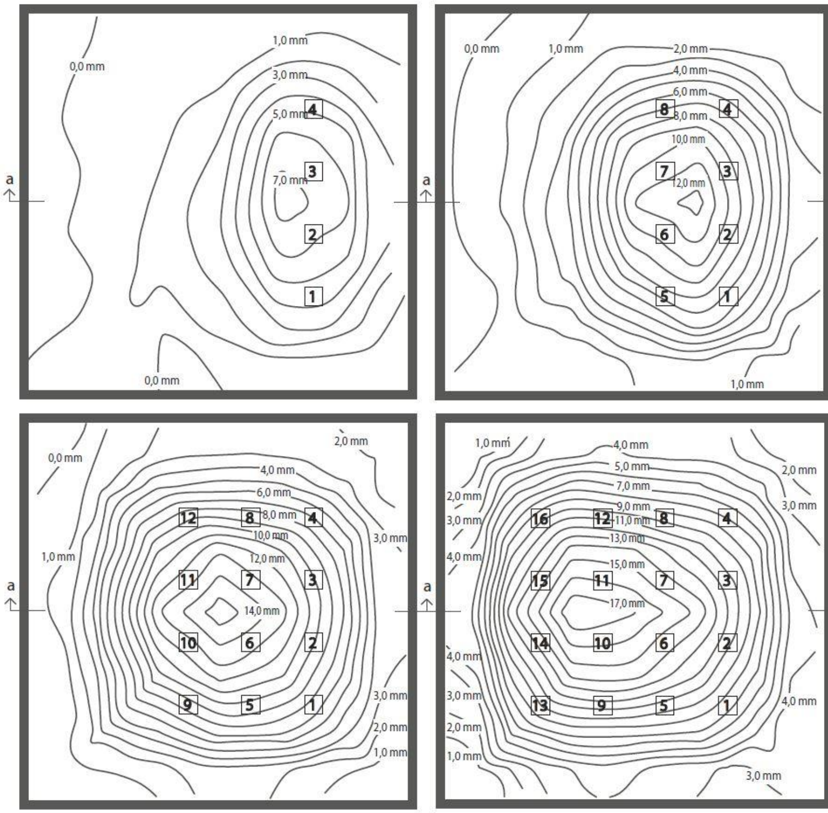

Figure 5. Vertical movements after installation of pile rows 1-4 in the tests without pre-auger (T1-NP). The contours indicate the vertical movements of the soil surface per 1 mm.

centerline of the driven pile row. As several pile rows are driven, the place where maximum heave occurs is pushed in the direction of the pile driving. The same is seen after the installation of all piles. The place of maximum heave is located left of the centre of the pile group. This is also seen from Figure 6, which is cross section a-a marked on Figure 5.

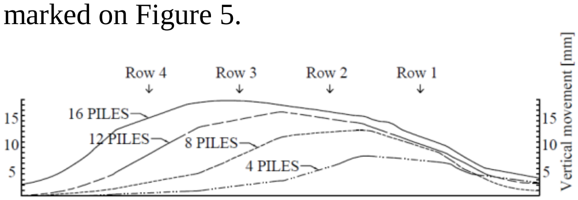

Figure 6. Cross section a-a marked on figure 5. The accumulated vertical movements after installation of pile row 1-4.

It can be seen from Figure 6 that the relative vertical movement profile after driving of each pile row is approximately the same. This indicate that soil displacement of the soil surface are cumulative and only to minor degree influenced by the presence of already installed piles. The maximum vertical movement caused by the last driven pile row is found to be 6-8 mm.

3.1.3 Influence of pre-augering on vertical movements

The direction of the soil movements shows the same tendency when the piles are pre-augered, however there is a significant difference in the size of the movements. In the model tests the maximum measured heave without pre-auger was 17 mm, cf. Figure 6, and with pre-augering 10 mm.

The average relative vertical movement profile after driving of each of the rows 1 to 4 is shown in Figure 7. The profile is shown in cross-section a-a perpendicular to the pile rows, and data from all tests are included.

From Figure 7, pre-augering is seen to reduce the measured average maximum vertical movement after driving of a pile row from roughly 7 mm to 4 mm. Maximum movement is seen to be shifted roughly 0.15 x/L from the centerline of the pile row. Vertical movements are reduced to around 2-3 mm at a distance equal to the pre-augering depth (x/L = 0.5) from the front of the pile row. At greater distances the vertical movements are seen to be only little influenced by pre-augering.

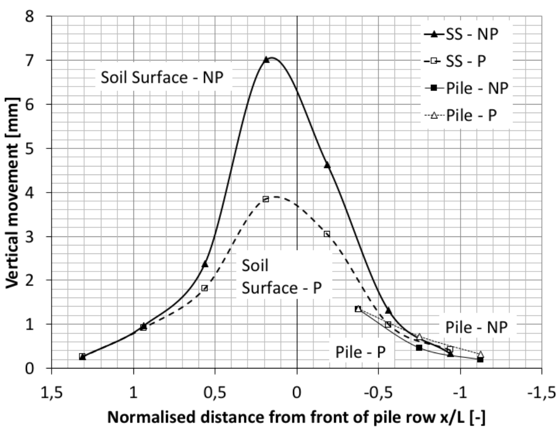

Figure 7. Average vertical movement profile after driving of pile rows. SS: soil surface, NP: without pre-augering, P: pre-augered.

3.1.4 Surface movement vs. pile movement

Measurements of the average vertical movement of already installed piles are also shown in Figure 7 for comparison with the surface movements. It is indicated that the pile top is experiencing less vertical movements than the soil surface close to the pile row, while movements of the pile is similar to the soil surface at distances greater than the penetration depth of the piles in the pile row.

3.1.5 Predicted vertical movements

Assuming that vertical movements from driving of single piles are cumulative, the theoretical SSPM approach may be used to derive the cumulative vertical movements for each of the pile rows in the model tests. Figure 8 shows the theoretical vertical movements of the soil surface compared to the average measured movements after driving of each pile row for piles without pre-augering (SS–NP) and piles with pre-augering (SS–P). Data from all tests are included.

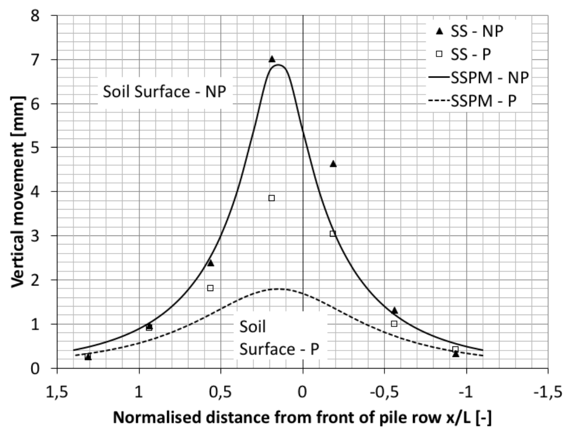

Figure 8. Theoretical calculated cumulative vertical movement of pile rows from installation of single piles. SSPM: corrected SSPM model, data points are measured values. SS: soil surface, NP: without pre-augering, P: pre-augered.

The predicted vertical movement using corrected SSPM (corrected using a factor of 8/3, cf. Figure 4, and shiftet 0.15 x/L from the centerline) is found to match the measured vertical movement quite well for piles without pre-augering, while it clearly underpredicts the movements, when piles are pre-augered. The predicted movement for pre-augered piles is determined as the difference in vertical movement for piles driven with pile length of *L* and *L/2* respectively. It appears that although pre-augering occurs over the first half of the pile length, the displacement of the soil from driving at depth results in quite large vertical movements close to the pile. This may be a result of the lateral restraining effect which increases with increasing depth.

3.2 Horizontal movements

Horizontal movements are registered in both the x and y direction. The results show that the movements are primarily in the direction away from the installed pile, hence in the pile driving direction. This means that the pile driving direction has a significant influence when several piles are driven.

Horizontal movements of the ground surface from the test without pre-augering is shown in Figure 9. The figure shows, that the cumulative movement is actually a lot longer than the actual final movement from beginning to end.

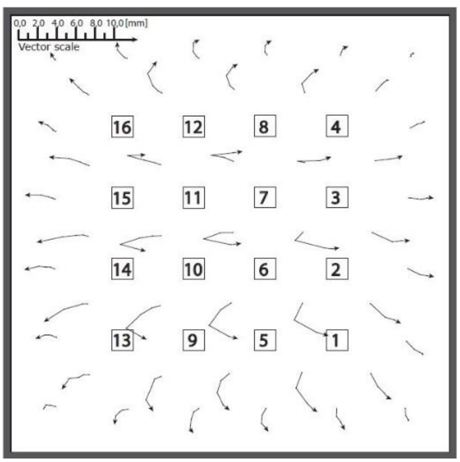

Figure 9. Cumulative horizontal movement of the soil surface from the model test without pre-augering (T1-NP). The vectors consist of 5 steps, corresponding to the start point and the movement after installation of pile row 1-4.

The measurement points follow the pile driving direction and the movement pattern is almost symmetrical around the middle of the entire pile group. The results also show, that the total cumulative movement decreases with the distance to the pile group.

The resulting horizontal movement vectors are all found to be more or less perpendicular to the vertical movement contours, which is illustrated in Figure 10. The figure shows the total movements, both horizontal and vertical, after the installation of all 4 pile rows. The horizontal vectors are greatest where the vertical heave is steepest, also the vectors have a clear direction away from the pile driving.

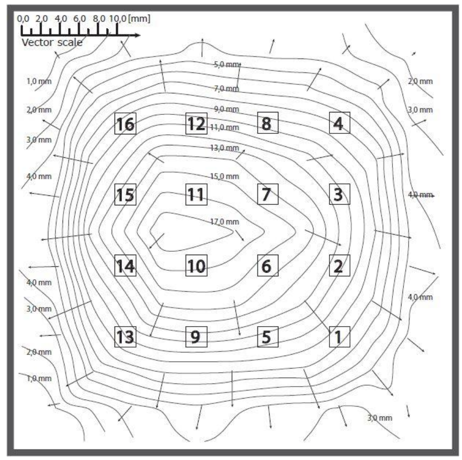

Figure 10. Illustration of the actual final horizontal movements (vectors) compared with the vertical movements (contours) from the test (T1-NP).

3.2.1 Influence of pre-augering on horizontal movements

The tendency of the soil movements is the same for the tests with pre-augering, though the movements are a lot smaller.

When the cumulative horizontal movements both with and without pre-augering is compared it is clear to see that the size of the horizontal movements have been decreased. The ground surface in the middle of the pile group in the model test without pre-augering had a total cumulative movement of 7.6 mm whereas the same measurement point in the model test with pre-augering had a total cumulative movement of 4.1 mm.

However, there was a large variation in the different lengths of the cumulative movements in such a way that it was not possible to derive a ratio of how much the pre-augering had reduced the horizontal movements.

4 DISCUSSION

It must be acknowledged that the results are obtained by model tests, hence in small scale and in a homogenized remoulded clay. Several factors deviate from the conditions in relation to driving of full scale piles in natural clays. Hence, the results may provide an indication of expected patterns of movement for full scale piles, pile rows and pile groups, while the magnitudes of movements cannot be reliably scaled to full scale piles.

Pre-augering is proven to reduce the movements both horizontally and vertically. The results show that pre-augering has an effect within a distance equal to the pre-augering depth from the pile row. From the tests it has not been possible to derive if this ratio changes with the depth of pre-augering, but this would not be unlikely.

5 CONCLUSIONS

From the model tests it has been possible to see the patterns of the soil movements both vertically and horizontally for single piles and pile rows. The pre-augering is proven to have a significant effect on the size of the movements. However, due to the test conditions it is assessed that the size and magnitude of the soil movements are not directly scalable to full scale piles without further considerations.

The tests clearly show that the soil movements are largest closest to the driven pile. When several pilerows are driven a cumulative effect causes the location where maximum heave occurs to be displaced in the direction of the pile driving. Even when all piles are pre-augered to half the pile length the soil movements are still largest close to the driven pile, though smaller compared to the tests without pre-augering.

When the results are compared to SSPM it is clear that SSPM underestimates the observed vertical movements in the tests and it is found that the theoretical values need to be shifted approximately 8/3 to obtain a better match with the measured values.

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