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Soil Heave Due to Pile Driving in Clay

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ABSTRACT Soil heave due to pile driving in clay is discussed and, in particular, its influence on adjacent piles. Finite element studies and results of model tests are presented and compared with field measurements. It is demonstrated that in the vicinity of the driven pile, the soil is displaced mainly in the lateral direction, similar to soil subjected to passive earth pressure. General rules of estimating soil heave inside and outside a pile group are examined. A method is proposed for estimating soil heave when driving a group of piles. Practical application of predicting soil heave is illustrated by an example.

INTRODUCTION

Driven piles are often a cost-effective foundation solution for different types of structures to be constructed on soft, compressible soils. Most design engineers focus on the axial capacity of piles without considering the potentially negative effects associated with pile driving, such as vibrations and soil displacement. Vibrations due to impact driving of piles and methods to analyze their propagation along a pile and into the surrounding soil were addressed by Massarsch and Fellenius (2008). When driving a group of piles, cohesive soil is displaced, resulting in lateral ground displacement at depth and heave of the ground surface. This paper addresses heave of the ground surface due to driving a group of piles into clay. In a companion paper to this conference, lateral displacements are discussed, (Massarsch and Wersäll, 2013). The present paper examines some of the rules of thumb applied by engineers to predict soil heave inside and outside a pile group. Results from model tests and finite element analyses are compared with field measurements and will be used to illustrate the displacement pattern and the zone of influence surrounding a pile group. The most important parameters governing soil heave are discussed. A method is presented for prediction of heave of the ground surface. Finally, an example is presented which illustrates how to predict ground heave in clay due to driving of a group of piles.

EFFECTS OF PILE DRIVING

Data of lateral soil movement and of ground heave due to driving of pile groups are scarce. Heave of the ground surface and of piles is more easily detected than lateral soil displacement and is therefore more frequently reported in the geotechnical literature. Hagerty and Peck (1970) investigated a number of case histories where heave of the ground surface and of piles in the vicinity were measured. They came to the following conclusions, which are frequently referred to in the geotechnical literature: a) saturated insensitive clay soils behave essentially incompressible during pile driving; b) approximately half of the volume of displaced soil appears as surface heave within the area of the pile foundation while the remaining half appears as surface heave outside the foundation area; c) under normal pile driving conditions (level ground surface, regular pile driving sequence) the soil surface heave within the foundation may be estimated as equal to half the volumetric displacement for the site; d) in the case of sensitive clay, the resultant soil displacement, especially beyond the limits of the area enclosed by the piles, may be less than that produced during driving in insensitive clay; e) when piles penetrate alternating strata of fine-grained soil and granular materials, the observed surface heave may be much less; f) when large differences of elevation exist within the foundation area, pile driving may displace the soil laterally preferentially toward the areas within which lower elevations occur; g) if the sequence of pile driving involves driving of piles first along the perimeter of the foundation, the heave of the soil surface in the central area of the foundation is increased and that of the surrounding area correspondingly decreased; h) the magnitude of pile heave in a foundation may be estimated by a simple procedure; i) lateral movements of soil and piles may occur during pile driving and for a considerable length of time thereafter; k) in general, driven piles tend to be displaced away from subsequent driving.

Loading of piles due to ground movement is a different mechanism compared to that caused by direct load application. The main consequences of ground movements are the effects of axial forces and bending moments affecting the structural integrity of piles. In the case of heave, tensile force can cause separation of pile joints or lifting off of the pile toe from the bearing stratum. Due to these potentially detrimental effects, it is commonly recommended not to drive piles at too close spacing (less than three pile diameters), to use pre-boring to reduce soil movements, to plan the sequence of pile driving in order to reduce cumulative soil movements, to re-drive piles that have been observed to heave excessively after installation of surrounding piles, and to avoid restraining the piles until all piles within the area of influence (e.g. 10 pile diameters) have been driven, Poulos (1994).

SOIL DISPLACEMENT

Hagerty (1969) reported results from field measurements of soil heave when driving a pile group in clay. Based on field observations, he suggested that soil movement close to the driven pile occurs almost exclusively in the vertical direction and decreases with increasing distance from the pile. The displacement mechanism is shown in Figure 1. Similar displacement patterns had previously been suggested by other investigators, indicating that pile installation results primarily in heave of the ground surface and, consequently, piles in the vicinity are affected by upward directed forces Terzaghi (1943), Meyerhof (1959).

Chow and The (1990) reported results from a theoretical investigation of pile heave due to installation of driven piles in clay. The method of analysis used provides closed-form solutions for the vertical displacements within an idealized, homogeneous half-space. It was concluded that ground surface heave increases with the pile diameter and the penetration depth of the pile. The rate of increase in surface heave is slow when the pile penetrates beyond a certain depth. Beyond this depth, major soil movement is near the pile toe, where the soil is deformed downwards as well as outwards.

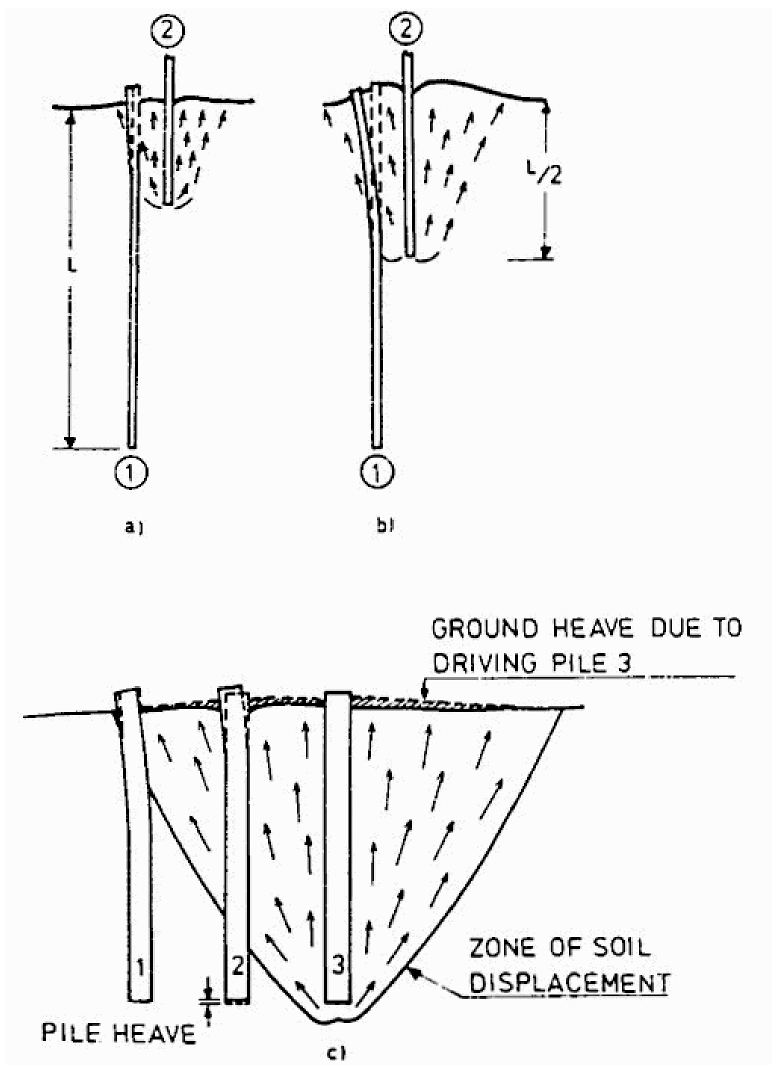


FIG 1. Pile displacement mechanism due to driving of adjacent piles in clay, after Hagerty (1969).

Massarsch and Wersäll (2013) analyzed displacement of clay during installation of a single pile. They concluded, based on an extensive review of model tests reported in the literature, that adjacent to a single pile, soil is displaced mainly in the lateral direction. Within a zone of approximately three pile diameters, vertical soil movement does not occur. This observation contradicts the generally accepted concept of soil heave occurring in the vicinity of driven piles, cf. Figure 1.

This paper focuses on the assessment of vertical ground movements occurring as a result of installing displacement piles. Starting from the problem of a single pile driven into clay, the more complex, cumulative displacement effects of a pile group will be discussed. It can be shown that heave of the ground surface is mainly the result of lateral soil movements along the pile shaft. The results of finite element analyses and of model tests are compared with field measurements. This concept will be used to propose a simplified method of determining ground heave outside and in the center of a group of piles.

SOIL DISPLACEMENTS DUE TO PILE DRIVING

Model Tests

Massarsch (1976) carried out model tests in the laboratory to study the displacement pattern when a group of piles is driven into clay. The geometric scale of the model tests was 1:25. The soil used in the investigation consisted of a mixture of kaolin, oil, glycerin, and an emulsifier. The clay was placed in layers into a 180 mm deep box with dimensions 500 x 250 mm. The clay surface was then preloaded by a steel plate for a time period of 20 h. The undrained shear strength of the clay after preloading was 35 kPa. Surface displacements and heave were measured by stereo-photogrammetry. The tests results with respect to lateral soil displacement were discussed by Massarsch and Wersäll (2013).

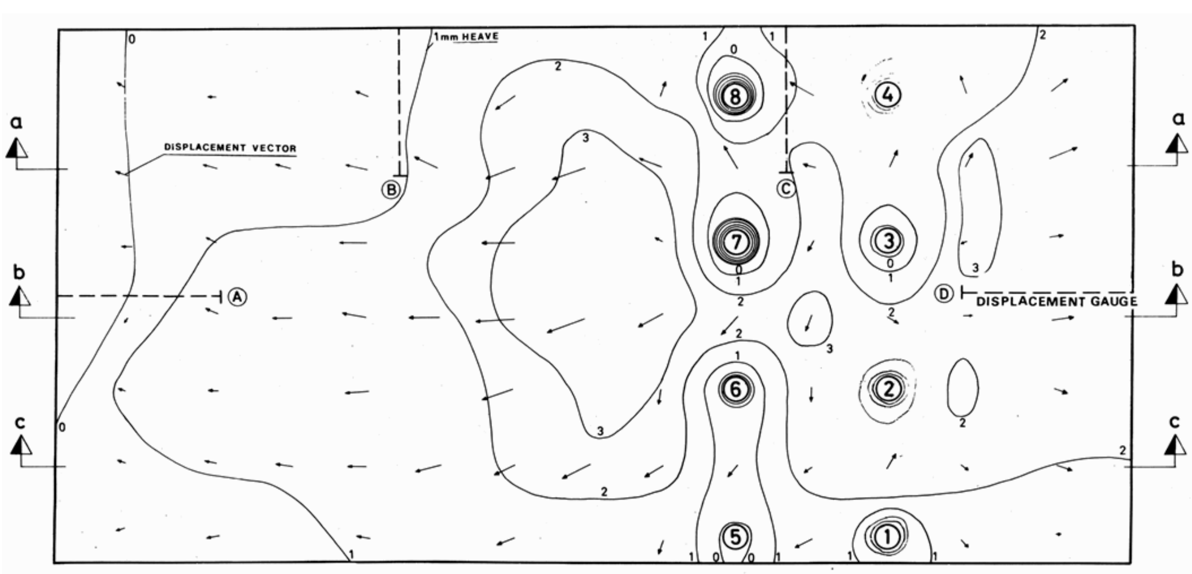


FIG 2. Surface movements due to installation of 8 model piles in clay (Massarsch 1976).

Surface movements occurred in the horizontal and vertical direction as illustrated in Figure 2. It should be noted that the effect of the rigid wall of the model test box influenced soil movements. However, it is apparent that the displaced soil volume (heave) was significantly larger in front of the most recently driven piles (Piles 5 – 8) compared to the zone within the piles. Figure 3 shows soil movements after installation of 20 piles in 8 by 4 pile rows. In this paper, focus is on heave, but it is interesting to note the complex displacement path of lateral soil movement, which affects the piles in the group. For instance, the net displacement of piles in Row 4 is very small, but the incremental movement as a result of driving individual piles is significant.

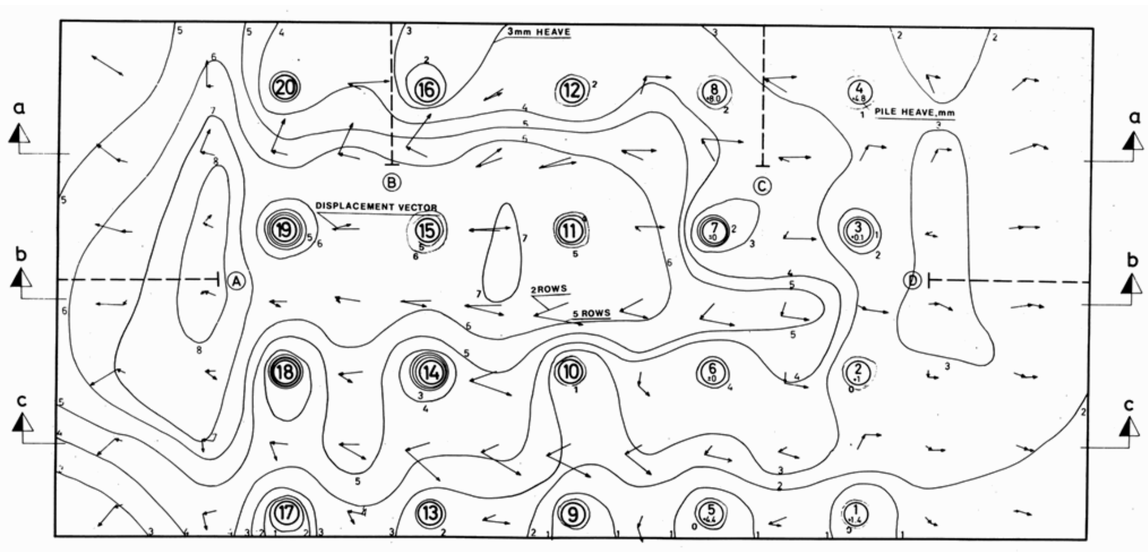


FIG 3. Surface movements due to installation of 20 model piles in clay, Massarsch (1976).

Figure 4 shows surface heave along three sections (a-a, b-b, and c-c) as indicated in Figures 2 and 3 after driving of Piles 1 through 4 and Piles 5 through 8 and after all 20 piles had been driven. The symmetrical arrangement of the pile group made it possible to investigate the distribution of heave within and outside the pile group. Heave was largest in front of the most recently driven piles and larger outside the pile group than inside.

Finite Element Analyses

Massarsch and Wersäll (2013) showed that soil displacements occur mainly radially away from a single pile and of a group of piles. The same conclusion was reached by Massarsch (1976), Poulos (1994) and Bozozuk et al. (1978) based on field measurements.

A two-dimensional (2D) finite element program (FEM), which is a further development of the LOCKS program by Nobari et al. (1971), was used for the following analyses. Stress and strain distribution can be calculated for arbitrary sequences of incremental construction and loading. The stress-strain relationships of

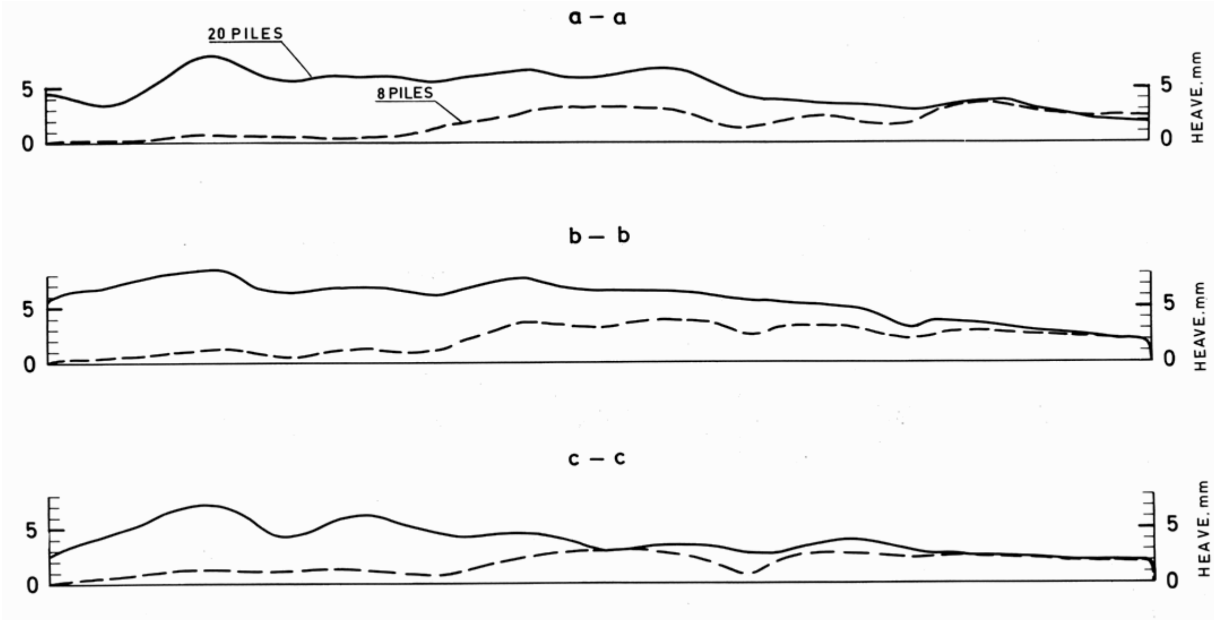


FIG 4. Surface heave along three sections with pile driving direction as indicated in Figure 2 and 3, Massarsch (1976).

soil elements can be non-linear, hyperbolic, or stress-dependent at loading, unloading, and reloading. The anisotropy of the soil is also taken into account considering the rotation of the major principal stress at failure. For details, see Massarsch (1976). The purpose of the analysis was to study the influence on lateral soil displacement of different geometrical and geotechnical parameters and stress conditions. The mesh used in the analysis consisted of 512 elements. The size of the studied soil model was 8 m deep and 22 m wide. Six different soil types were studied. *Soil I* corresponds to a soft slightly overconsolidated clay without a dry crust. The coefficient of lateral earth pressure at rest, K_0 = 1.0. The undrained shear strength increases from 5 kPa at the surface to 15 kPa at 8 m depth. The properties of *Soil II* are similar to *Soil I* but a lower value of lateral earth pressure, K_0 = 0.6 was chosen. This soil type is considered typical for Scandinavian normally consolidated clays. *Soil III* is similar to Soil II but has a 2 m thick dry crust. Soil *IV* is similar to Soil III with the exception of higher lateral stress, K_0 = 1.0. Soil *V* is again similar to Soil *II* but the undrained shear strength at passive loading was assumed to be 50 % of that at active loading. The geotechnical properties of Soil *II*, which is the soil type used in this study, are shown in Figure 5. The elastic modulus at small strain, E_i is also shown in Figure 5.Displacement due to the driving of a row of piles was simulated by laterally expanding in increments a 5 m long vertical section at the left boundary. It is assumed that soil displaces equally in all directions. The lateral expansion due to installation of a pile can then be calculated according to Figure 6 where u_{eq} corresponds to the cross section area of one quarter pile divided by the spacing between piles. Note that soil is also displaced in the perpendicular direction and needs to be considered when assessing heave within a pile group.

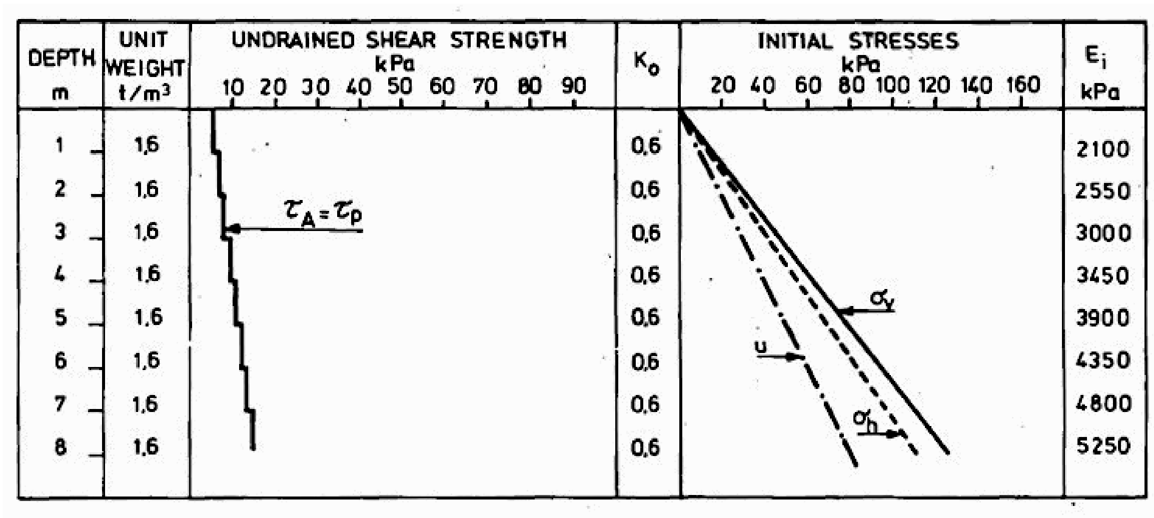


FIG 5. Geotechnical profile of Soil II.

The displacement pattern for Soil *II* caused by the lateral expansion by 10 mm of a 5 m deep zone is shown in Figure 7. Displacement vectors were initially horizontal but tilted progressively upward and vertical soil movement was minimal. This displacement pattern is similar to soil movements due to passive loading of a retaining structure. Soil heave at the ground surface is the result of the vertical component of the displacement vectors and no heave occurs immediately adjacent to the pile. Heave of the ground surface depends on the depth of the expanding boundary (length of pile) and can extend to a large distance from the expanding boundary.

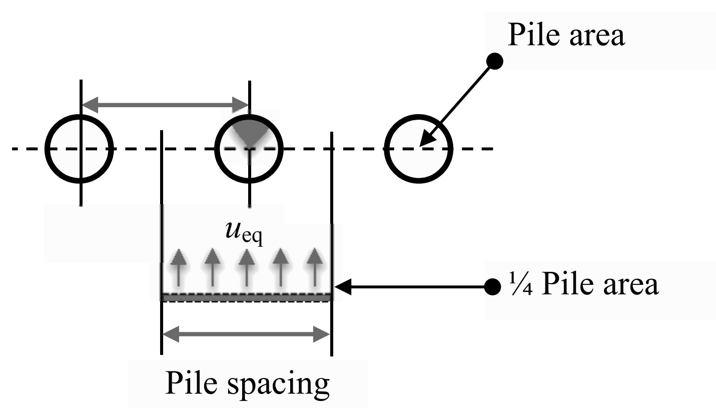


FIG 6. Definition of equivalent soil displacement, u_{eq}, caused by one pile row.

Lateral expansion was carried out in five increments of 10 mm, each. The displacement vectors in the near field are shown in Figure 8. Note the rotation of the displacement vectors towards the vertical direction as distance from the expanded zone increases.

Case History - Gothenburg

Several case histories where measurements of soil movements due to driving of pile groups in clay have been reported by Massarsch (1976). In a recent study, Edstam (2011) described detailed measurements of vertical and horizontal soil movements due to pile driving in soft clay. Driven piles were installed in the city of

Gothenburg for three bridge foundations. The 52 m long piles had square cross section with side length of b = 0.275 m. The shortest distance between piles was c = 1.3 m, with a pile spacing ratio of 4.7 (c/b). Several of the piles were installed at an inclination of 9V:1H and 7V:1H. Various measurements were carried out, including measurement using settlement gages and inclinometers of soil heave and lateral displacement at different locations and distances, during and after installation of the pile group.

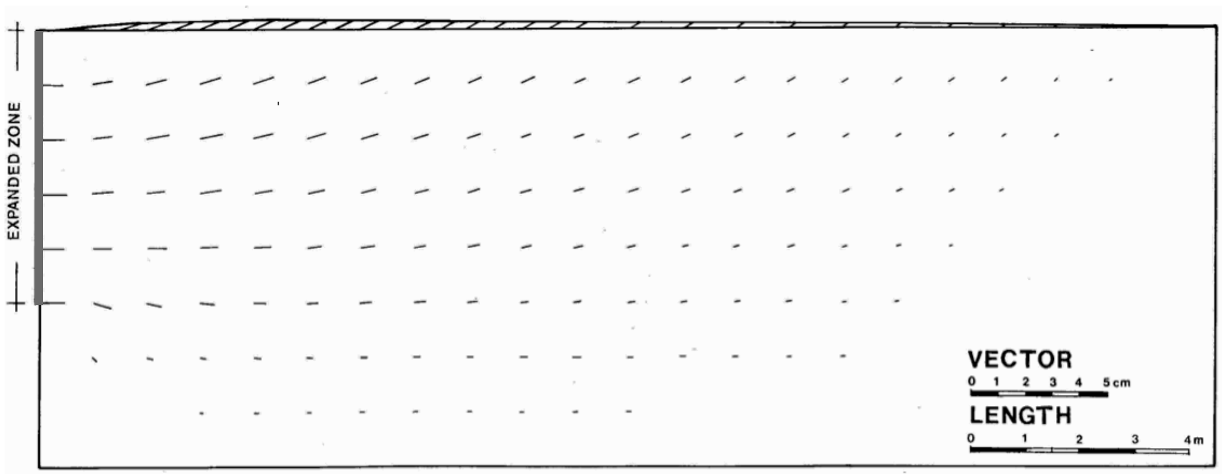


FIG 7. Displacement pattern for Soil II caused by the lateral expansion of a 5 m deep zone.

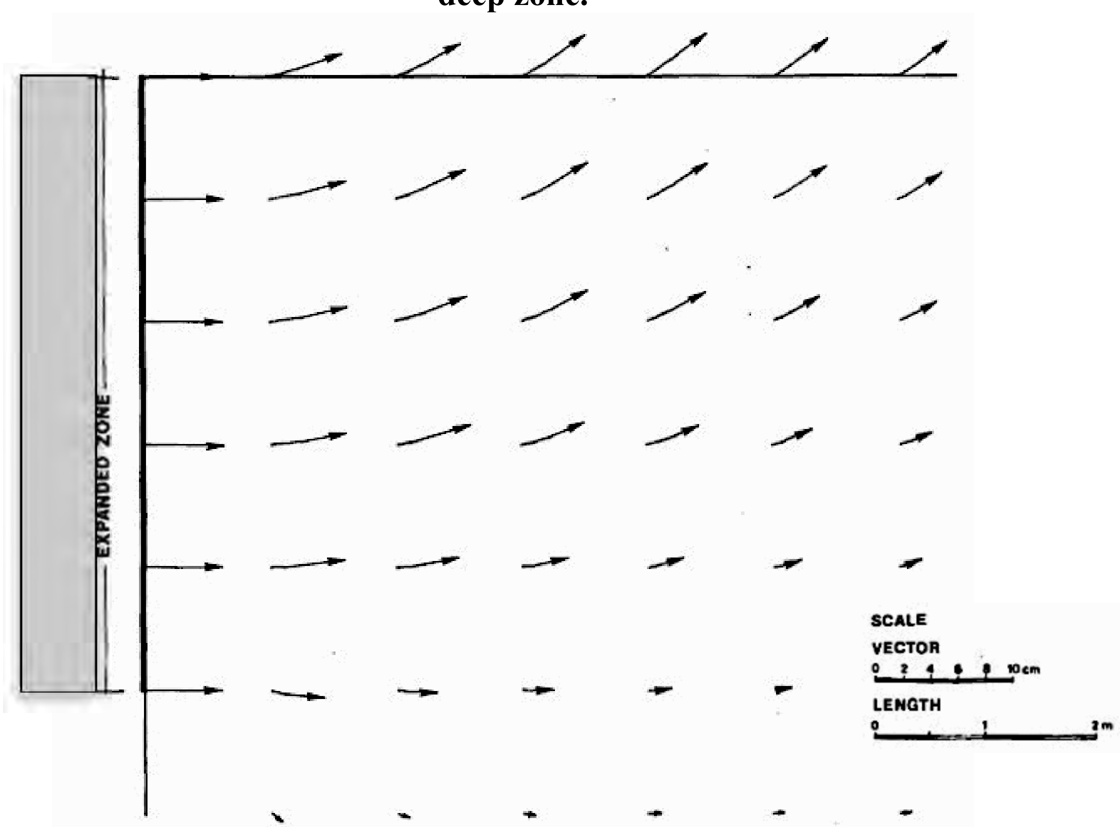


FIG 8. Deformation pattern in the vicinity of the expanded cavity, showing displacement vectors for five expansion increments of 10 mm, respectively.

The geotechnical conditions at the site are typical for soft, normally consolidated Scandinavian clay. The clay deposit extends to a depth of at least 80 m. A 1 to 2 m thick surface fill was removed prior to the investigation. The ground surface was essentially level. Below an approximately 2 m thick dry crust follows homogeneous plastic clay with water content close to the liquid limit, ranging from 60 to 80 %. The undrained shear strength determined by field vane test increased almost linearly from about 15 kPa at 5 m depth to 80 kPa at approximately 50 m depth.

Horizontal ground movements were measured using surface markers as well as by inclinometers. The inclinometer tubes extended, however, only to a depth of 40 m while the piles were 52 m long. Therefore, the inclinometer measurements were adjusted using lateral displacement measurements at the ground surface. Displacement vectors after the installation of all piles were calculated from settlement and inclinometer measurements, Figure 9.

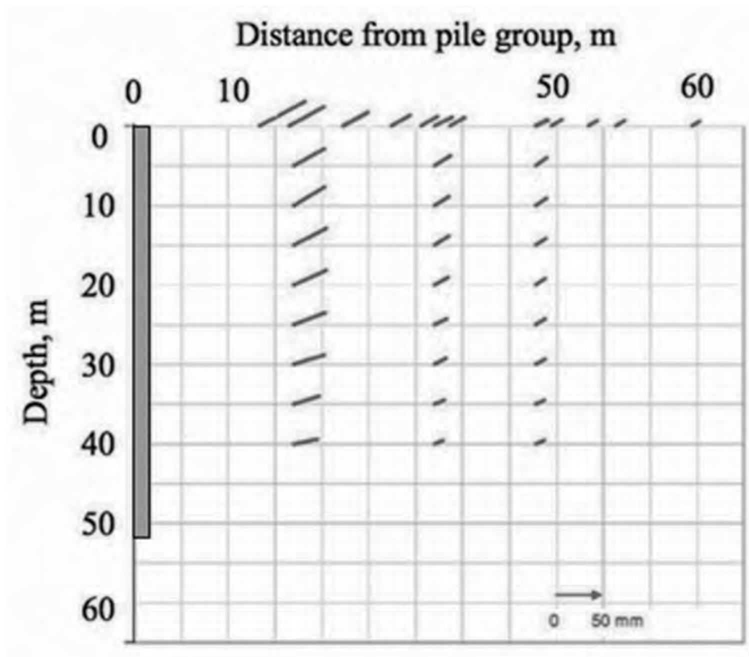


FIG 9. Displacement vectors in the north-south direction outside the pile group, after Edstam (2011).

Close to the pile group, the measured soil movements were mainly in the horizontal direction but their inclination increased toward the vertical direction with increasing distance. This displacement pattern was in good agreement with above presented results of 2D FEM analyses, cf. with Figures 7 and 8.

ASSESSMENT OF SOIL HEAVE

The results of FEM analyses have been described above, assuming that soil heave is due to lateral displacement when a row of piles is installed. Lateral displacements were determined according to Figure 6, using equivalent soil displacement, u_{eq}. The two-dimensional FEM analysis of soil heave was carried out applying four increments of lateral displacement (increments of 10 mm) for six different soil types, (Massarsch, 1976). Figure 10 shows, for *Soil II*, soil heave h_s normalized by lateral expansion u_{eq} as a function of the distance from the expanded zone X, normalized by the depth of the expanded zone, L.

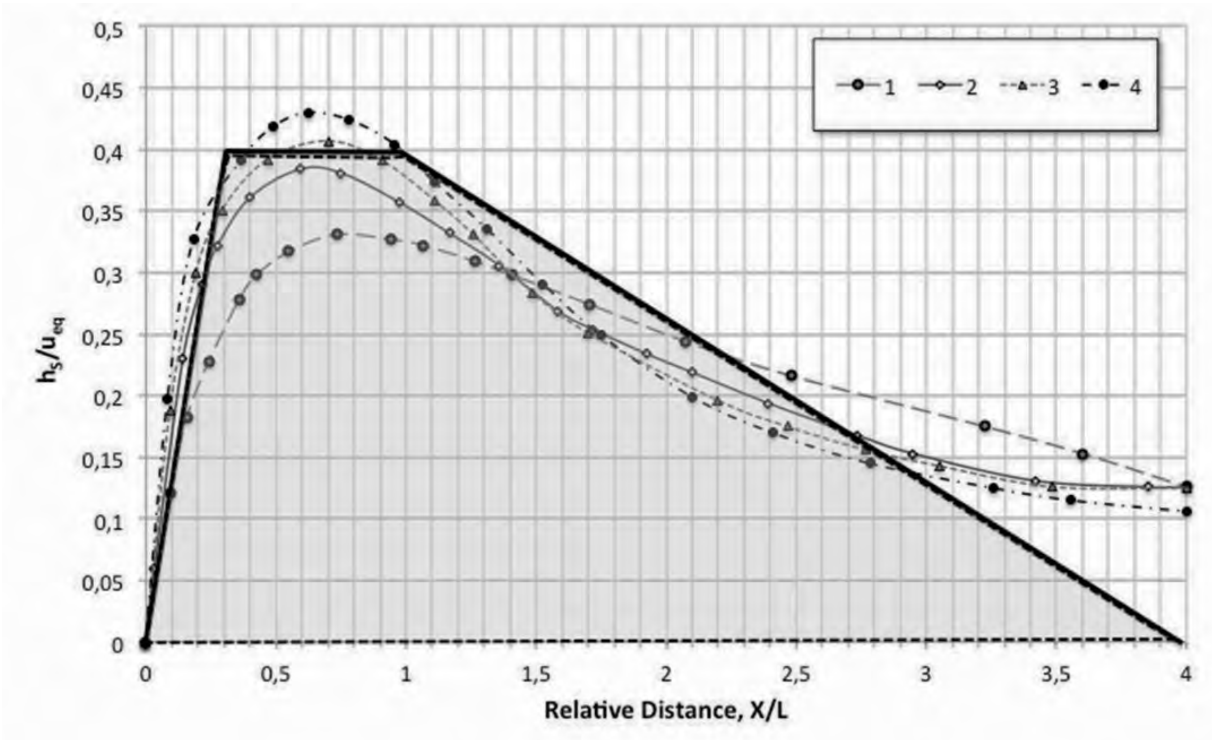


FIG 10. Heave of ground surface as a result of lateral displacement of 10 mm, due to four displacement increments - Soil Type *II*.

Magnitude of soil heave due to the first displacement increment is lower but extends to a larger distance than the following increments. In the case of the fourth displacement increment, the peak of soil heave occurs closer to the expanded zone and is larger than for previous expansion increments. Also, soil heave decreases more rapidly than in preceding expansion increments. This effect is probably due to a strain softening effect of the soil that developed at higher strain levels. Similar distributions of surface heave were obtained from analyses of other soil types, (Massarsch, 1976).

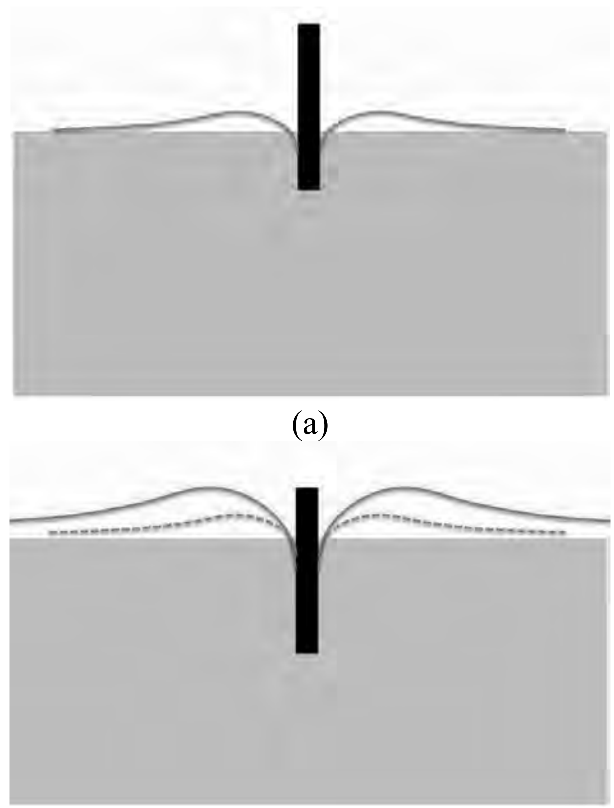
An important conclusion of the FEM analysis is that heave h_s increases initially from zero with growing distance X from the pile row and reaches a maximum at a normalized distance of approximately 0.3 – 1.0 L/X, where L is the depth of the expanded zone (pile length). Heave is directly related to lateral soil displacement, i.e pile spacing and pile area. The peak normalized heave $h_s/u_{eq} \approx 0.40$. At a distance of $4L$, soil heave can be assumed to become negligible for practical purposes. Therefore, it is possible to estimate the distribution of soil heave adjacent to a pile row using the simplified shape shown in Figure 10.

In the case history discussed above, piles were installed to a depth of 50 m at a spacing of 1.3 m (corresponding to a relative pile spacing of 4.7 pile diameters). The equivalent lateral displacement (due to driving of one pile row) is approximately 30 mm, resulting in a maximum heave of the ground surface of approximately 12 mm, occurring at a distance of about 25 m. Soil heave decreases gradually with increasing distance and is negligible at a distance of 40 m. However, it is necessary to consider the cumulative effect of several pile rows which increases lateral soil displacement.

This aspect, which has been described by Massarsch and Wersäll (2013), will be discussed in the following section, including guidance for its practical application.

Conceptual Model of Soil Heave

In the following, a hypothesis is presented which describes the soil displacement effect due to pile installation in an area of level ground surface. A sketch of the shape of soil heave due to pile installation is shown in Figure 11 for two depths of pile penetration. The amount of soil heave depends primarily on the degree of lateral displacement (pile diameter) while the lateral extent of soil heave (zone of heave) depends on pile length. Maximum soil heave occurs at a distance of approximately 0.3 to 1.0 times the penetrated depth. During the initial phase of pile penetration (Figure 11a), maximum heave occurs relatively close to the pile. With increasing pile penetration, maximum surface heave occurs at larger distance as the area of influence expands, cf. Figure 11 b.



(a)

(b)

FIG 11. Heave of ground surface during pile penetration at (a) shallow, and (b) deeper pile penetration. The extent of the zone of soil heave increases with depth of pile penetration.

Cumulative heave of the ground surface due to the installation of several rows of piles is shown as a principle sketch in Figure 12. Heave occurs incrementally as a result of driving each row of piles and soil displacement is symmetrical perpendicular to the pile row. In this example it has been assumed that previously installed piles do not affect horizontal and vertical soil displacement. This aspect will be discussed in more detail below. Figure 12 illustrates that, with the exception of very long piles, most of soil heave occurs outside the pile group, which is also apparent when considering the shape of soil heave as shown in Figure 10. The effect of pile length on soil heave is further illustrated by comparing two cases; four rows of piles, 10 and 30 m long, are installed at the same pile spacing, cf. Figure 13. A comparison of the two cases shows the effect of pile length on soil heave. The longer the pile, the larger is the zone of soil heave surrounding the pile group. The volume of soil heave inside the pile group decreases with increasing pile length, compared to the size of the pile group. Thus, the widely used rule of thumb that approximately half of the heave occurs within a pile group is not supported by this investigation. The rule appears to be restricted to a case of a large group of short piles.

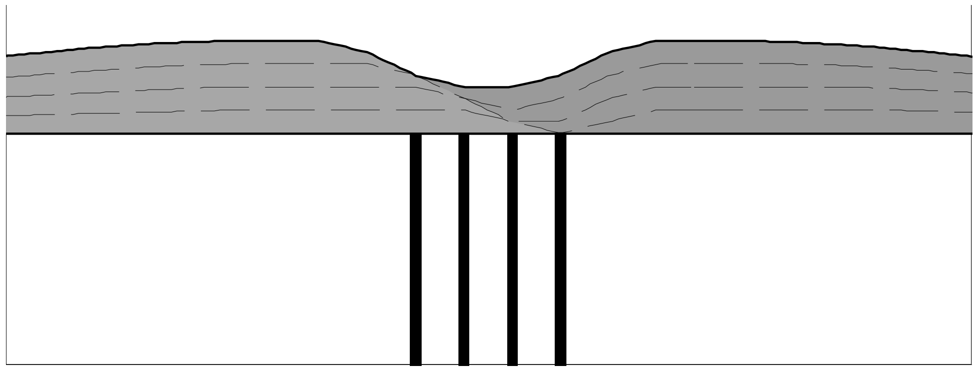


FIG 12. Principle sketch of ground heave determined from the superimposed heave of four pile rows. Blue implies heave to the left and grey to the right of the installed pile.

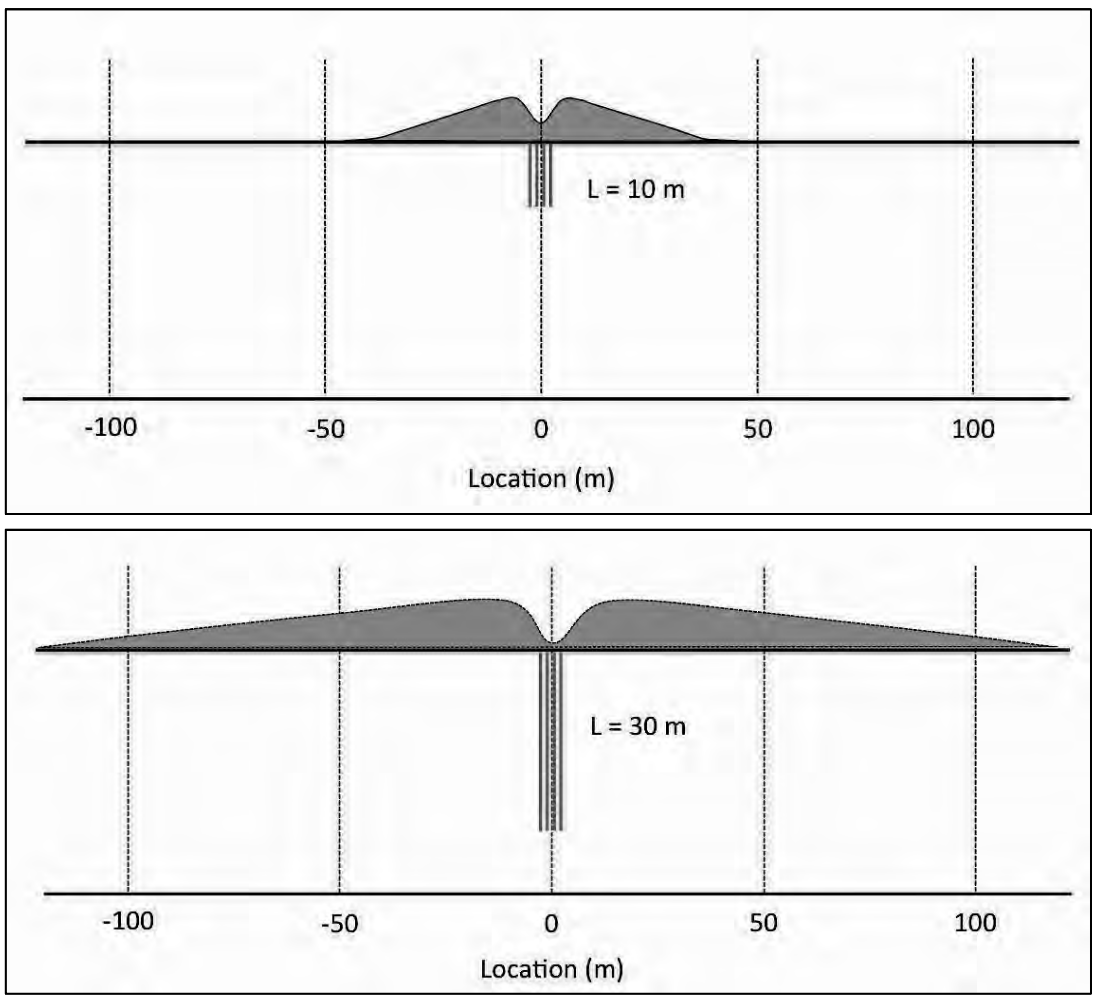


FIG 13. Illustration of lateral extent of soil heave due to installation of 10 and 30 m long piles, respectively. Note that maximum heave is the same for both cases and thus independent of pile length.

This example shows that pile spacing and length of pile are the two most important parameters when assessing the distribution of soil heave within and outside a pile group. Pile diameter and pile spacing affect heave while pile length determines the zone of influence.

It is important to note that the proposed, simplified method of estimating soil heave is based on the assumption that already installed piles do not affect vertical and horizontal soil movement and that displacement by individual piles can be replaced by a continuous, infinitely long wall with equivalent area, cf. Figure 10. The latter assumption implies that calculation is essentially 1D. Accurate determination of surface heave due to installation of a group of piles would require more sophisticated analytical methods, preferably 3D FEM analyses.

The assumption of an expanding wall is strictly valid for a long row of piles located close to the middle of that row. Surface heave at some distance (approximately 5 pile diameters) outside the pile group can be calculated with reasonable accuracy according to Figure 6. However, towards the edges of the pile group, the accuracy of heave prediction will decrease. This is illustrated by Figure 14 which shows a 9x9 pile group. Surface heave in the center of the pile group is caused by soil displacement (and thus heave) from two perpendicular directions, marked in gray. Heave inside the pile group results from the sum of heave caused by soil movements in perpendicular directions. The location where total heave can be determined accurately by the proposed method is in the center of the group. In the case of a symmetrical pile group, total soil heave will be twice the value calculated for one direction. For all other locations, total heave will be range between heave determined from one and two direction.

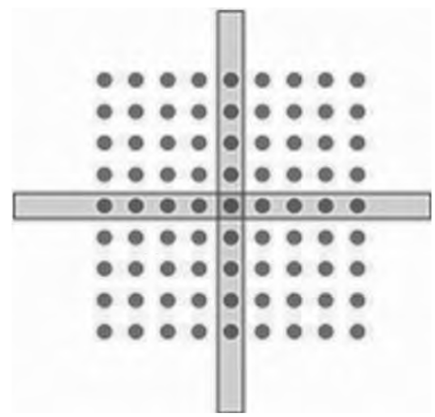


FIG 14. Determination of soil heave for pile group in two perpendicular directions. Heave in center of pile group is obtained by superimposing heave determined from two perpendicular directions.

Effect of Driven Piles on Heave

It is generally accepted that the lateral resistance of piles can be neglected when estimating lateral soil movements, (Massarsch and Wersäll, 2013). When a group of piles is driven into soft, normally consolidated clay, pore water pressure increases. This, together with mechanical disturbance (incremental displacement of soil) can cause a reduction of soil stiffness. Consequently, there could be a tendency of soil movement toward recently driven piles. This reduction in clay strength and stiffness can be compensated by the increased stiffness due to the installed piles. With regard to lateral soil movements it is therefore a realistic assumption to disregard the effect of already driven piles. This, however, may not apply to heave of the ground surface.

The resistance of piles against uplift is larger than that to horizontal forces. Model tests and field observations suggest that heave is larger in front of a pile group, close to most recently driven piles, cf. Figure 2, 3 and 4. Thus, there appears to be a difference between already installed piles and previously installed piles with regard to how vertical and lateral soil movements are affected. Several case histories in the literature describe the heave of driven piles, (Hagerty and Peck, 1970, Poulos, 1994 and Massarsch, 1976). In normally consolidated, medium or no-sensitive clay, the shaft resistance of piles will be at least partially mobilized within a few hours after driving. Massarsch (1976) analyzed the effect of already driven piles by FEM analyses. Figure 15 shows how vertical and horizontal soil displacements are affected by a previously installed row of piles, driven into a stiff bottom layer, assuming that these piles are not allowed to move vertically. It has been assumed that the pile toe is rigidly connected to the bottom layer. Lateral movements appear not to be affected by previously installed piles while the distribution of vertical movements and, consequently, the amount of heave of the ground surface are affected significantly. Soil heave increases in the zone between the existing piles and the driven piles, but are reduced surrounding the existing piles. Figure 16 shows the effect of one previously driven row of driven piles on soil heave. The normalized soil heave is compared with the case without piles, cf. Figure 10. Normalized soil heave increases from approximately u_{eq} = 0.40 to u_{eqP} = 0.50, an increase by approximately 25 %.

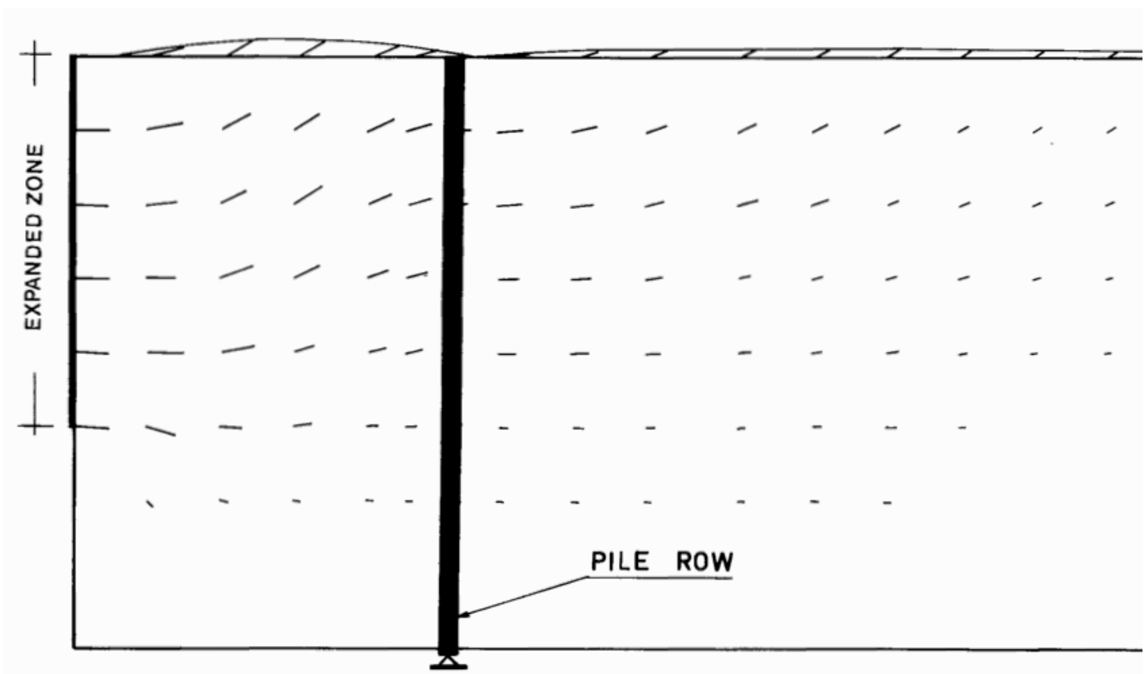


FIG 15. Effect of previously driven piles on soil movement and heave, cf. Figure 7.

It can be concluded that already driven piles resist upward movement of soil and affect the distribution of soil heave, which is increased close to the pile and decreases around the previously driven pile. The total volume of displaced soil is not affected. It is important to recognize that the above example is intended to illustrate a hypothetical case of an existing pile row that needs to be interpreted with judgment.

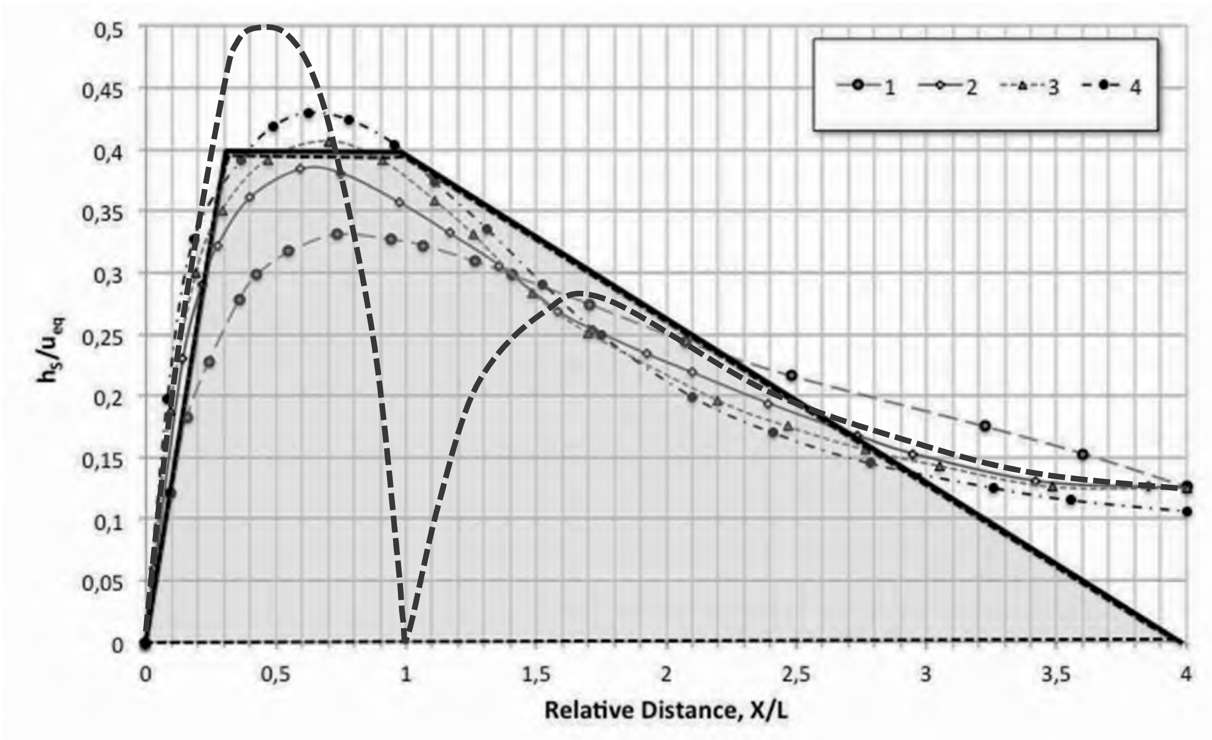


FIG 16. Effect of previously driven pile on normalized soil heave (broken line according to Figure 15) and normalized soil heave without pile row, cf. Figure 10.

EXAMPLE

The following case is intended to illustrate how the above-presented concepts can be used to predict heave due to installation of a pile group, installed in soft clay, Figure 17. Thirty-six concrete piles are installed in 4 rows in a square grid at spacing of 1.5 m, corresponding to a spacing of 5 pile diameters. The piles have a side length of 0.30 m x 0.30 m. Two cases have been assumed to illustrate the effect of piles with an effective length of10 and 30 m, respectively. The ground surface is assumed to be level.

The pile group shall be installed at a distance of 3 m from the closest pile row of an existing bridge foundation, supported by six piles. The piles are driven in four rows from right to left, starting with the row closest to the existing bridge foundation <1>. The 36 piles and the 6 piles of the existing bridge foundation are shown in Figure 17, also indicated is the sequence of pile installation.

Lateral displacements due to pile installation for the same example have been analyzed in the companion paper by Massarsch and Wersäll (2013). In this section, the distribution of soil heave inside and surrounding the pile group is estimated. The analysis is based on the concept of normalized heave shown in Figure 10. The effect of previously driven piles on lateral displacement and heave is neglected. From the above information of square pile cross-section, the equivalent pile radius has been calculated, r_0 = 0.17 m. Each pile row has been replaced by an equivalent continuous strip, having the same cross-sectional area as a quarter of the sum of individual piles

(Figure 6). Assuming that the soil is incompressible, equivalent displacement becomes 15 mm. Figure 18 shows the calculated heave according to the above described principle. In the top figure, piles have a length of 10 m and in the bottom figure, a length of 30 m, respectively. The maximum heave is 24 mm and occurs in both cases outside the pile group. It can be seen that the extent of heave, radially, is greatly influenced by pile length. Note that maximum heave is the same for both cases as the pile spacing and lateral displacement are the same. However, the total volume of heave is larger for the longer piles. On the other hand, the volume of heave is larger within the group for the case of shorter piles. This is observed more clearly in Figure 19, showing an enlargement of heave within the pile group. It is noteworthy that for long piles, heave within the group constitute only a minor part of the total volume of displaced soil. The bridge foundation, to the right of the pile group experiences the maximum heave in the case of short piles. The longer piles cause maximum heave at a greater distance than at the location of the bridge foundation.

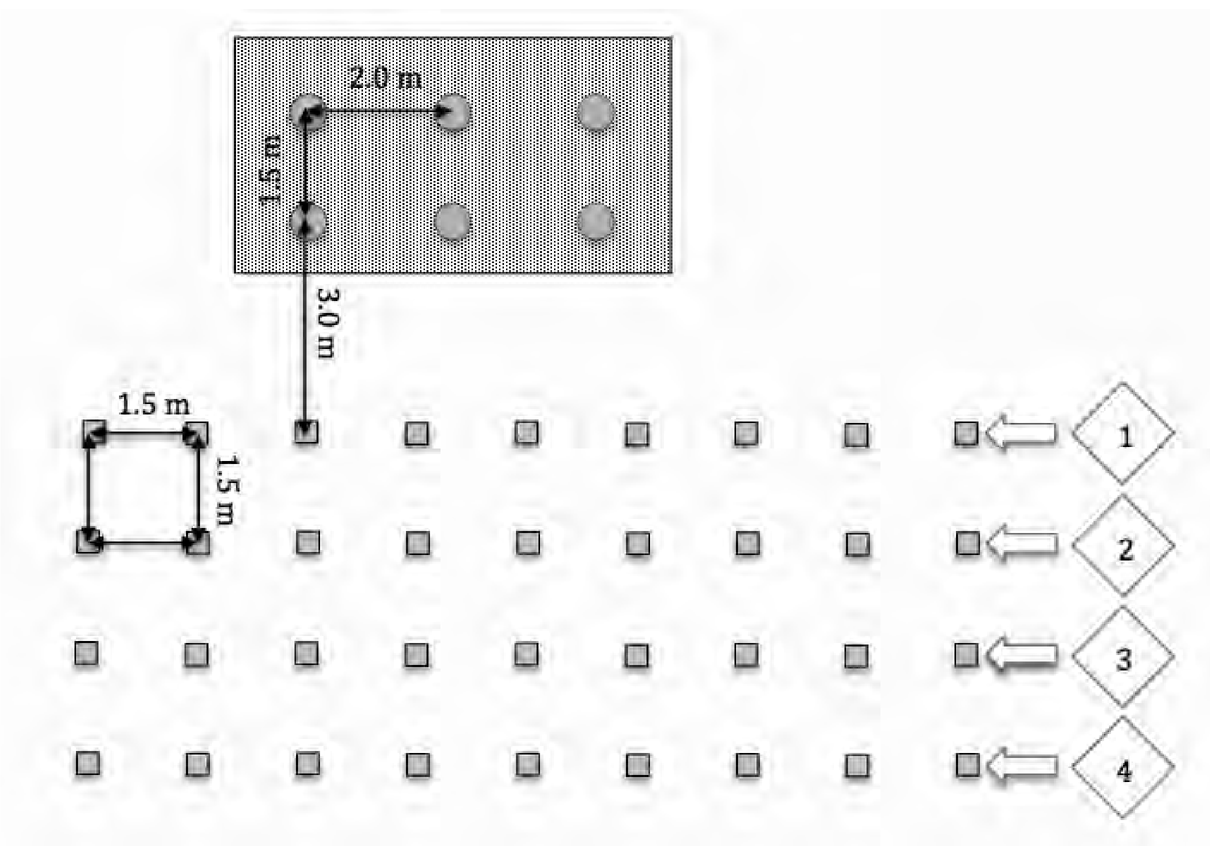


FIG 17. Pile group driven adjacent to an existing pile-supported bridge foundation. Sequence of driving pile rows and driving direction are indicated.

Figure 19 also shows the upper bound of soil heave within the pile group considering 2D heave effects, as a dotted line. This is assumed to be twice the value of heave calculated in one direction, cf. Figure 14. The true total heave would be between the 1D calculated (solid) and the maximum doubled (dotted).

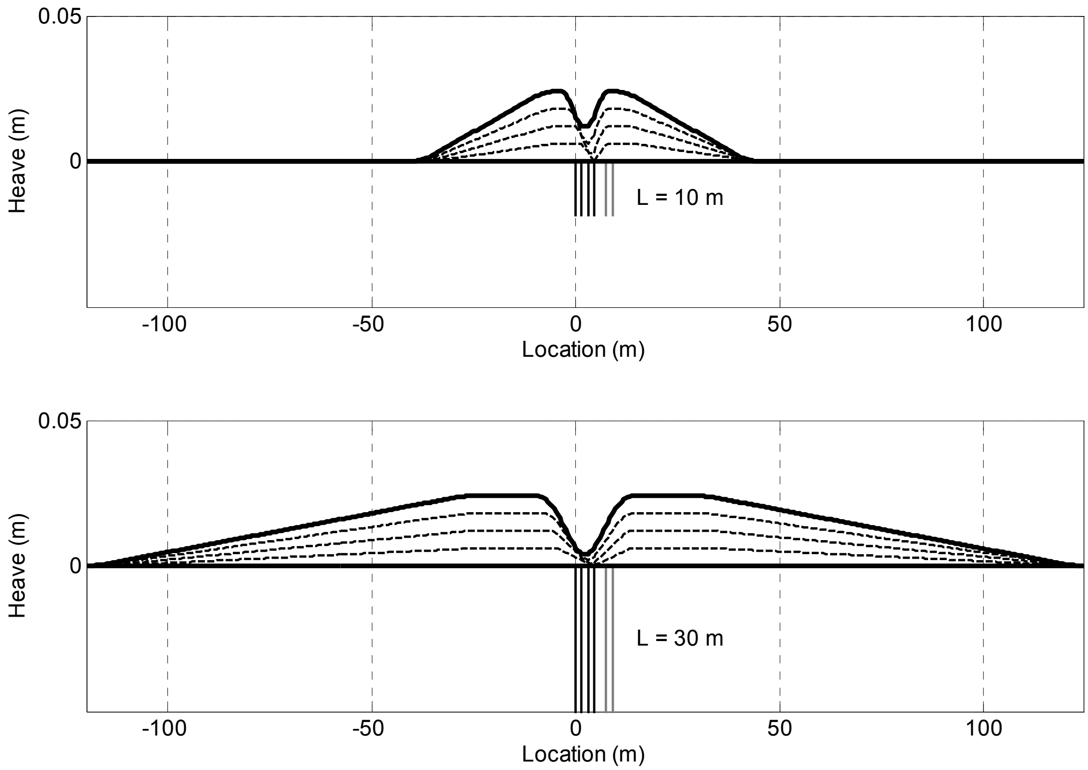


FIG 18. Calculated heave from installation of 4 pile rows (black lines). The piles of bridge foundation are shown in gray.

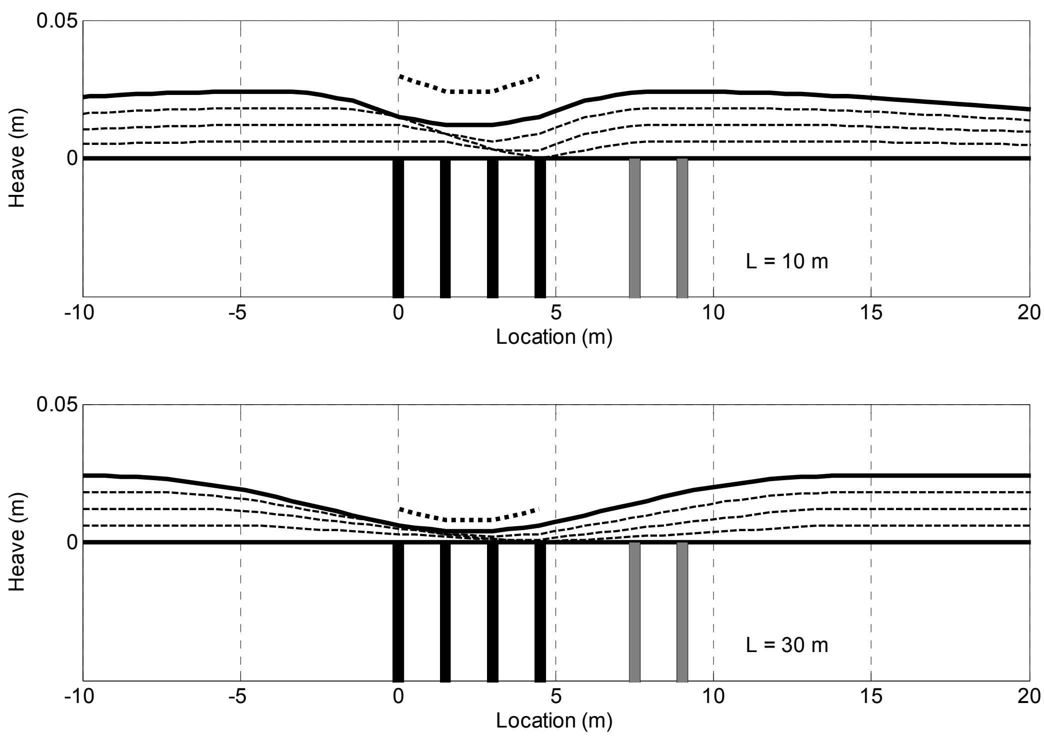


FIG 19. Enlargement of Figure 17 in vicinity of pile group, showing the calculated heave due to installation of 4 pile rows (solid). Total heave indicated by dotted line.

CONCLUSIONS

The effect of soil movement due to installation of preformed piles is documented by case histories reported in the geotechnical literature. This paper addresses heave of the ground surface due to installation of piles in clay. Cumulative lateral displacement has been analyzed in a companion paper to this conference, (Massarsch and Wersäll, 2013). Rules of thumb, which have been proposed and are frequently used for estimating the distribution of soil heave caused by pile driving in clay, are reviewed. Based on model tests, FEM analyses and review of field observations, the following conclusions are made. These are illustrated by a case history.

- Heave is due to lateral displacement caused by pile penetration. Close to the pile, heave is generally small. This observation contradicts the simplified concept of soil heave adjacent to a driven pile.
- Soil heave depends on lateral soil displacement, which is governed by pile cross-section area and pile spacing while pile length has negligible influence on heave.
- Model tests suggest that soil heave occurs mainly outside (in front of) the most recently driven piles while lateral soil displacement appears not to be affected by previously driven piles.
- Soil displacement was studied by 2D FEM analyses, simulating the installation of a pile row by the lateral expansion of a vertical boundary. Different soil types were studied and lateral displacement was increased in five increments to study the effect of strain-softening.
- Equivalent lateral soil displacement u_{eq} due to installation of one pile row is used to estimate soil heave. It can be determined, based on pile diameter and pile spacing.
- Based on the FEM analyses, a simplified concept is proposed to estimate surface heave, which assumes that maximum heave corresponds to approximately 0.40 u_{eq} and occurs at a distance of between 0.30 and 1.00 pile length. In most cases, soil heave occurs primarily outside of a pile group. The rule of thumb that approximately half the displaced soil appears as heave inside a pile group cannot be justified, as lateral distribution of soil movement depends on pile length. Only in the case of a large group of short piles (pile length about 1/3 of pile group size), this assumption may be valid.
- At a distance exceeding four pile lengths, soil heave is small but still noticeable. For practical purposes, it is assumed that all soil heave occurs within a radius of four pile lengths and increases linearly toward the pile group boundary.
- While previously driven piles have negligible effect on lateral soil movement, vertical displacements are reduced due to the mobilization of shaft friction. Consequently, soil heave increases in the zone between the new and recently driven piles and decreases beyond. This effect can explain the reason for increased soil heave in front of a row of driven piles.

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