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Cumulative Lateral Soil Displacement Due to Pile Driving in Soft Clay

K. Rainer Massarsch[1], Dr. Sc., and Carl Wersäll[2], M.Sc.

[1] Geo Risk & Vibration Scandinavia AB, Ferievägen 25, SE-168 41 Bromma, Sweden. <rainer.massarsch@georisk.se>

[2] Department of Civil and Architectural Engineering, Royal Institute of Technology, SE-100 44 Stockholm, Sweden. <carl.wersall@byv.kth.se>

ABSTRACT Installation of preformed piles in clay causes lateral displacements of soil and of foundations of nearby structures embedded in the ground. The problem has been assessed by first analyzing the displacement effects of a single pile based on model tests and numerical analyses. Lateral soil displacement can be predicted using cavity expansion theory. Model tests were performed to study lateral displacements of soil due to installation of a group of piles. The results of theoretical analyses and model tests were compared with field measurements. A method is proposed to estimate cumulative lateral soil displacements caused by the installation of a pile group. The effect of sloping ground on lateral soil movements is addressed. Prediction of lateral soil displacement due to installation of several rows of piles in clay is illustrated by a practical example.

1. INTRODUCTION

In many countries with difficult ground conditions, driven piles are a widely used foundation method to support road embankments, bridge approach abutments, industrial or residential buildings, and other types of structures. Densely populated areas are frequently located along the coast or near lakes where deep deposits of soft and sensitive clay occur. In some regions of Sweden, it is not uncommon that piles are driven to bedrock at between 50 and 100 m depth. Preformed concrete piles or timber piles are a cost-effective foundation alternative for many infrastructure projects. Concrete piles with square cross section typically have a side length ranging between 0.22 to 0.30 m and are placed at a spacing of 1 to 2 m, corresponding to approximately 4 to 6 pile diameters. Extensive research has been carried out in Sweden to improve the understanding of the driving process and to assess the capacity of piles. Stress-wave measurements are performed routinely to check that the required pile capacity is reached. However, comparatively few investigations have considered the effects of pile driving in the construction phase, and in particular soil displacement effects.

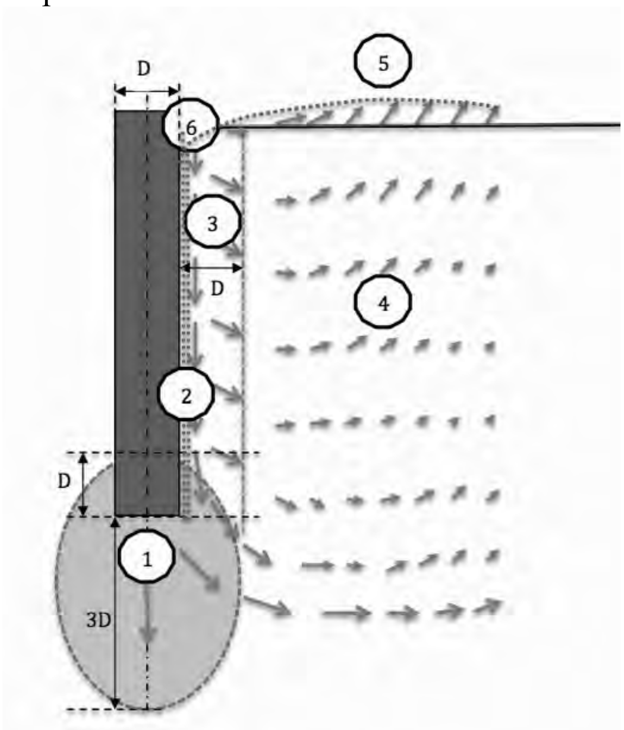
Driving of piles into soft deposits of clay and silt will result in horizontal and vertical soil movement, which manifests itself as heave of the ground surface. Although the ground is also displaced laterally, such movements are more difficult to detect than heave. However, lateral soil movements can have a detrimental effect on foundations of structures or installations in the ground. An important consequence of driving a group of piles in clay is the effect of ground movements on already installed piles, affecting axial forces and bending moments and potentially jeopardizing the structural integrity of piles.

Lateral soil displacement due to pile driving in clay is reported only in a limited number of publications. A major reason is that engineers at the design stage of a project are not aware of the potentially detrimental effects of soil displacement. Detecting lateral ground movement on a construction site is a difficult task and the risk of damage to instrumentation is high. Once lateral movements of piles or structures are observed, it is usually too late to modify the pile installation process.

In a companion paper to this conference, heave of the ground due to pile driving is discussed, (Wersäll and Massarsch 2013). This paper addresses lateral soil displacement caused by driving a group of piles into soft clay. As a first step, the problem of lateral soil displacement due to installation of a single pile is analyzed, using results of model tests. However, model tests have limitations due to the scale effect and influence of boundary conditions. Another important problem is preparation and manufacture of the test soil, which often involves mixing of artificially manufactured clay. Therefore, results of model tests need to be interpreted with judgment. Also, construction site situations, such as the sequence of pile installation and time effects, are difficult to model. Cumulative lateral soil displacement can be analyzed using the theory of an expanding cylindrical cavity. However, the effect of previously driven piles is neglected. A computer program was developed which makes it possible to calculate cumulative lateral ground displacements for the case of level and inclined ground. Finally, an example is presented which demonstrates the practical application of the proposed method of estimating lateral soil displacement.

2. SOIL DISPLACEMENTS AROUND SINGLE PILE

In order to analyze the effects of pile driving in clay it is important to understand the displacement field that is developed during pile penetration. Massarsch (1976) reported results of model tests in a box filled with artificially manufactured clay and proposed that the zone of soil disturbance extends approximately one pile diameter from the perimeter of the pile. Soil displacement was assumed to be caused by an expanding cylindrical cavity without taking into account soil movements at and below the pile toe. Randolph et al. (1979) used radiographic techniques to investigate the deformation pattern around a pile driven into clay. These results are considered fundamental in understanding the disturbance effect caused by pile penetration. Ni et al. (2010) reported results from small-scale model tests in an artificial mixture of clay and oil by particle image velocimetry, from which the soil displacement pattern during pile installation was obtained. Figure 1 shows the displacement field adjacent to the pile during penetration into soft clay, based on observations from these model tests. Six areas have been identified, which are of importance for understanding the displacement field and soil disturbance caused by penetration of a single pile.



(1) Zone of disturbance below pile toe.

(2) Smear zone along the pile shaft.

(3) Zone of disturbance adjacent to the pile shaft.

(4) Displacement pattern adjacent to the zone of disturbance.

(5) Displacement at ground surface.

FIG 1. Schematic illustration of the displacement field and zones of disturbance during pile installation.

Zone (1): is the most important zone with regard to ground movement when the pile penetrates into incompressible soil. At the pile toe, a bulb with high pressure is created during driving. This bulb moves progressively downward as the pile penetrates into the ground. The width of the bulb is approximately three pile diameters. Thus, the zone of intense soil disturbance extends approximately one pile diameter from the pile shaft, one pile diameter upward and three pile diameters downward from the pile toe as has been shown in the model studies reported by Randolph et al. (1979) and Ni et al. (2010). At the perimeter of the bulb, the soil is displaced primarily in the lateral direction. As the pile toe passes a given level, significant lateral movement occurs, but thereafter only little further movement can be observed. Consequently, in the case of a straight-shaft pile, soil displacement is primarily due to the expansion of the pressurized bulb of Zone 1.

Zone (2): is the smear zone, which is created by the relative movement of the pile shaft against the adjacent soil. However, model tests show that the downward component in this zone is relatively small. The structure of the soil is almost completely destroyed but the width of this smear zone is thin. In sensitive clay, this zone turns into a liquid and the smear zone width can reduce to a few millimeters and is almost independent of the diameter of the pile.

Zone (3): mechanical disturbance occurs within a zone of approximately one pile diameter from the pile shaft. Behind the pressure bulb, a zone of disturbance is created within which the undrained shear strength of the soil is reduced. This disturbance is caused by the progressive downward movement of the pressurized bulb at the pile toe and not by the pile shaft. At the perimeter of Zone 3, the soil is displaced primarily in the lateral direction.

Zone (4): during pile penetration, this zone is subjected to resistance caused by passive earth pressure, resulting from the expansion of the pressure bulb of Zone (1). The displacement pattern in this zone is based on results of finite element analyses (Massarsch, 1976) and confirmed by field measurements (Massarsch, 1976 and Edstam, 2011). The flow pattern from the pile is initially lateral, but the displacement vectors gradually rotate toward the ground surface.

Zone (5): heave of the ground surface resulting from pile driving is small in the vicinity of the pile and reaches a maximum at a distance of about 0.3 to 1.0 times the pile length; thereafter heave decreases with increasing distance.

Zone (6): adjacent to the driven pile, it is common to find a gap and/or depression between the pile shaft and the surrounding soil. This effect is the result of the downward movement of the pile toe during the initial phase of driving.

Figure 1 suggests that soil movement due to driving a single pile can be investigated by assuming a simplified displacement pattern. The main cause of soil displacement is the progressive penetration of a pressurized bulb. Below the pile toe, soil displacement occurs mainly downward and in the lateral direction. Radial displacement occurs suddenly as the pile toe passes a given level. Negligible further soil movements occur as the pile continues to penetrate. Above the pile toe, at the perimeter of the zone of disturbance (3), soil displacements vectors point primarily in the lateral direction and with increasing distance rotate progressively towards the ground surface.

3. LATERAL SOIL DISPLACEMENT DUE TO PILE INSTALLATION

3.1. Expansion of Cylindrical Cavity

As shown in the previous section, the pattern of ground movement due to installation of a single pile is complex. However, for practical purposes, it is considered sufficient to assume that ground movements at the toe of the pile at a distance of approximately one pile diameter from the pile shaft occur primarily in the lateral direction. Thus, total radial stress change and soil displacement can be estimated on the basis of modeling pile installation as the expansion of a cylindrical cavity. Assuming an incompressible soil and plain strain conditions in the direction of the pile axis it is possible to calculate lateral soil movement, u, at distance X due to the expansion of the pile radius R_0 (Randolph et al., 1979), as expressed in Eq. 1.

$$\frac{u}{R_0} = \left[\left(\frac{X}{R_0} \right)^2 + 1 \right]^{0.5} - \frac{x}{R_0} \tag{1}$$

Figure 2 shows calculated lateral ground displacement due to expansion of a cylindrical cavity according to Eq. 1. Results from field observations (Cooke and Price, 1973) and of several model tests are also shown. The model tests reported by Ni et al. (2009) were carried out at a small scale and displayed significant variations of soil movement, of which average values are plotted in Figure 2.

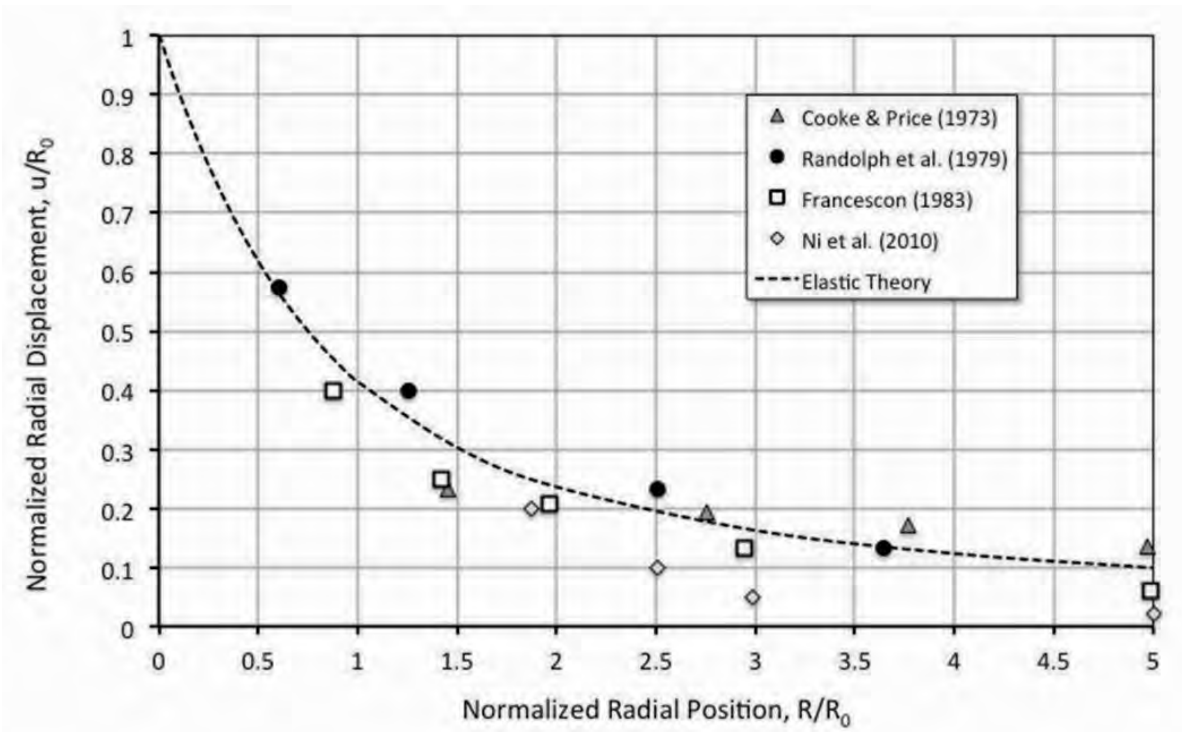


FIG 2. Variation of radial soil displacement according to Eq. 1 and comparison with model tests reported in the literature.

Agreement between theoretical predictions and observed lateral soil displacement in clay is surprisingly good. It can be concluded that Eq. 1 reasonably represents lateral soil movements caused by the installation of a single pile in clay. It should be pointed out that pile length does not affect lateral ground movements in the close and medium distance from a pile. When a pile is driven into water-saturated, soft clay, the displaced soil volume corresponds to the volume of the pile driven into the ground.

3.2. Model Tests of Pile Group Installation

Model tests were carried out in the laboratory to study soil displacements when a group of piles is driven into clay. A detailed description of the tests and the interpretation of results have been given by Massarsch et al. (1976). The 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 hours. The undrained shear strength of the clay after preloading was 35 kPa. Surface displacements were determined using stereo-photogrammetric measurements. Figure 3 shows the tests arrangement.

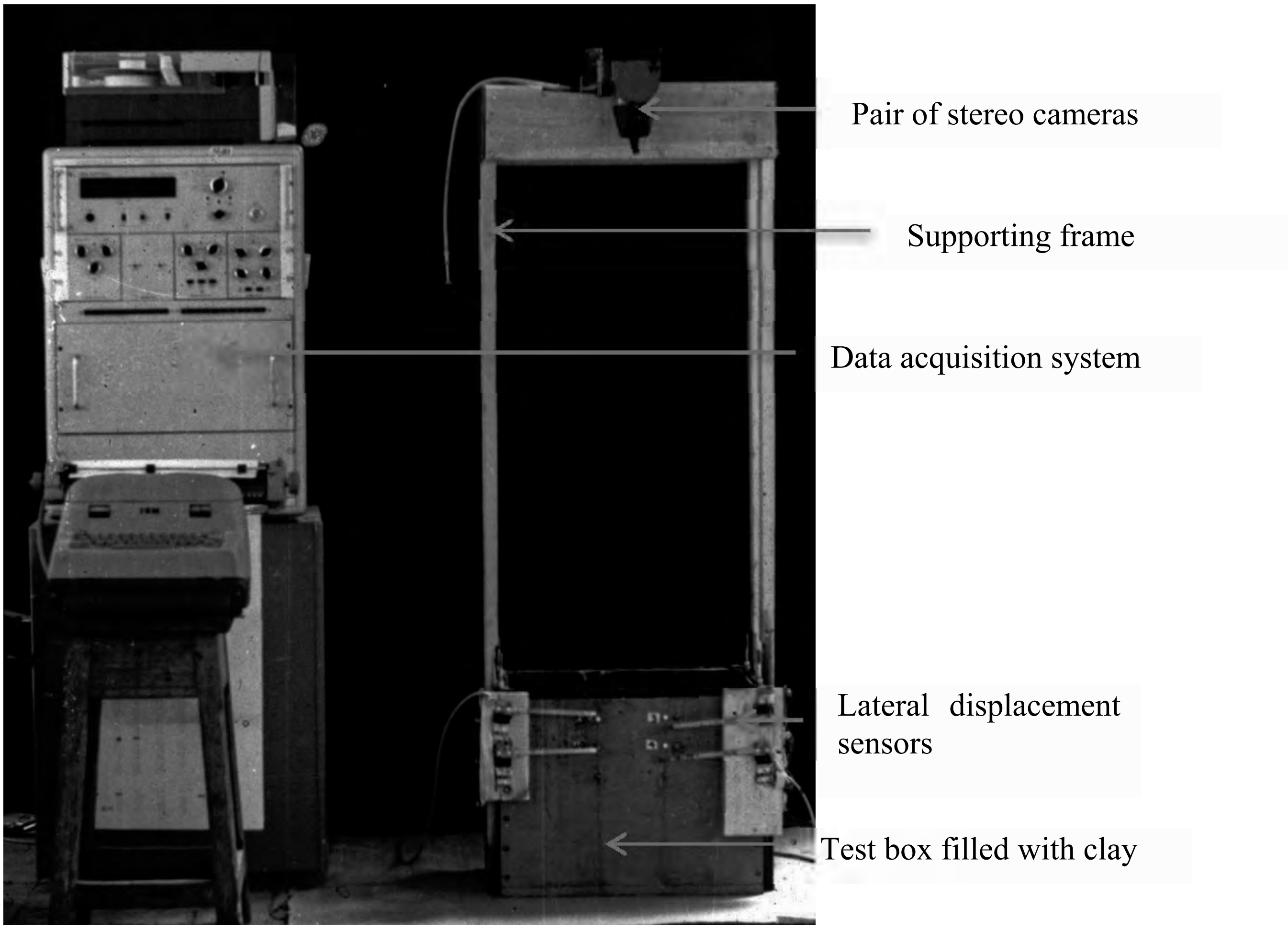


FIG 3. Stereo-photogrammetric equipment for measurement of surface displacements.

For the stereo-photographic measurements, 71 targets were placed on the surface at a spacing of 35 mm, as shown in Figure 4. The three-dimensional deformations of the soil surface were determined by two stereo cameras of type Wild C40 with 40 cm base, cf. Figure 3. The distance from the camera plane to the soil surface was 910 mm. Four fix-targets on the frame of the test box were used as reference points. The accuracy of displacement measurements was 0.08 mm (lateral) and 0.11 mm (vertical), respectively.

Twenty wooden piles with diameter 12.3 mm and 200 mm length were driven to the bottom of the test box. The spacing between piles was 70 mm, corresponding to a relative spacing of 5.7 pile diameters. The surface of the test box with measuring targets and two rows of piles installed (8 piles) is shown in Figure 4.

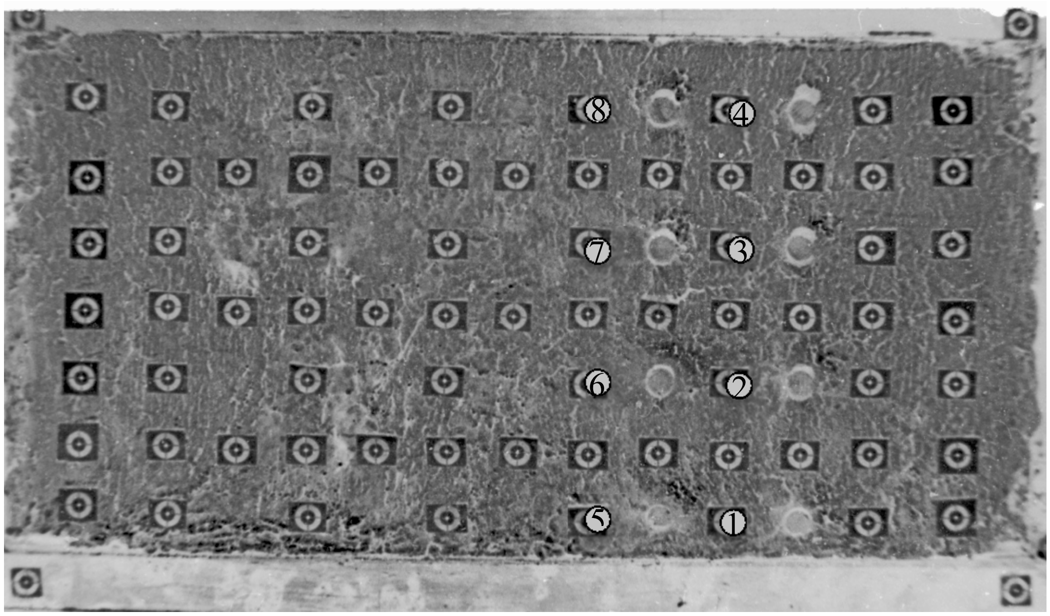


FIG 4. Surface of model box filled with clay after installation of two pile rows (8 piles), showing measuring targets and order of pile installation.

3.3. Lateral Soil Movements from Model Tests

The cumulative horizontal and vertical soil displacements measured on the surface are shown in Figure 5 after installation of eight piles, cf. Figure 4. The constraining effect of the box walls is apparent. However, it is obvious that movements occurred primarily in the direction away from the piles. Soil heave, which is discussed in the companion paper, is clearly seen in front of the second pile row.

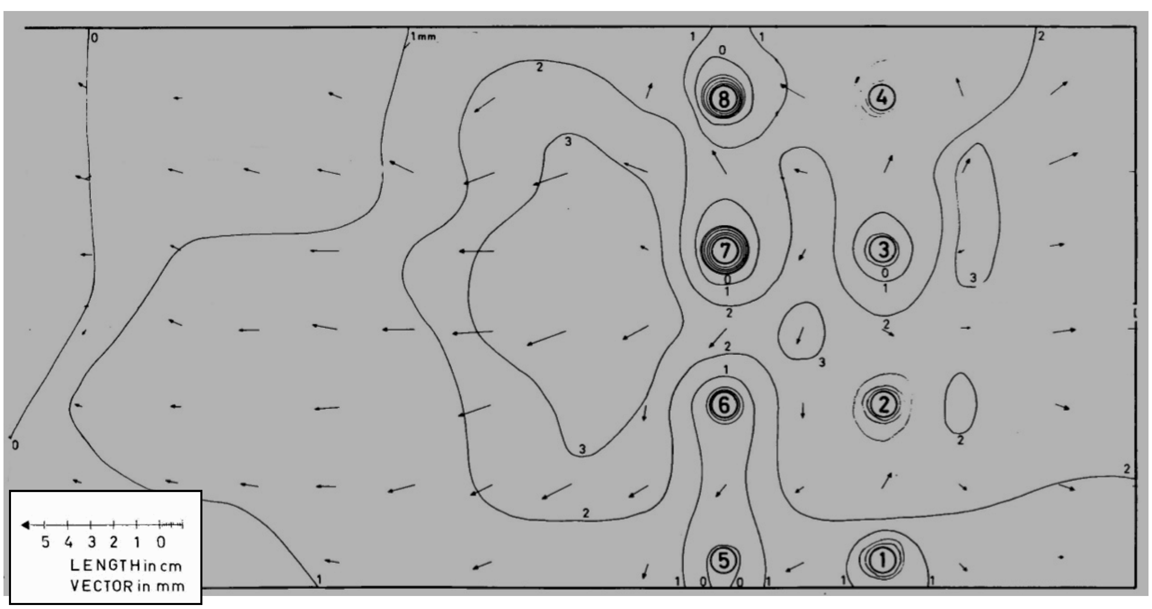


FIG 5. Cumulative surface displacement after driving of two pile rows, showing lateral displacement vectors and heave of soil surface, cf. Figure 4.

Incremental soil movements after the installation of 8 (2 rows), 12 (3 rows) and 20 piles (5 rows) are shown in Figure 6. The cumulative path that a point on the surface travels due to pile driving can be complex. The path of incremental displacements is significantly longer than the vector from the start to the end point. It is apparent that the displacement pattern is influenced by the order of pile installation, cf. also Figure 2. For instance, a point in the center of a pile group can at first be moved in the direction of pile row installation and thereafter be pushed back to its original position, as is illustrated by the point between piles (10) and (11) in Figure 6. Consequently, the movements of the first installed pile will be significantly larger than that of later installed piles and the last driven pile will not experience any lateral movements. It can also be observed that already installed piles move with the ground and provide little or no lateral resistance to ground movements. It can be assumed that the reinforcing effect of already installed piles on lateral ground displacement is negligible.

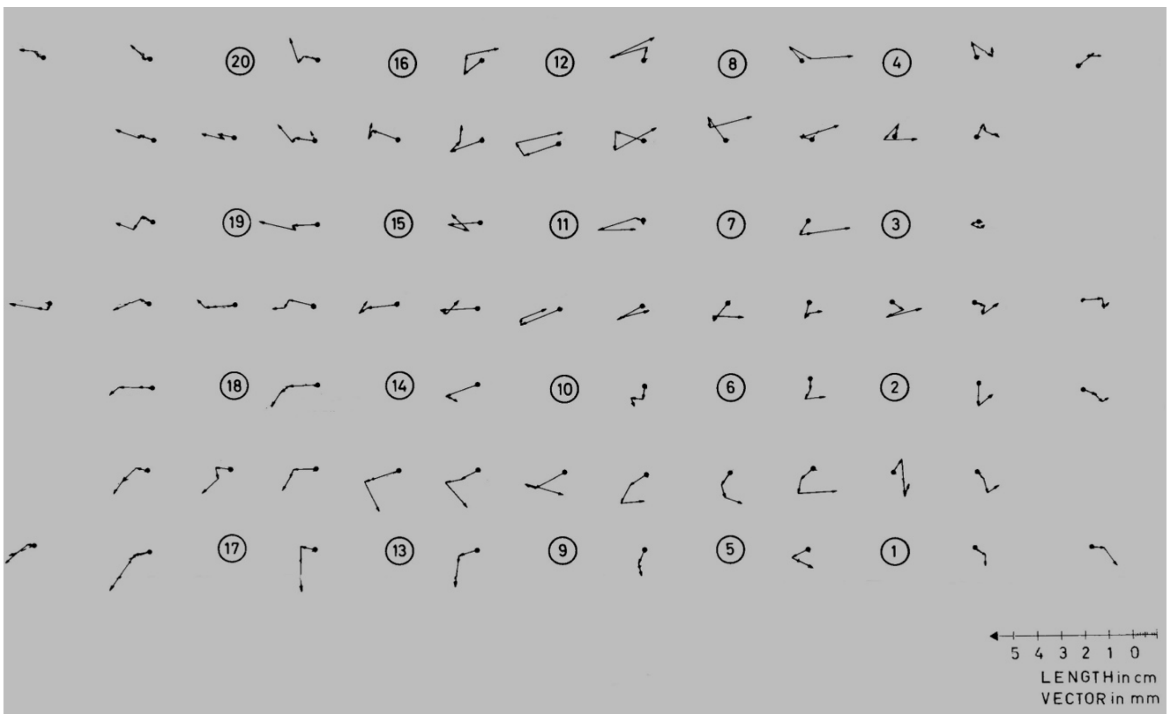


FIG 6. Incremental surface displacements after driving of two, three and five pile rows.

3.4. Case History, Eastern Canada

A well-documented field study of ground movements due to installation of piles was reported by Bozozuk et al. (1978). Soil disturbance in connection with the driving of two pile groups in sensitive marine clay was studied in a construction project. The geotechnical conditions are presented in Figure 7. Below a surface fill, consisting of gravel to a depth of 2.3 m, was a highly plastic grey silty clay. From 2.3 m to 15 m, the grey silty clay included bands of uniform silt and sand. This soil layer was highly plastic with a natural water content of 60 %, which was close to the liquid limit. The sensitivity varied from 15 to 20. The in situ undrained shear strength measured with the vane increased linearly with depth through the soil formation from 50 kPa to about 75 kPa. From 15 m to 19 m depth, the soil consisted of grey clay and silt. From 19 to 24.4 m depth, the soil changed to grey sandy silt with traces of gravel. Between 24.4 and 30.5 m, a very dense glacial till with boulders was encountered. The geotechnical information indicates that layers of silt and sand within the clay deposit can potentially be compacted and thus reduce the volume (heave) of displaced soil.

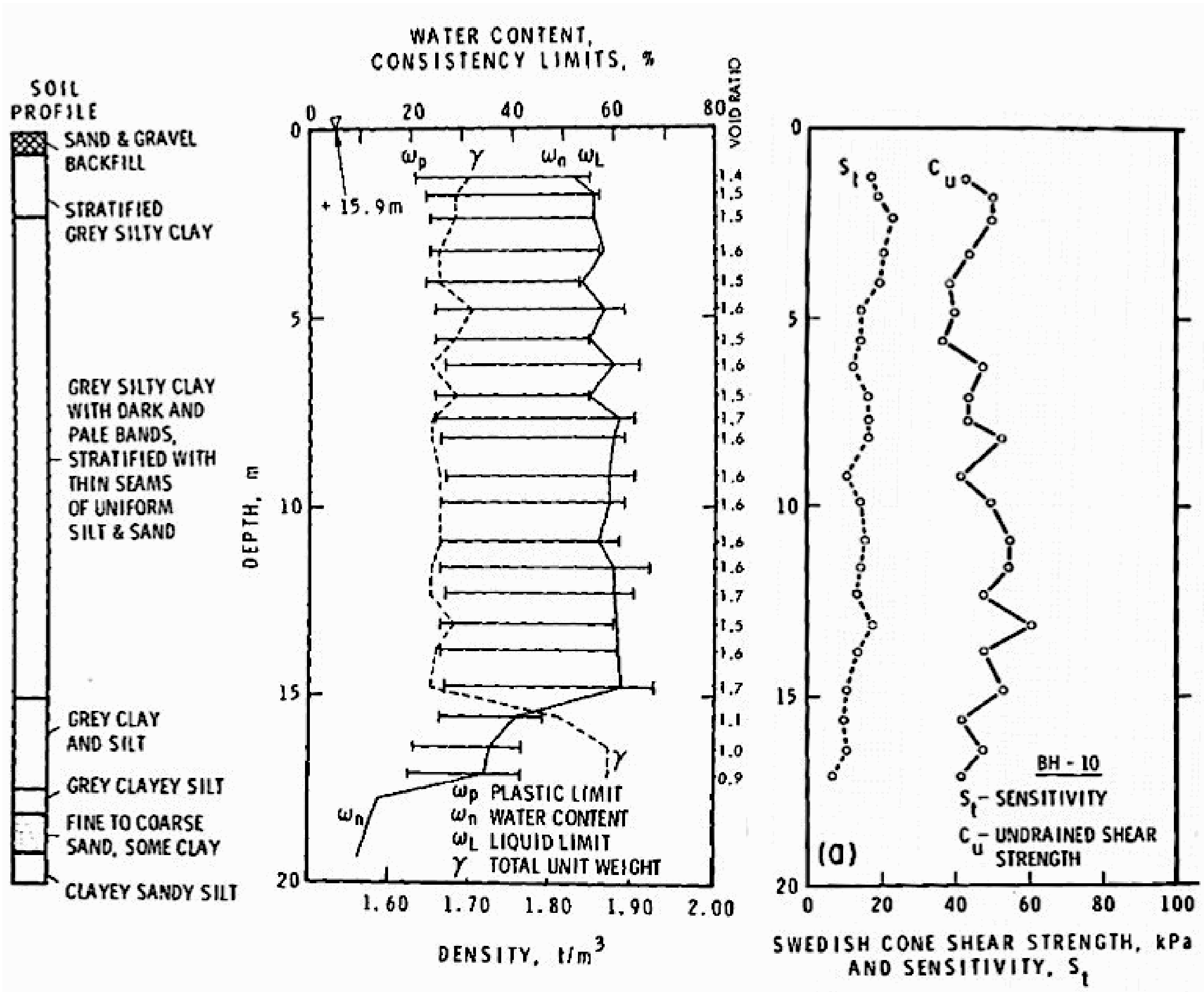


FIG 7. Geotechnical properties at piling site, from Bozozuk et al. (1978).

Standard precast concrete piles of hexagon shape with a diameter of 300 mm were driven to an average depth of 26 m. The pile spacing on centers was generally 5 to 6 pile diameters with a minimum spacing between two piles of 4.3 diameters. In this section, reference is made only to lateral soil movements, which were determined using stereo-photogrammetric technique similar to that used for the above described model tests. Horizontal soil movements below the ground surface were also measured by inclinometers. Terrestrial photogrammetry was used to monitor movements of markers placed on the ground surface and on piles.

Figure 8 shows the results of these measurements. The following observations were reported by Bozozuk et al. (1978): *"The general direction of movement of in-*

place piles was approximately away from and in a direction perpendicular to the area of pile driving. The magnitude of these movements varied within the area. When the piles were driven in Zone II those in Zone I moved as much as 175 mm (dashed vector for pile 28). The solid vectors indicate pile movements due to piling in Zone III; the dotted vectors due to piling in Zone IV. The movements of some of the piles changed direction as the piling proceeded from one area to another. The magnitude of the movements can be obtained from the pile movement scale shown on the figure."

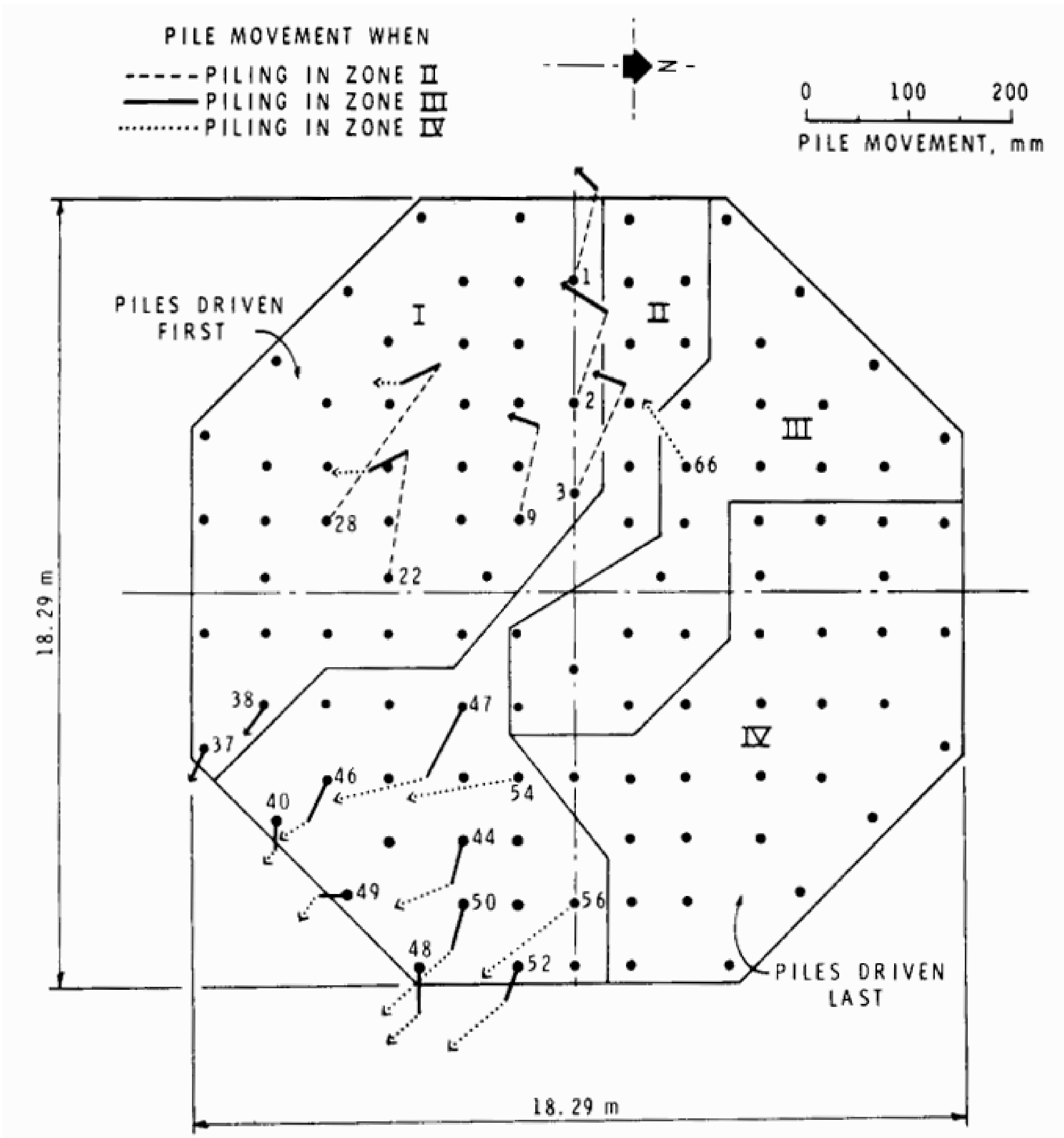


FIG 8. Photographic measurements of horizontal pile movements due to pile driving, Bozozuk et al. (1978).

The observations reported by Bozozuk et al. (1978) are in agreement with the more detailed model tests reported by Massarsch (1976) showing the complex paths of surface movements due to installation of a group of piles. Bozozuk et al. (1978) also carried out inclinometer measurements within and adjacent to the pile group during pile installation. Difficulties were encountered to determine the absolute lateral soil movements as the inclinometers could be installed only to 18 m depth, while the pile length varied between 25 and 28 m. It is worth quoting the observation reported by the investigators: "*The measurements indicated that the pile driving generally pushed the soil laterally away from the pile group in large blocky masses*". Of particular interest for this paper are the measurements by inclinometer 52, installed closest to the pile group, cf. Figure 9. It is apparent that the lateral displacements are similar to those of a cylindrical cavity as shown in Figure 1.

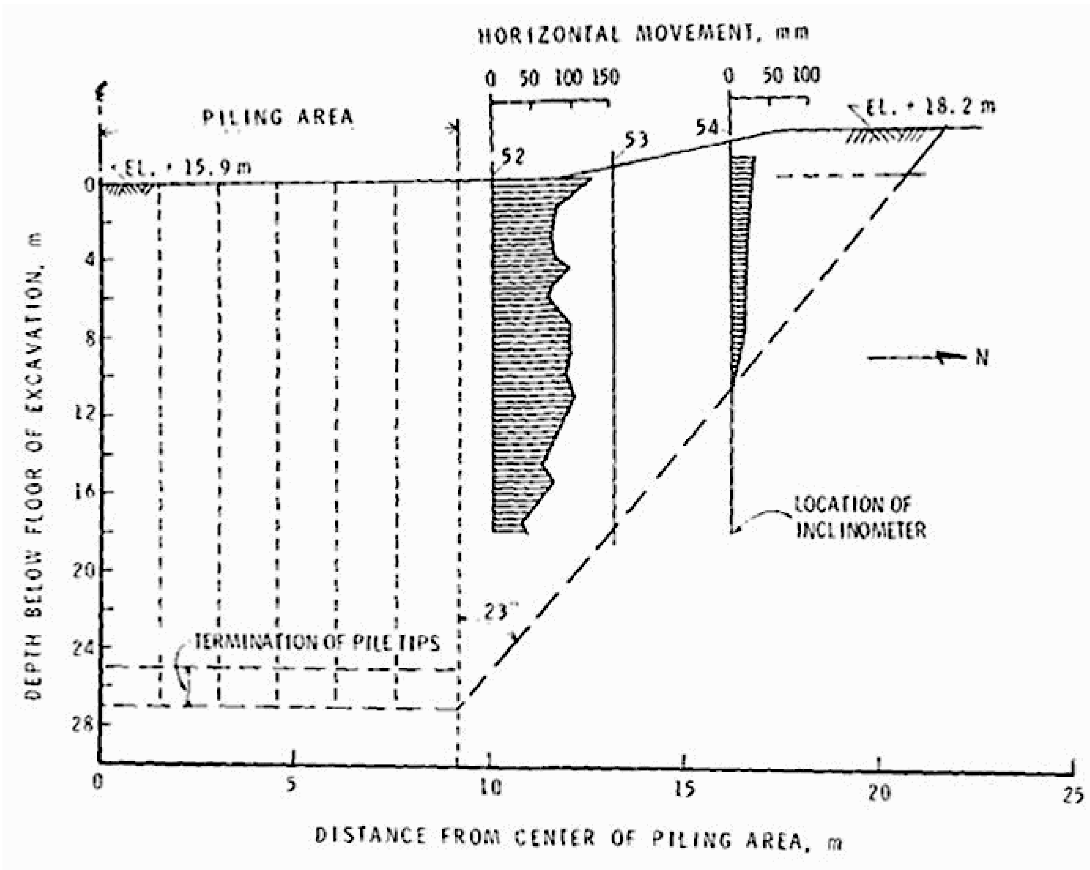
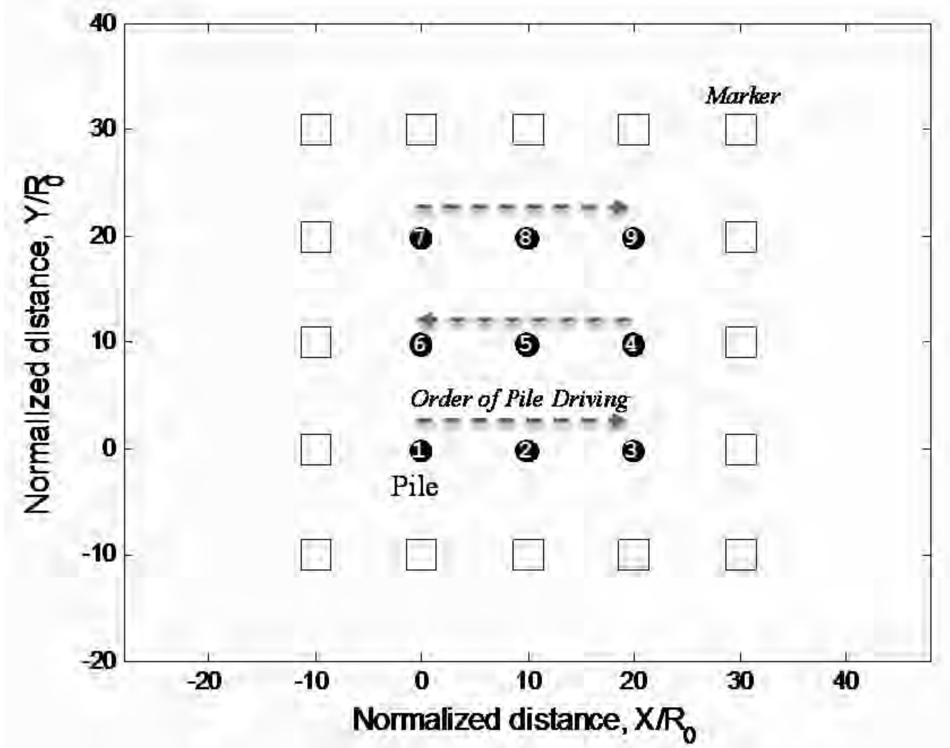


FIG 9. Horizontal soil movements determined by inclinometers north of the piling area, Bozozuk et al. (1978).

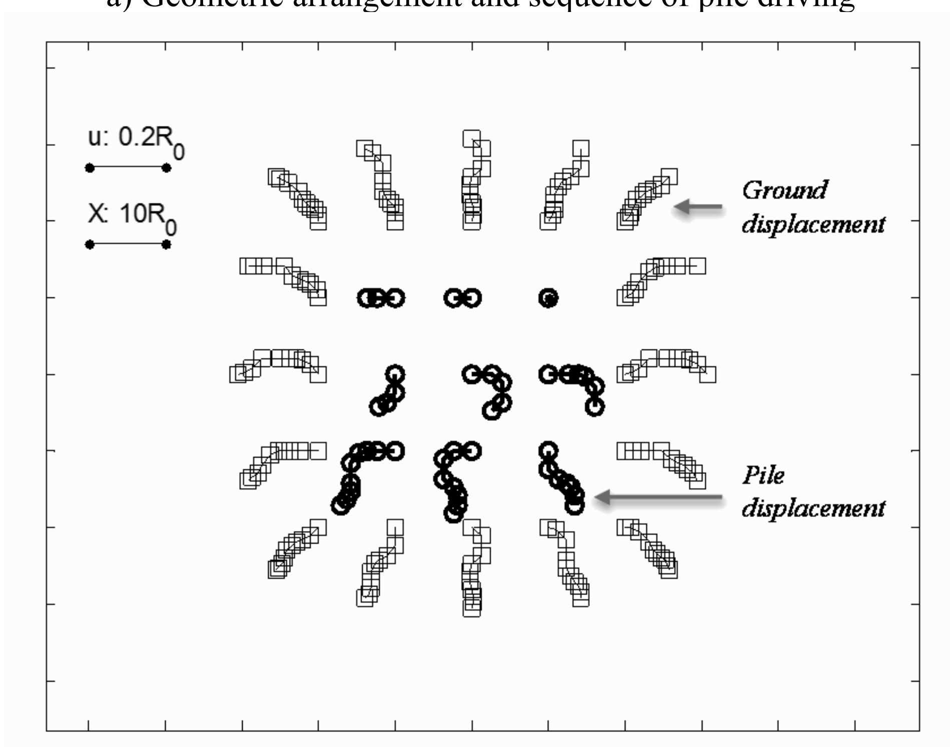
4. CUMULATIVE LATERAL DISPLACEMENTS

4.1. Horizontal Ground Surface

Based on the conclusions drawn from Figure 2, a computer program was written which makes it possible to calculate lateral soil displacement at a given distance from a pile according to Eq. 1. It is assumed that already installed piles do not affect lateral movements. The displacement vectors, u, due to the installation of each pile were calculated. The potential reinforcing effect, which is often small or does not exist at all, has been neglected in the displacement calculations. Figure 10a shows the geometric arrangement of 9 piles (circles) with the order of their installation. Markers (squares) surrounding the pile group are used to indicate the movement of the ground surface. The calculated displacement paths of each pile and of each of the markers surrounding the pile group are indicated in Figure 10b.



a) Geometric arrangement and sequence of pile driving



b) Lateral displacements due to driving of pile group

FIG 10. Lateral displacement of piles and of markers at the perimeter of the pile group due to installation of 9 piles.

Note that all distances and displacements are given in dimensionless form with pile radius as reference. Displacements are magnified by a factor of 50. One scale mark, equal to a distance of 10 times the pile radius (R_0), corresponds to a displacement of $0.2R_0$. The final lateral movement of markers surrounding a group of 9 piles is identical and directed away from the pile group. If a pile diameter of 0.3 m (R_0 = 0.15 m) is assumed, the spacing between two adjacent piles in Figure 10 is 1.5 m. At a distance of 10 pile radii (1.5 m), lateral ground displacements are approximately $0.2R_0$, corresponding to 0.03 m (30 mm). Lateral movements of the ground surface depend mainly on pile diameter while pile length does not appear to be of significance.

It is interesting to note that in the case of level ground surface, the final lateral displacements of the points surrounding the pile group are symmetrical and almost identical, while the displacements of the piles depend on the order of their installation. An important conclusion is that movements of the ground and of the piles are not by straight lines, but follow an incremental path in a direction that depends on the order of pile installation. Piles can be displaced only after they have been installed and are therefore only affected by subsequently driven piles while the displacement of a given element of soil depends on the cumulative effect of all installed piles, regardless of their order of driving. Obviously, the last driven pile (9) in Figure 10 will not be moved laterally while the largest movements must occur at the first driven pile (1).

4.2. Inclined Ground Surface

The influence of an inclined ground surface has been taken into account in a simplified way when calculating lateral ground movements. Figure 11 shows the assumptions for calculating the passive resistance acting against an expanding cylindrical cavity, cf. Eq. 1. The weight of the wedge W can be determined by considering the inclination of the ground surface, β, and of the passive failure surface, α, to the horizontal plane.

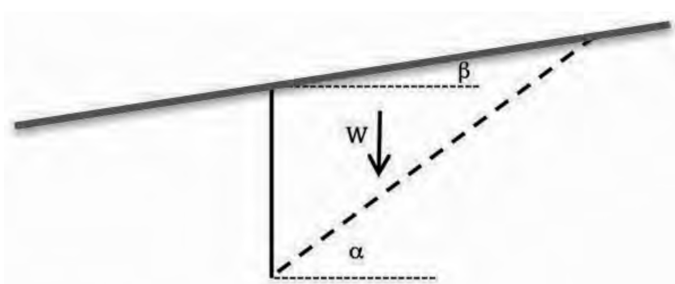


FIG 11. Assumptions regarding the effect of inclined ground surface on expansion of cylindrical cavity.

Assuming that the inclination of the failure plane (α) is straight and independent of the inclination of the ground surface (β) then the ratio between the weight of the wedge assuming inclined ground surface ($\beta \neq 0$) and that for horizontal ground surface ($\beta = 0$) can be calculated by

$$\frac{W_{incl}}{W_{hor}} = \frac{1}{1 - \dfrac{\tan\beta}{\tan\alpha}} \tag{2}$$

where W_{incl} is the weight of the wedge for $\beta \neq 0$ and W_{hor} is the weight of the wedge in the case of a horizontal ground surface. If undrained, rapid loading is assumed in clay then $\alpha = 45^{\circ}$,

$$\frac{W_{incl}}{W_{hor}} = \frac{1}{1-\tan\beta} \tag{3}$$

If the force resisting lateral displacement is assumed to be proportional to the weight of the soil wedge, it is possible to calculate the displacement u_{incl} compared to the displacement for the case of a horizontal ground surface u_{hor}

$$\frac{u_{incl}}{u_{hor}} = 1-\tan\beta \tag{4}$$

Figures 12a – 12d show the influence of ground slope on soil displacements due to pile installation. The order of pile installation and the displacement of level ground are shown in Figure 10. The significance of the order of driving piles in a clay slope can be studied by comparing Figures 12a and 12d. In Figure 12a, piles are driven from the top of the slope toward the bottom. In Figure 12d, piles are driven from the bottom of the slope toward the top. There is a marked difference in pile displacements between these two alternatives. Starting pile driving at the top of the slope results in significantly smaller pile movements compared to the case when pile driving is started at the bottom. However, the displacements of markers surrounding the pile group are the same for both driving sequences.

The above calculations of ground surface and pile top displacements in a slope are based on a simplified model. They do not take into account plastic soil movements due to a low safety factor against sliding nor the effect of strength loss/gain (soil disturbance and reconsolidation) that can be caused by – and following – the pile installation process. Also, the calculations do not consider possible stress changes (total and pore water pressure) that can affect soil movements. However, as model tests and field investigations have shown, piles have a relatively low resistance to lateral forces and their reinforcement effect with respect to lateral soil movements can be neglected. The information provided in Figures 12a -12d can be used as a guide when assessing the sequence of pile driving in a clay slope.

5. APPLICATION EXAMPLE

The following example is intended to illustrate how the above-presented concepts can be used to predict lateral displacements at the ground surface due to installation of a pile group in soft clay, Figure 13.

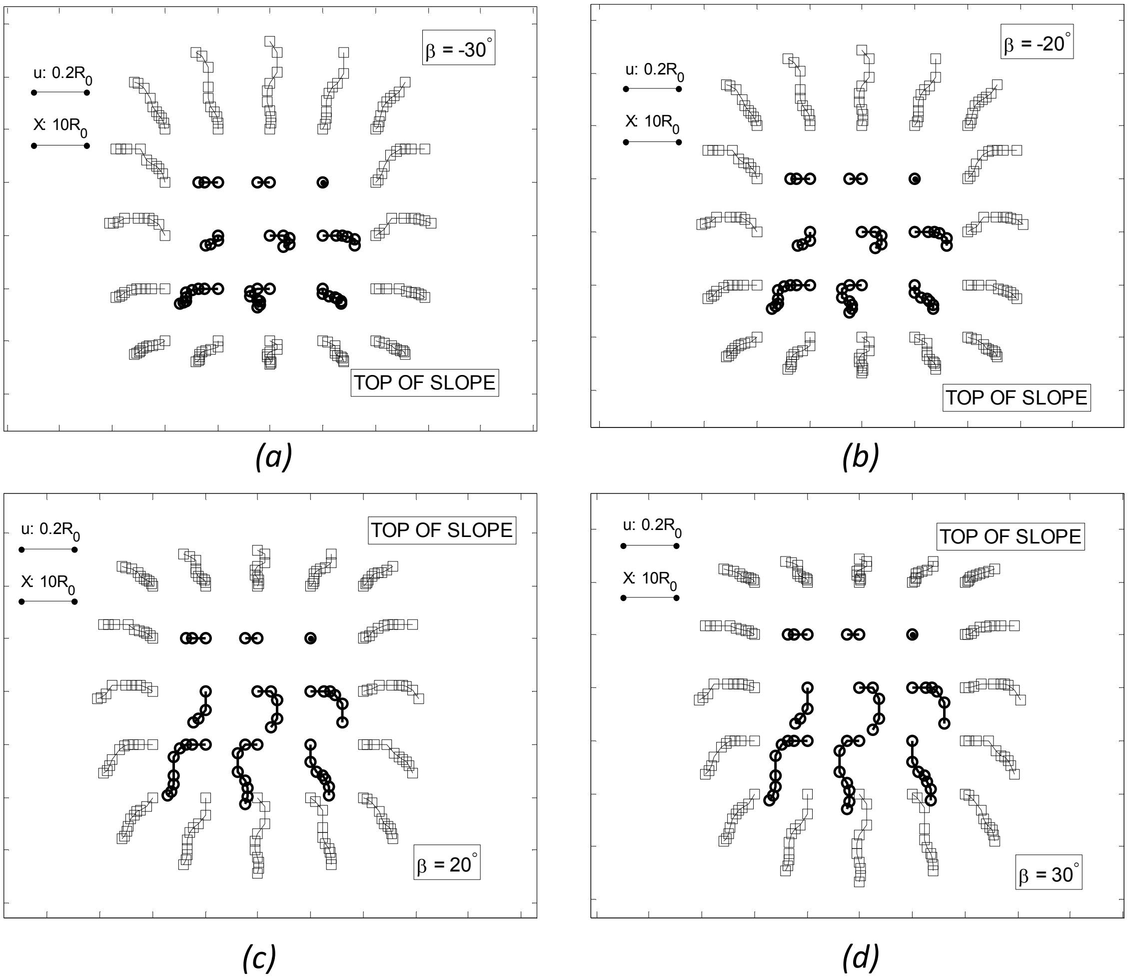


FIG 12. Effect slope inclination on lateral displacement of soil and piles.

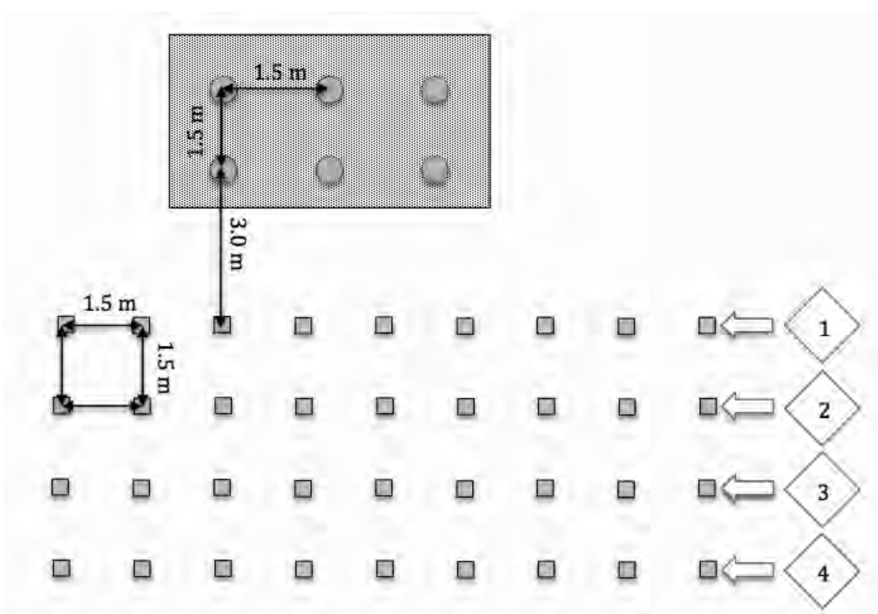


FIG 13. Pile group driven adjacent to an existing pile-supported bridge foundation. Sequence of driving pile rows and driving direction are indicated.

The pile group is to 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. Using the concepts of calculating cumulative lateral displacements due to pile driving, the lateral movements of the 36 piles and the 6 piles of the existing bridge foundation have been calculated and are shown in Figure 14. The sequence of pile installation is shown in Figure 13. As mentioned above, the resistance to lateral displacement by previously installed piles is considered negligible and has been neglected in the cumulative displacement calculations. Soil disturbance may even reduce the stiffness of soil between recently driven piles and can result in increased lateral displacements. It should be noted that already driven piles can have a more significant effect on soil heave, which is discussed in the companion paper, (Wersäll and Massarsch, 2013).

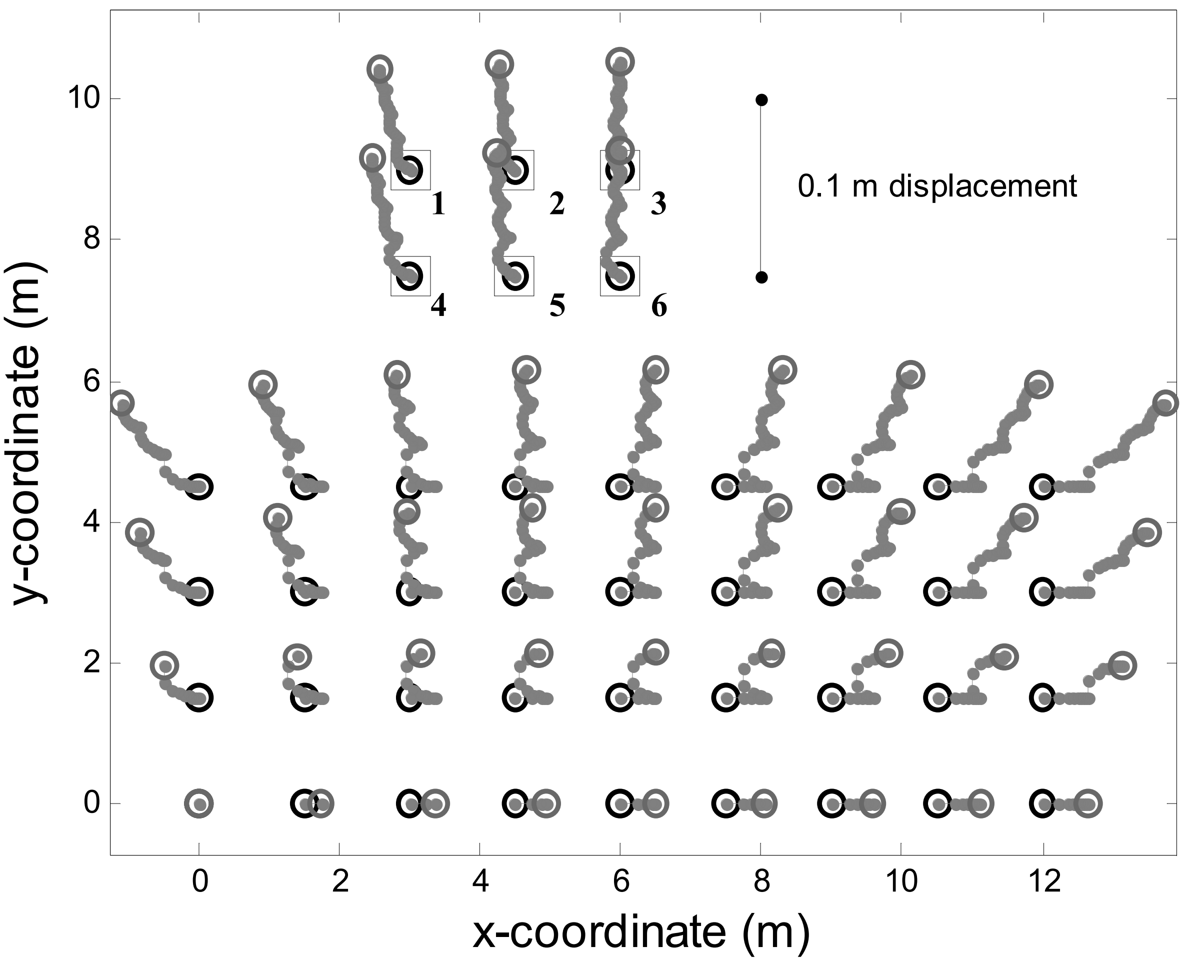


FIG 14. Calculated lateral displacements of heads of driven piles and of existing piles of bridge foundation (refer to Table 1 for pile numbers). Black and red circles indicate the start and end point of the displacement path. Pile displacement 25 times magnified.

Lateral displacements are generally in the direction away from the piles being driven. However, the displacement path is affected by the sequence of piles installed in each row. The first driven piles are displaced generally away from the pile group, with a maximum displacement of almost 0.1 m. Obviously, the last pile driven in the pile group is not displaced at all. The cumulative displacement paths of the six piles of the bridge foundation (foundation piles) are summarized in Table 1. Movement of pile heads is generally in the direction away from the driven group of piles. It should be noted that lateral displacements decrease gradually with depth and can be assumed to be close to zero in the case of end-bearing piles.

TABLE 1. Direct and cumulative displacement of heads of six bridge foundation piles due to driving of 36 piles; cf. Figure 14.

Pile number	Direct displacement	Cumulative displacement
	m	m
1	0.060	0.067
2	0.061	0.069
3	0.063	0.070
4	0.070	0.083
5	0.071	0.086
6	0.07	0.086

At a distance ranging from 3 m (piles 4, 5 and 6) from the closest pile row to 4.5 m (piles 1, 2 and 3), the cumulative displacement paths of pile heads are about 0.07 and 0.09 m, respectively. The direct (start to end point) displacement paths are 0.06 to 0.07 m, respectively. The cumulative displacement path is between 15 and 20 % longer than the direct path (start to end point of movement). Lateral soil displacements occur according to Figure 14 in all directions away from the driven pile. It is possible to estimate lateral soil displacements by a simplified approach, assuming that 25 % of the soil volume displaced by the pile is moved perpendicular to the pile row. With a pile spacing of 1.5 m and a pile cross section of 0.3 m x 0.3 m, the average lateral displacement caused by the installation of one pile row would correspond to 0.015 m. The installation of 4 pile rows would correspond approximately to a lateral displacement of 0.06 m. This value is in reasonable agreement with the average direct displacement shown in Table 1.

6. CONCLUSIONS

Theoretical calculations of lateral soil displacement based on cylindrical cavity expansion theory are in excellent agreement with results of model tests reported by different researchers. Based on results of model tests and field observations it can be concluded that the lateral resistance to horizontal soil movements by already driven piles is low and can be neglected.

Lateral displacements of the ground surface during installation of a pile group can be complex and the direction of displacement vectors depends on the sequence of pile installation. This observation has been confirmed by model and field tests using stereo-photogrammetric technique.

A simplified method of calculating the cumulative lateral displacement path of the ground surface provides realistic results. The cumulative displacement path can be significantly longer than the direct path (start to end point of pile position). The direction of soil movement is affected by the sequence of pile installation.

When driving piles in a slope, pile displacements can be minimized by starting installation from the top of the slope and proceed downwards. However, the displacement of the ground will not be affected by the sequence of pile installation. This conclusion is based on the assumption that the installation process does not change the strength and stiffness of the clay between the driven piles.

7. ACKNOWLEDGEMENTS

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