THE BEHAVIOUR OF A COHESION PILE GROUP IN SOFT CLAY

LE COMPORTEMENT D'UN GROUPE DE PIEUX DANS DE L'ARGILE MOLLE
РАБОТА КУСТА ВИСЯЧИХ СВАЙ В ПЛАСТИЧНОЙ ГЛИНЕ

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SYNOPSIS. The paper summarizes field data obtained in connection with foundation construction and subsequent construction of a building founded on a piled raft. The piles-timber piles about 15 m long - were driven into a 35 m deposit of soft, highly plastic, normally consolidated clay. The results that are presented comprise mainly determinations of the distribution of vertical displacement and pore pressure in the soil along closely spaced piles within a group. The changes in strength and compression characteristics of the soil due to pile driving have also been examined. During pile driving a maximum heave of 0.12 m was measured. The maximum value of measured excess piezometric head was 12.5 m of water. Measurement of soil vertical displacements at different elevations along the piles has provided a good demonstration of piles/soil interaction. The settlement during one month of reconsolidation amounted to only 8 mm. This small value can partly be explained by the mobilization of negative skin cohesion on the piles. During excavation the piles seem to have prevented heave of soil beneath foundation level. The results clearly show that the main source of building settlement is the compression of soil located at a depth greater than 0.6 times the length of piles.

INTRODUCTION

Cohesion piles, used in order to obtain acceptable settlements of buildings founded on thick deposits of highly compressible clay, in many cases - e.g. in Mexico City (Zeevaert 1962) and in Gothenburg, Sweden (Torstensson 1971) - have given satisfactory results. Furthermore, during excavation cohesion piles seem useful in reducing heave and subsequent recompression of clay beneath foundation level.

The main purpose of cohesion piles is to reduce settlements both by reinforcing the upper portion of a clay deposit and by transmitting the foundation load to deeper and less compressible clay layers. When making settlement predictions for structures founded on cohesion piles a common assumption is that soil and piles act as a unit to a depth of 2/3 to 3/4 times the embedded pile length.

Owing to disturbance effects during pile driving the strength and compression characteristics of the soil are changed. The influence of these changes on the behaviour of a friction pile foundation seems not yet to be fully understood.

The present paper describes and interprets the results of a field investigation on the behaviour of a cohesion pile foundation in a very soft, highly plastic clay. The studies comprise determinations of vertical displacements at 1 m intervals and pore pressure changes at three elevations in the soil within two pile groups. The results contain observations continuously made during pile driving, excavation and building construction and during a period of 3.5 years after building completion. The changes in strength and compression characteristics of the soil between the piles have also been examined.

SOIL CONDITIONS

The building site is located in the city of Uddevalla about 80 km north of Gothenburg in the southwestern part of Sweden. The original ground surface within the building area was practically level. A soil profile from a boring to 20 m depth below ground surface is shown in Fig. 1. Beneath a 1.5 m thick fill layer the soil is composed of postglacial and glacial sediments. To a depth of 6 m the soil consists of an organic soft silty clay. This layer is underlain by a very soft plastic clay which appears to be rather homogeneous to a depth of at least 20 m. Soundings have shown that this plastic clay probably extends to a depth of about 30-35 m where it is underlain by a silt layer with a thickness of more than 25 m.

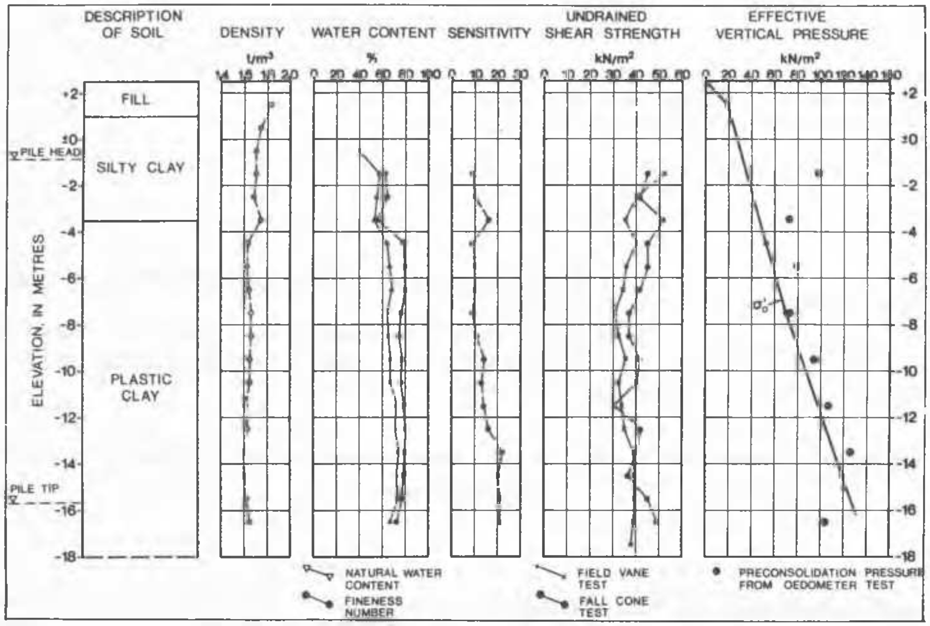
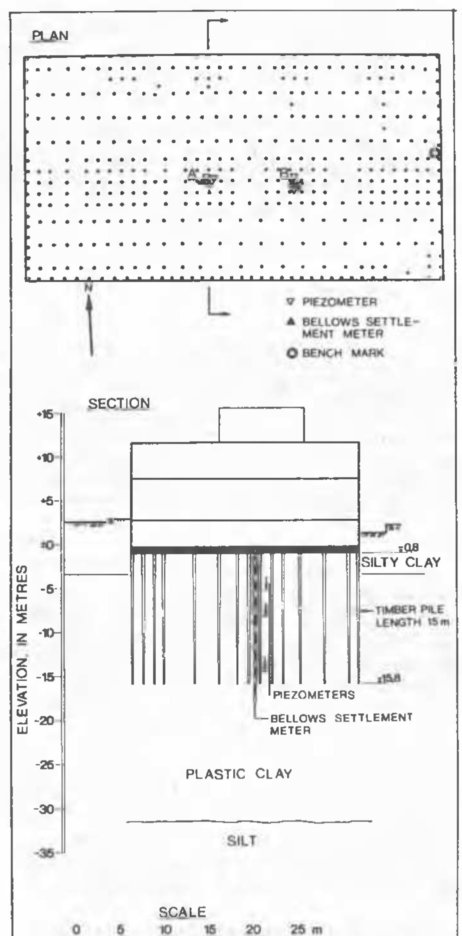


Fig. 1. Soil profile

Fig. 2. (right) Plan and cross section of building and the layout of piles and soil instrumentation.



Piezometers, installed at three depths in the plastic clay, indicate that the pore pressure corresponds to a free ground water level at about +1.5 m, i.e. 1.0 m below original ground surface. Oedometer tests have shown that the clay seems slightly overconsolidated to a depth of about 8 m.

DESCRIPTION OF BUILDING AND FOUNDATION

Fig. 2 shows a plan and cross of the building and the layout of piles. The building is a two-storey office building with a width of 26 m and a length of 48 m. The total building weight, including 25 % of the design live load, corresponds to an average foundation pressure of 53 kN/m^2. The building is founded on a 0.8 m thick concrete raft resting on more than 430 timber piles about 15 m in length. The structural load is transmitted to the raft by walls and columns. The piles are concentrated in groups beneath the columns. Assuming that the total weight of the building, reduced by hydrostatic uplift, is carried only by the piles the mean load per pile is about 73 kN giving a factor of safety of approximately 4. For this load, test piles showed a settlement of about 0.5 mm.

The piles were driven from the original ground surface. The design level of the pile heads is at -0.8 m, i.e. about 3.3 m below ground surface. In order to reduce the disturbance effects the piles were prebored to elevation -5.5 m.

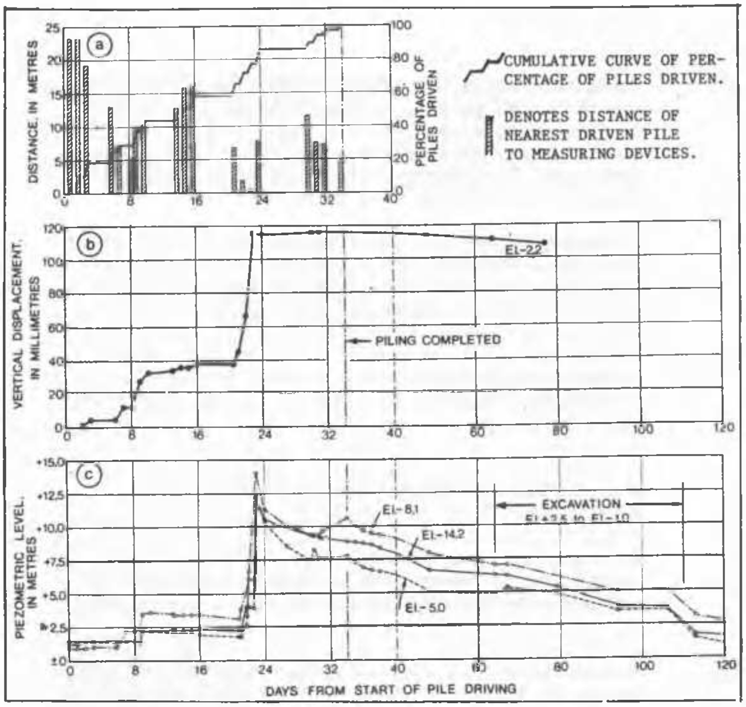


Fig. 3 a-c. Vertical displacement and pore pressure data compared with percentage of piles driven.

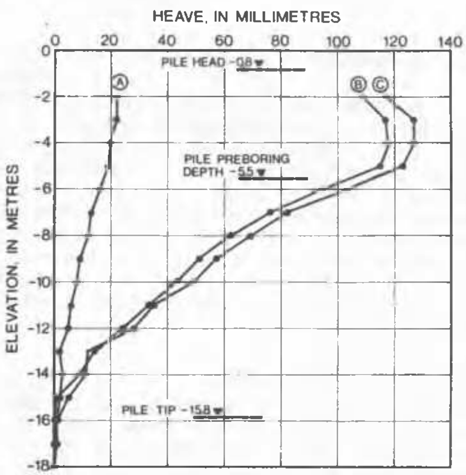


Fig. 4. Distribution of heave in soil along the piles.

The weight of excavated soil corresponds to a decrease in pressure at foundation level of about 58 kN/m^2 which means that the weight of building is fully compensated. For this reason and also since the clay is slightly overconsolidated in the upper portion of the deposit the benefit of piles may naturally be questioned. However, the field measurements have provided a good demonstration as well of disturbance effects due to pile driving as of piles/soil interaction. The results obtained may therefore be of general interest.

SOIL INSTRUMENTATION

The studies were made on two pile groups, each situated beneath a column in the central part of the building. The pile groups consist of 25 and 30 piles on 1.3 m centers, see fig. 2.

Prior to pile driving piezometers and settlement meters were installed in the centre of the pile groups. The piezometers were type SGI which has a closed oil system (Kallstenius and Wallgren 1956) The piezometers were installed at three levels along the piles, see fig. 2. The settlement meter - named "bellows settlement meter" - has been described elsewhere (Fellenius, Broms 1969). This device makes it possible to determine the distribution of vertical displacement at 1 m interval in the soil along the piles. The accuracy is about ± 2 mm. The installation of a "bellows settlement meter" is shown in fig. 2. In order to check the readings obtained with this device an ordinary movement meter, consisting of a rod welded to an auger, was installed in each pile group at elevation about -2 m. A steel rod inserted to a depth of 65 m below ground surface and provided with a 50 m long pipe casing has served as a reliable bench-mark during the whole measuring period.

The measurements of vertical displacements and pore pressures have shown that the two studied pile groups have behaved almost identically. For this reason a detailed presentation will only be given for the results concerning pile group A in fig. 2.

OBSERVATIONS OF DISTURBANCE EFFECTS DUE TO PILE DRIVING

Pore Pressure Changes and Soil Displacements

Figs. 3 b and 3 c present vertical displacement and pore pressure data obtained during pile driving and after piling completion. In Fig. 3 is given both the cumulative curve of percentage of piles driven and the distance from the closest piles driven to the measuring devices. Pile driving proceeded mainly from the eastern towards the western part of the foundation area.

As was to be expected driving of piles immediately adjacent to the measuring devices (nearest pile at a distance of 0.3-0.5 m) caused a sharp increase in the measured values of vertical displacement and pore pressures, Figs. 3a-c.

The cumulative heave at elevation -2.2 m reached a maximum value of about 0.12 m. A maximum value of excess piezometerie head of approximately 12.5 m of water was measured at elevation -8.1 m.

Fig. 4. presents some of the "bellows settlement meter" data obtained during pile driving. As can be seen these results provide a good picture of heave in the soil between piles. The effect of preboring in reducing heave is clearly visible. Assuming that the measured heave represents an average value within the pile group, about 40 % the displaced soil volume appears as heave within the area of the pile group. This value is in fair agreement with what has been reported elsewhere (Hagerty and Peck 1971).

Changes in Soil Properties

Immediately adjacent to a driven pile the soil is subjected to a high degree of remoulding. In a more extensive region about the piles the soil is displaced more or less as a unit with rather small relative displacements between soil particles. In the present case the results given in Fig. 4 indicate a relative vertical expansion of the soil between the piles ranging from 0.5 % on the pile tip level to 2 % at the depth of preboring.

Measurements of undrained shear strength by means of field vane tests showed that the soil within a distance of 0.5 m from the pile surfaces lost about 10 % of its initial strength due to pile driving. Repeated tests during a period of 2.5 months showed no tendency of regain in shear strength although almost all excess pore pressures had dissipated.

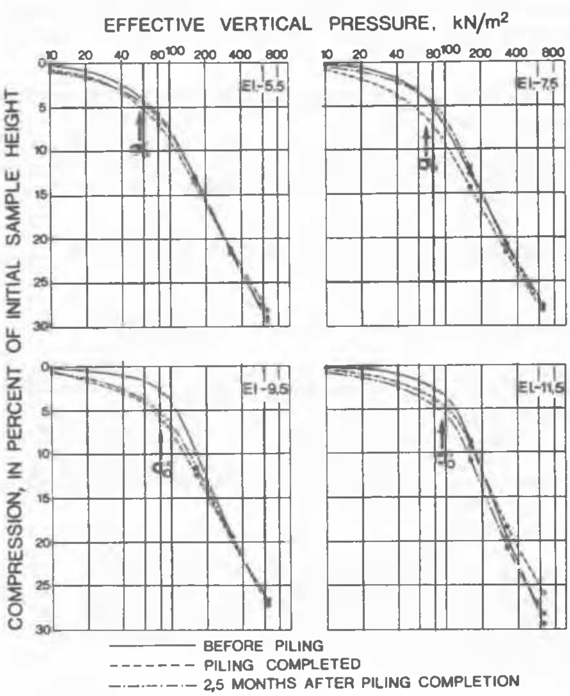


Fig. 5. Oedometer curves for soil samples from four elevations.

Oedometer curves for samples from four elevations are presented in Fig. 5. The tests have been made on samples taken both before pile driving and on two occasions after piling completion (2.5 months interval). The samples were taken at a distance of about 0.5 m from the pile surfaces.

Disregarding natural local variations of soil samples, the oedometer curves indicate a certain disturbance of soil structure. Owing to the high excess pore pressures immediately after pile driving the soil is only partly consolidated under its own weight and a full reconsolidation to the initial effective overburden pressure would lead to soil compression ranging from about 1 to 3 %, as can be seen in Fig. 5.

BEHAVIOUR AFTER PILING COMPLETION AND DURING EXCAVATION

Pore pressure and vertical displacement data obtained during the periods of soil reconsolidation and excavation are presented in Figs. 3b, 3 c and 6.

As can be seen in Fig. 3 c, the excavation was not begun until about 1 month after piling completion. At this time the remaining excess piezometric head varied between 3.5 and 5.5 m of water. During excavation period the excess pore pressures decreased rapidly. At the beginning of raft construction the pore pressures were about equal to the initial values.

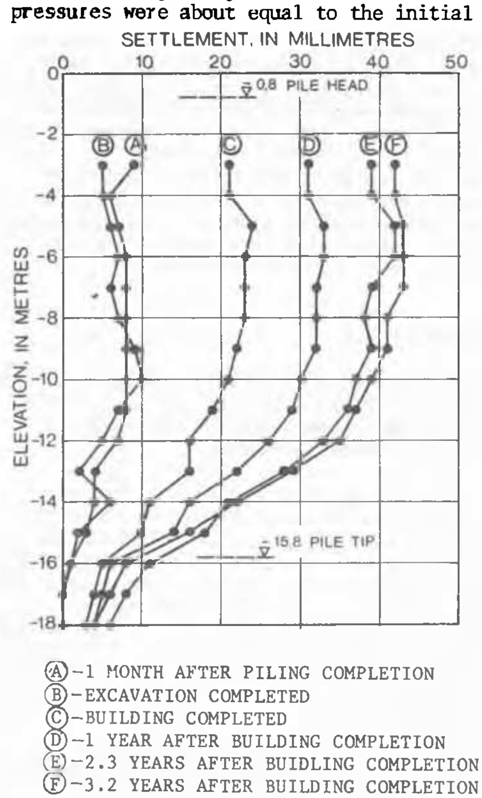


Fig. 6. Settlement profiles in soil between the piles.

The results of settlement measurements indicate very small movements due to recompression of the soil between the piles. About 1.5 months after piling completion the reconsolidation settlement at elevation -2.2 m equals approximately 8 mm, see Fig. 3 b.

Some results of settlement measurements made by means of the "bellows settlement meter" are presented in Fig. 6. The curves that are shown represent settlement profiles in the soil between the piles obtained at different time intervals after piling completion.

During 1.5 months of reconsolidation the soil compression between elevations -3 and -11 m is negligible as can be seen from curve A in Fig. 6. This effect is probably due to the fact that the effective weight of the soil along the upper portion of the piles is mostly carried by negative skin cohesion. The maximum available drag load per pile is about 11 kN per m of depth. Along the lower part of the piles this drag load must of course be transferred into the adjacent clay by means of positive skin cohesion leading to a re-establishment of the intitial overburden pressure on the level of the pile tips. As indicated in Fig. 6 the relative recompression of the soil within the zone of positive skin cohesion amounts only to about 0.2 %.

It can be noticed that there is a good correlation between measurements made by the ordinary movement meter at elevation -2.2 m and the "bellows settlement meter", cf. Fig. 3b and Fig. 6, curve A.

Curve B in Fig. 6 represents the results from a reading taken after completion of excavation. As can be seen, the piles seem to have prevented heave of the soil within the pile group. It is possible that tension forces were mobilized in the piles during excavation.

BEHAVIOUR DURING BUILDING CONSTRUCTION AND AFTER BUILDING COMPLETION

Some results of the settlement measurements, made continuously during building construction as well as during a period of 3.5 years after building completion, are shown in Figs. 6 and 7.

The immediate settlement at the end of building construction (August 1968) amounted to 17 mm. Since the reduction in overburden pressure due to excavation is about equal to the average foundation pressure of the building (Fig.7) one would not expect any time dependent settlement to occur after building completion. However, during a period of 3.2 years after construction the "consolidation" settlement amounts to 18 mm. Probably, this additional settlement to a great extent can be related to the effects of the disturbance of soil structure during pile driving. The rate of settlement is at present only about 2 mm/year. Most of this value may be due to a general subsidence in the area.

In Fig. 6 it is clearly seen that the main source of building settlement is the compression of clay beneath elevation -9 m, i.e. at a depth beneath the raft of about 0.6 times the pile length. This result

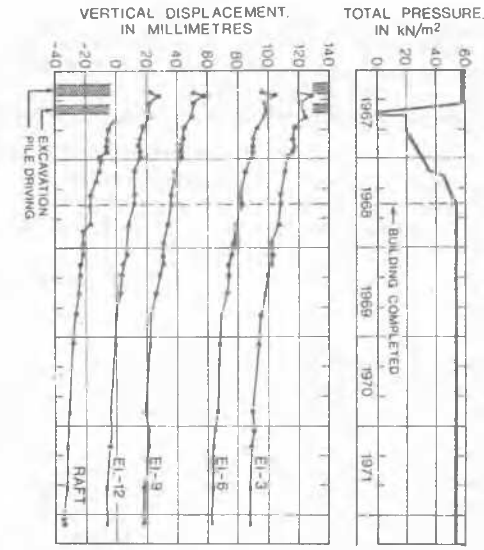


Fig. 7. Approximative loading diagram and time-settlement graphs for the raft and for the soil at four elevations along the piles.

happens to support the design assumption — an equivalent raft at two-thirds the pile length — commonly used when making settlement predictions for cojesion pile groups.

Since the pile heads must have undergone the same settlement as the raft, the distribution with depth of the relative displacement between piles and soil can be determined, see Fig. 8. It is known that the relative displacement required to mobilize maximum skin cohesion is very small; often within the elastic compression of a pile. For this reason the data presented in Fig. 8 indicate that the soil between elevations -11 and -16 m is in a state of continuous

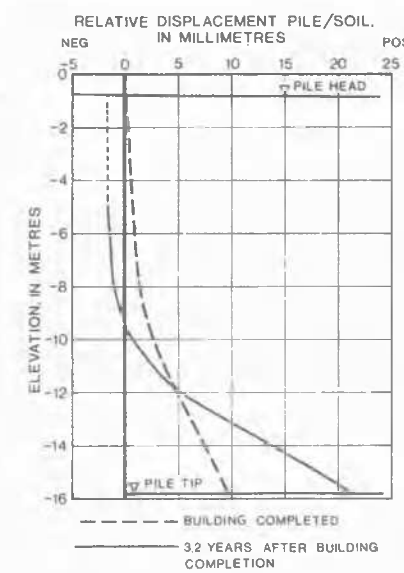


Fig. 8. Distribution with depth of relative displacement between soil and piles.

failure adjacent to the pile surfaces. The load carried by positive skin cohesion within this zone can be estimated to at least 100 kN per pile. It is possible that a drag load of an equal magnitude was mobilized in the piles already during the first month after piling completion, i.e. before excavation.

The shape of the "pile/soil displacement"curves in Fig. 8 indicates that a part of the load carried by positive skin cohesion may be caused by drag forces acting on the upper portion of the piles.

CONCLUSIONS

The main purpose of the investigation was to develop an understanding of the effects of soil disturbance during pile driving on the behaviour of a cohesion pile group.

The measured distribution with depth of vertical soil displacements during foundation and building construction as well as after building completion has provided a good demonstration of piles/soil interaction.

Related to the actual soil conditions the measured settlements must be regarded rather small.

The following conclusions can be drawn from the results of the investigation :

1. The reconsolidation of disturbed soil between the piles led to a mobilization of negative skin cohesion along the upper two-thirds of the pile length. This effect aided in reducing recompression of the soil between the piles.

2. During excavation the piles seem to have prevented heave of the soil within the pile group. Thus the piles probably reduced the immediate settlement during building construction.

3. The major part of the time dependent settlement obtained during the first three years after building construction is believed to be delayed effects of the soil disturbance.

4. The main source of building settlement is the compression of the disturbed soil along the lower one-third of the pile length.

It may finally be mentioned that during the last year a nearly identical building has been constructed adjacent to the one described. This building is founded on a raft without piles. The results of settlement measurements on this building have shown that the immediate settlement during construction was about twice the value obtained for the building on cohesion piles.

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