REDUCTION OF NEGATIVE SKIN FRICTION ON STEEL PILES TO ROCK

REDUCTION DU FROTTEMENT LATERAL NEGATIF DES PIEUX EN ACIER SUR ROCHE

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SYNOPSIS The paper summarizes the result of measurements of negative friction on piles driven to rock through deposits of soft clay at sites where settlements are still occurring due to recent filling. In all cases where observations have been made the loads in the piles caused by negative skin friction were so large that yielding of the piles occurred at or near the points, resulting in additional settlements of the pile. A method whereby the piles were coated with bitumen was developed to reduce the negative friction to insignificant values; to protect the bitumen from being scraped off when driving the piles through the fill special precautions were taken.

INTRODUCTION

The following paper deals with the special problems of the negative skin friction on piles to rock which is typically encountered in the design of pile foundations on filled-in areas where the settlements are still not completed. The results of five years measurements of negative friction on piles in Norway are summarized. Main emphasis is, however, given to the description of a method of reducing the negative friction on piles by coating the piles with bitumen, which has been applied on two actual jobs.

OBSERVATIONS OF NEGATIVE SKIN FRICTION

In two papers (Bjerrum and Johannessen, 1965; Johannessen, 1965) the measurements of the negative skin friction on a special test pile in the Harbour of Oslo are described. Since then, a number of additional piles have been instrumented and today observations are available from altogether 6 piles at 5 different sites. The result of these measurements are summarized in Table 1.

Table 1 Results of previous tests on unprotected steel piles.

Site Pile No.	Pile data type	Pile data length m	Time after driving years	Down-drag tons	Settlement during observation ground	Settlement during observation pile	K tan φ'
Sörenga							
B	I	53	5	≈400	≈ 200	10.0	0.20
C	II	57	2	300	≈ 27	5.3	0.18
G	II	41	2	250	≈ 7	3.2	0.23
Heröya							
85	III	32	1½	300	≈ 30		0.25
A	IV	≈30		120	≈ 20	3.3	0.26
Alnabru							
F 6	III	32	1	≈300			

Pile type: I: KP 24, 47 cm, II: Tubular steel pile, Ø 50 cm, III: Tubular steel pile with concrete, Ø 50 cm; IV: Tubular steel pile, Ø 30 cm.

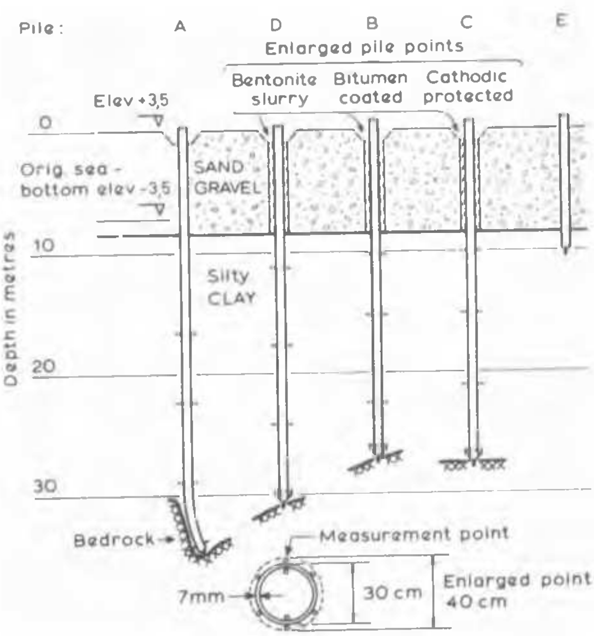


Fig. 1 Test site Heröya - Section Test Pile

All piles were tubular steel piles closed at the lower end and equipped with a conventional hardened Oslo-point of the type, shown on Fig. 2, which can be hammered into rock to secure a reliable bearing on rock (Bjerrum, 1957).

The compression of the piles were in all cases measured with a mechanical system. The principle of this system is to measure the shortening of the pile between the top of the pile and various points located at different depths inside the pile. This was done by installing a system of guided steel rods which extend from the top of the pile to the measuring points (Johannessen, 1965).

In Table 1 pile B at Sörenga in the Harbour of Oslo is the special test pile on which the negative skin friction was measured for the first time, and it is this pile which is described in detail in the above mentioned papers. The Sörenga site represents probably the worst possible conditions for the development of negative skin friction: More than 10 m of fill was placed after the test piles were driven and the observations had started. The fill rests on about 40 m of normally consolidated marine clay. Within the period of observation the settlement of the areas has thus been 200 cm. The drag load on the test pile is today about 400 tons. The stresses in the steel just above the point are most likely near yielding and the steel point has been pressed about 6 cm into rock. In spite of the fact that the pile does not carry any load at its top its settlement amounts to about 10 cm.

Similarly large values of negative skin friction were observed on two other piles, piles C and G, driven in the same part of the Harbour of Oslo, but at sites where the settlements are considerably smaller. Of these piles, pile G is of special interest in an area which was filled in more than 70 years ago and where therefore the rate of settlement was as small as 1-2 mm per year. However, due to the pile driving the settlements increased to a few centimeters per year during the period of observation. The additional settlements of the two piles due to the drag load amounts to 3-5 cm.

At Heröya near Porsgrunn observations of negative skin friction on two piles, piles 85 and A in Table 1 are available. Both piles will be described in some detail below. At these two sites the additional loads in the piles due to the settlement of the surrounding clay were also very large, and the additional settlements of pile A exceed 3 cm.

The last pile in Table 1 is a concrete-filled steel tube pile located in the outskirts of Oslo. This pile also shows a large negative friction.

In the above mentioned paper (Johannessen and Bjerrum, 1965) an empirical method was forwarded for estimating the maximum negative friction on a pile. The method assumed that at any depth the specific value of the negative friction on the surface of a pile could be assumed to be equal to the vertical effective overburden pressure multiplied by a constant $K \tan \varphi'$. The computed values of $K \tan \varphi'$ for 5 of the piles are given in Table 1; for the piles at Sörenga in the Harbour of Oslo a value of 0.18 - 0.23 was found, whereas the piles at Heröya where the clay is more silty gave a value of 0.25 - 0.26. The values of $K \tan \varphi'$ are so consistent and the scattering so small that there is reason to believe that the maximum value of the negative skin friction on steel piles for Norwegian marine clays can be reliably estimated by the proposed method.

PILE FOUNDATION HERØYA

The conclusion which can be drawn from the available observations of drag loads on piles driven to rock at any reclaimed site where settlements are still occurring is that the piles will inevitably be subjected to additional loads from the surrounding clay which are so large that they most likely will cause yielding in the lower part of the pile. The engineering approach to the problem of designing pile foundations on reclaimed sites seems therefore logically to be a development of methods which can reduce the negative skin friction.

In the search for a method of reducing the adhesion between pile and clay it was obvious to consider coating the piles with bitumen. This solution was even more obvious to the Norwegian Geotechnical Institute as a detailed study of the result of loading tests on a number of concrete piles, of which some were uncoated and others coated with bitumen, had clearly demonstrated the surprising ability of a bitumenous coating to reduce the adhesion between a pile and the surrounding clay (Hutchinson and Jensen, 1968).

Another method considered for reduction of the negative skin friction on steel piles is to apply a direct electric current as done for a cathodic protection of steel piles against corrosion. By putting the pile negative in relation to a nearby anode and applying an electrical current, a reduction of the effective stresses and thus of the friction on the surface of the pile is obtained at the same time as the corrosion of the steel is reduced. This method has frequently been used to reduce temporarily the adhesion between clay and steel when steel piles or tubes had to be pulled out of the ground.

An opportunity to test in practice the methods of reducing the negative skin friction on piles arose in 1966 when Norsk Hydro decided to build its ammonium plant No. 2 at Heröya near Porsgrunn, about 120 km south of Oslo. Plant No. 1 had been built 2 years earlier at a reclaimed area where the settlements of the ground surface were still proceeding. The plant therefore had to be supported on steel piles driven through the fill and the soft clay to rock at a depth of 20-30 m. As large negative friction could be expected the design load on the piles was reduced by about 50%. One of the piles, pile 85 in Table 1, was instrumented and the observations confirmed the expected large negative friction, the load resulting from the down-drag being measured to about 300 tons. For comparison it can be mentioned that the design load on the piles is only 120 tons.

Plant No. 2 likewise had to be built at a site where the fill which was placed only 2-4 years earlier was still settling at a rate of 15-25 cm per year. Consequently large negative skin friction could be expected. As the total length of piles required exceeded 30 kilometres, there was good reason to consider any alternative solution which could reduce the negative skin friction on the piles. As consultant on the foundation the Norwegian Geotechnical Institute proposed to the owner to carry out a large-scale field test at the site to find out whether the two proposed methods for reducing the negative skin friction mentioned above would work satisfactorily in practice. In spite of the fact that only 3-4 months were available before pile driving had to be started the owner agreed upon the proposal.

The test pile installation was completed in May 1966. It consisted of the piles shown in Fig. 1, all instrumented with a system of guided steel rods which permitted the measurement of the shortening of the piles between the top and various points located at different depths. All piles in the test installations were cylindrical steel piles with an outside diameter of 30 cm and a wall thickness of 0.7 cm.

Pile A was a reference pile used to measure the negative skin friction which would develop on the piles if no precautions were made for its reduction.

Pile B should show whether it was possible to reduce the negative skin friction by coating the pile with bitumen. Based on the studies carried out on the piles from Khorramchar (Hutchinson and Jensen 1968) and theoretical considerations, it was decided to use a straight-run bitumen with the penetration 80/100 and to cover the pile surface with a layer about 1 mm in thickness. The most serious problem was, however, to develop a means of preventing the bitumen from being scratched off during the driving of the piles through the upper fill which consisted of sand and gravel. Several alternative solutions were considered, but finally it was decided to equip the pile with an enlarged point. This enlarged point, which is shown in Fig. 2, had a diameter of 40 cm so that when driven into the ground it formed a hole which is 10 cm greater in diameter than the shaft of the pile. To prevent the hole from closing it was stabilized by filling it with a thixotropic slurry made up of 120 kg bentonite (Yellowstone) mixed with 1 m^3 of water.

Pile D was included in order to measure separately the effect of the enlarged point and the bentonite slurry on the negative skin friction. The pile was therefore tested exactly as pile B, but without the coating with bitumen.

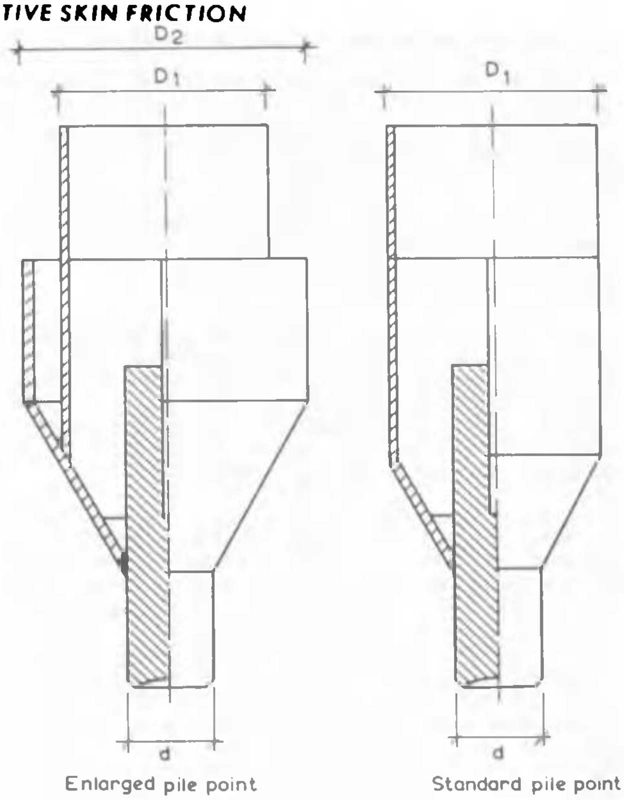
Pile C should measure the effect of a direct current on the negative skin friction. At a distance of 7 m from the pile a 20 m long pipe with a diameter of 5 cm was driven into the ground to act as the anode. As a source of direct current a selenium rectifier was used and it was decided to put on the pile a current corresponding to what was needed for a cathodic protection against corrosion. This requirement led to a current of 4 amperes at 0.6 volt.

Pile E is a standard steel pipe pile without enlarged point which was driven through the fill only. A pulling test with this pile would show the maximum friction which could be expected in the fill.

At the site of the test installation the soil conditions are as shown in Fig. 3. Below 8-10 m of fill consisting of sandy gravel a normally consolidated marine silty clay was found. The shear strength of the clay was 1-3 t/m^2 before the fill was placed. At the time the test piles were installed the clay had consolidated so much that the shear strength had increased to 4-5 t/m^2. The depth to rock varied from 25 to 35 m.

The fill at the site of the test piles was placed in 1962-63. The rate of settlements observed during the period of testing was about 0.4 mm per 24 hours and during the year following the driving of the piles the settlements of the area amounted to 16 cm.

As mentioned above, all piles were instrumented such that the compression of the pile could be followed. Fig. 4 shows how the total compression of the piles developed with time permitting a direct evaluation of the average value of the negative friction on the piles. From the diagram it is readily observed that measurable deformations of pile A occur immediately and that they are large compared with the deformation of the other piles and first and foremost piles B and C. When in June 1966 the first observations became available the deformations of piles B and C appeared so surprisingly small that it was feared that the point of the piles were not in contact with rock. It was consequently decided to test load the three piles with 50 tons. These loading tests confirmed that the points of all three piles were in contact with rock and that the measurements therefore were reliable. As observed from the curves on Fig. 4 the negative skin friction on all piles decreased temporarily in March 1967. The explanation of this reduction is that in this period piles for the foundation of the factory were driven at a distance of only 10-12 m. Excess pore pressures resulting from the pile driving caused a temporary reduction in effective stresses in the clay surrounding the piles and thus a decrease in friction between pile and clay.



Site	D1	D2	d
Heröya	300	400	120
Sörenga	500	680	100

Dimension in mm

Fig. 2 Standard pile point and enlarged pile point

Fig. 5 shows the compression of the piles over the various depth intervals over which the measurements were made, as observed about $1\frac{1}{2}$ years after the piles were driven. From the observed compressions the stresses in the steel have been computed and by multiplying the stresses with the cross section of the steel tube finally the forces in the piles are derived. The conclusion which can be drawn from the measurements shown in Fig. 5 is as follows:

The negative friction on pile A amounted to 120 tons. The explanation why the maximum force was observed at a depth of 25 m is that when during the driving the pile point reached this depth it hit a local gorge in the rock. That part of the pile which is below the depth of -30 m was probably resting on the rock wall of the gorge. The 120 tons drag load observed caused stresses in the steel of 1800 kg/cm^2, and in addition to a compression of the pile of 10 mm the pile showed a further settlement of 20 mm.

Pile B which was coated with bitumen and was driven with an enlarged point showed a drag load of less than 10 tons, which is less than 10% of the value observed on pile A. This value did not increase in the $2\frac{1}{2}$ years of observation, but it varied from about 13 tons in the colder winter periods to values somewhat below 10 tons in the warmer summer periods.

Pile C which was protected by a direct current showed a drag load of 57 tons. This load was roughly 60 tons lower than the load on the reference pile A. Now pile C differed from pile A partly by the enlarged point which kept the pile free of the fill and partly by the direct current ; the 60 tons difference in drag load can approximately be divided up into a 20 ton contribution resulting from the fact that the pile was free of the upper fill and a contribution of about 40 tons resulting from the electric current. An estimate of the effect of the electric current can also be obtained by a comparison of the forces observed in piles C and D, and such a comparison leads to an approximately identical evaluation of the effect of the electric current. It is, however, worth while mentioning that it proved throughout possible to reduce the negative skin friction to negligible values provided the current was increased from 4 to about 80 amperes. A current of this order of magnitude represents, however, not an economical solution to the problem.

Less than three months after the test piles were driven the conclusion could be drawn that the negative friction on the piles could be reduced to insignificant values proved (1) the piles were coated with a 1 mm thick layer of bitumen and (2) the piles were equipped with an enlarged point so that the bitumen was protected from being damaged when the pile was driven through the fill, and (3) that the hole between fill and pile was stabilized permanently by a bentonite slurry. These precautions would furthermore prevent corrosion of the steel so that the steel as well as concrete cross sections could be utilized to their full extent in the design of the foundation. By taking these precautions the design load on the piles could be increased from the 120 tons, used on Plant 1, to 250 tons.

The foundation of the factory was carried out in agreement with this proposal. The piles for the foundation had a diameter of 50 cm. The coating used on the actual piles was identical to that used on test pile B. The enlarged point was given a diameter which was 10 cm larger than the diameter of the pile shaft. The cost involved in the coating of the piles including the enlarged points and the bentonite slurry amounted to about 50 Norw. Cr. per metre, or about 20% of the cost of the completed pile.

Due to the increase in design load the total length of

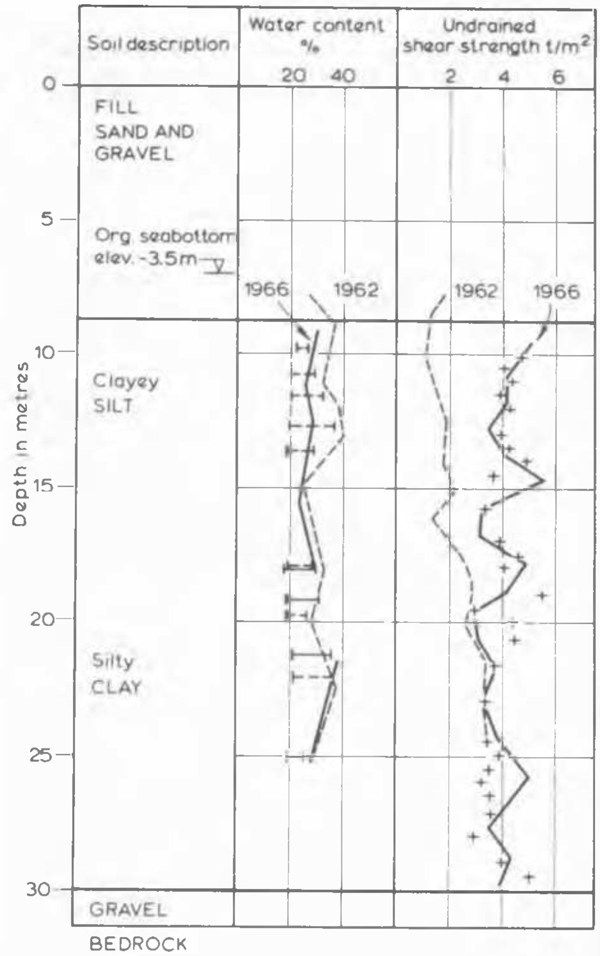


Fig. 3 Soil conditions at Heröya.

piles required was reduced from an initial estimate of more than 30 km to about 20 km. The resulting net saving on the job amounted to 5-6 mill. Norw. Cr.

It may be mentioned that some difficulties were encountered when driving the coated piles. Due to the fact that the adhesion between the pile shaft and surrounding soil was reduced during the driving, the piles showed a "spring-like" behaviour and due to the uplift the hollow steel piles had a tendency to rise. In order to remedy this situation it was decided to cast the concrete in the piles successively as the individual lengths of pile pipes were driven. This method proved, however, not to be the right solution to the problem. The adhesion between concrete and steel was not large enough to prevent the concrete from rising in the tube during the further driving with the result that cracks and openings were formed in the concrete core. The final solution used was to keep the piles filled with water during the driving.

WAREHOUSE SØRENGA

In the fall of 1966, i.e. shortly after the pile driving at Heröya had started, the Institute got a second opportunity to establish a test pile installation. At Sörenga in the Harbour of Oslo, where measure-

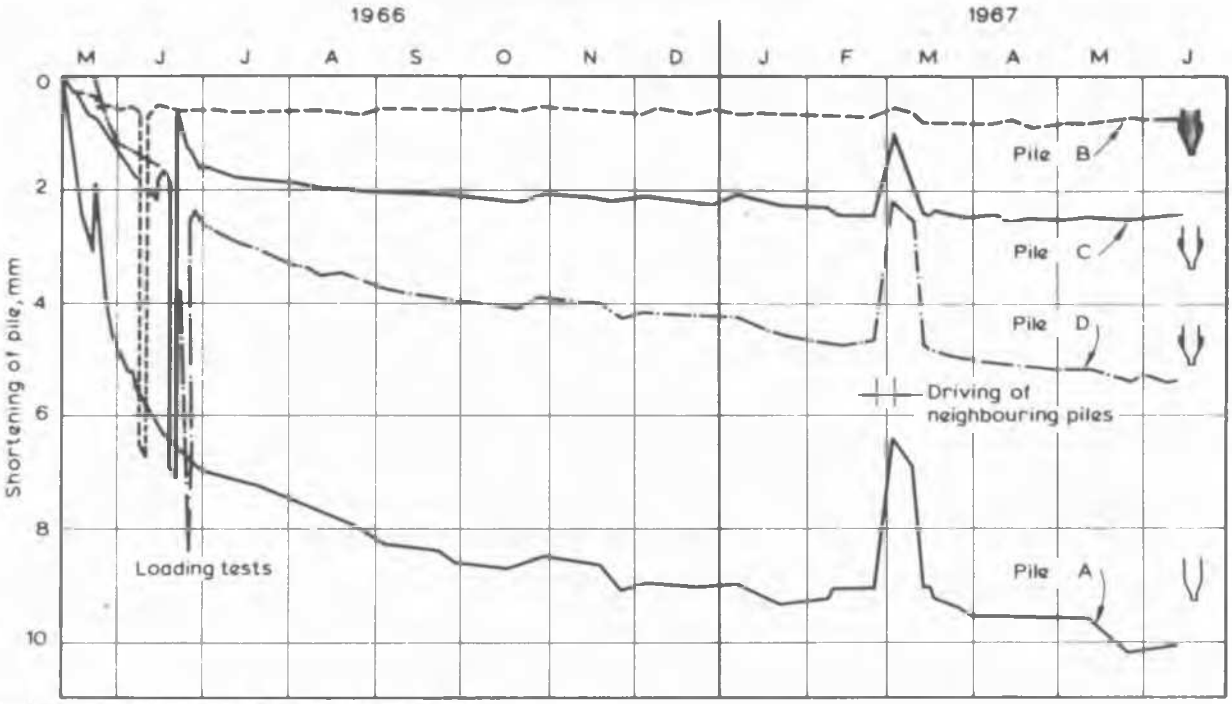


Fig. 4 Total shortening of piles against time.

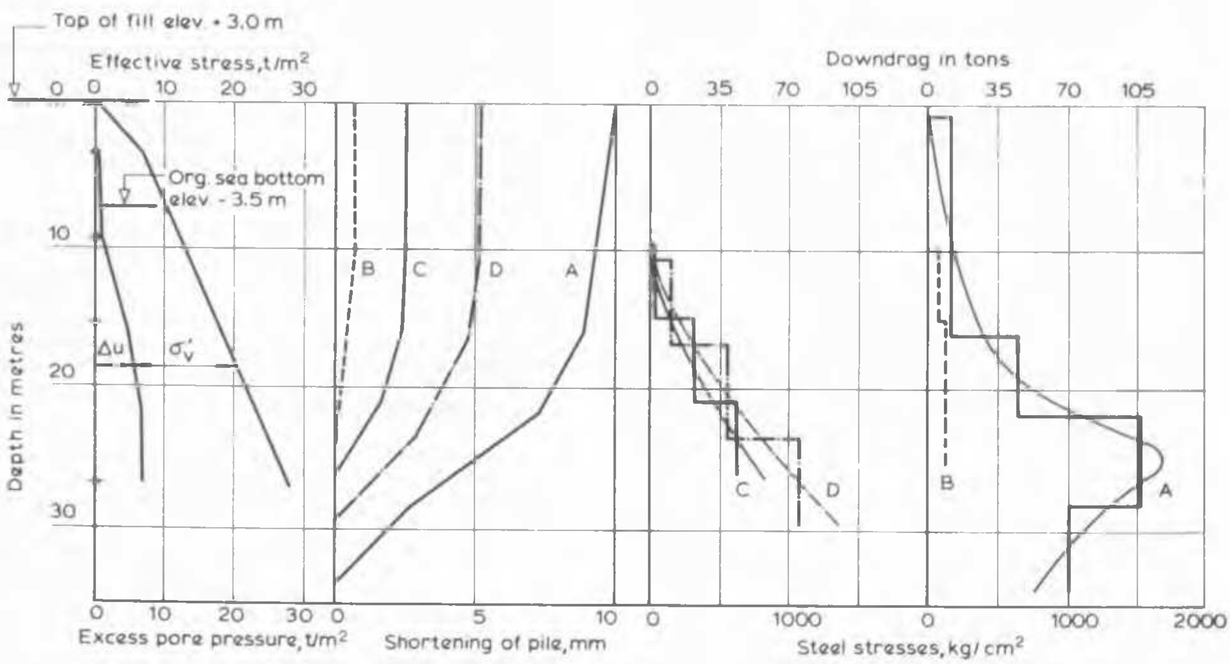


Fig. 5 Distribution of effective stress excess pore pressure, shortening of pile and steel stresses with depth.

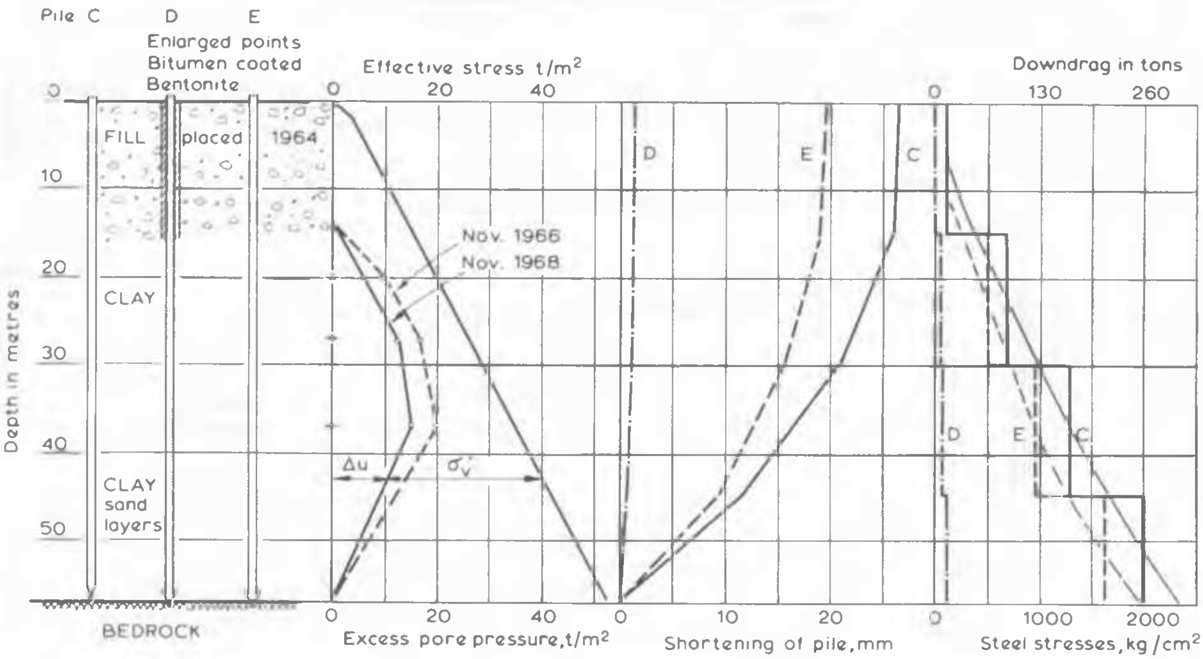


Fig. 6 Sörenga - Test piles and soil description. Test results from piles on the recently reclaimed area.

ments at test pile B (see Table 1) had demonstrated that very large drag loads could be expected a new warehouse had to be built. As at Herøya, the selected approach to the problem was to establish a test pile installation and to base the design of the pile foundation on the results obtained. As the soil conditions varied from one end of the building to the other, two test pile installations were established.

In one end of the site the fill showed a thickness of 15 m and as it was placed only a few years earlier the rate of settlements was as large as 10-15 cm per year. The depth to rock was 55-60 m (see Fig. 6), so that the thickness of the marine clay was about 40 m. The fill through which the piles had to be driven consisted of rock-fill remains from demolished buildings, boulders, etc. The test installation at this location included three piles. All test piles were full-scale steel-tube piles with a diameter of 50 cm and a wall thickness of 8 mm. Pile C (see Fig. 6) was the reference pile. Pile D and E were both coated by a 1 mm thick layer of bitumen with the penetration 80/100. Both piles were driven with an enlarged point with the diameter 69 cm. In order to protect the bitumenous coating on pile D from being damaged during driving through the fill, an outer casing with a diameter of 63 cm was driven down through the fill jointly with the first pile section. The space between the pile and the casing was filled with a bentonite slurry in order to prevent it from being filled with sand. In contrast to the pile-driving technique at Herøya a casing was found necessary at Sörenga; the reason being that the fill at Sörenga is so coarse and pervious that the bentonite slurry used for stabilizing the hole around the piles at Herøya would have disappeared into the fill. No further precautions other than the enlarged point were undertaken to protect the bitumen on pile E when it was driven through the fill.

About a year after the driving of the test piles the negative friction on the reference pile, pile C, had reached a value of about 300 tons just above the point and the stresses in the steel was 2300 kg/cm². The pile top had then settled more than 5 cm of which $2\frac{1}{2}$ cm was due to the penetration of the pile point into rock. Pile D which was coated with bitumen and driven with an outer casing so that the bitumen was protected from being scratched off during the driving showed at the same time a negative skin friction of only 15 tons. The necessity of using a casing through the fill to protect the bitumen was clearly illustrated by the observations on pile E. In spite of its coating of bitumen the negative skin friction amounted to 210 tons.

Below the other end of the building the fill showed a thickness of 13 m. The fill had already been placed at the end of the last century and it consisted mainly of sawdust and sandy organic mud. As the fill was more than 70 years old the consolidation of the below clay had been completed and the rate of settlements was very small. As shown on Fig. 7, the depth to rock was 40 m and the thickness of the soft marine clay was thus only 27 m.

The test installation at this location had only the purpose to find out how large the negative friction would be at that part of the site where the settlements were completed. Therefore, only two piles were induced, a reference pile, pile G, and an identical pile with an enlarged point, pile H. After two years of observation the drag load on the two piles had increased to 250 and 210 tons in piles G and H respectively, which correspond about to the values observed on those areas where the rate of settlement still is large.

Based on the results of the test piles the foundation of the warehouse at the previously reclaimed area was designed with 50 cm bitumen coated steel piles similar to those used at Herøya.

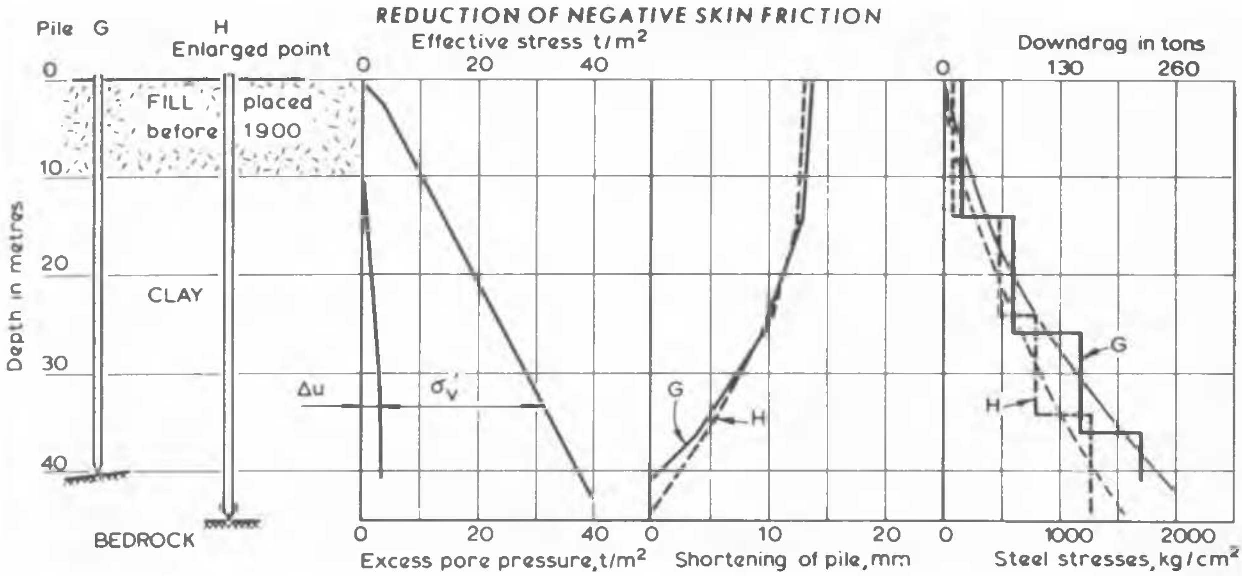


Fig. 7 Sörenga - Test piles and soil description. Test results from piles on the previously reclaimed area.

CONCLUSION

Five years ago very little was known about negative friction on piles driven to rock and on most jobs the problem was ignored in the design of the piles. During the past few years the Norwegian Geotechnical Institute has tried to develop a rational approach to the problem, partly by measurement of the negative skin friction on piles on actual jobs and partly by field testing of methods to reduce the negative skin friction. This approach proved to be fully economically justified on the two jobs at which it has been applied. In addition, much has been learned from the observations. Today measurements have been carried out on altogether 15 piles. The experiences which can be derived from these measurements can be summarized in the following points :

1. Altogether, negative friction has been measured at "standard" piles driven to rock at five different sites. In all cases the drag loads were very large and caused yielding in the lower part of the piles. The settlements of the piles before any load was put on the top varied from 1 to 10 cm depending on the conditions. The negative friction was large even at sites where the settlements of the ground were small. The negative friction developed very quickly and only small relative movements were required to fully develop its maximum value. In two Norwegian clays the specific maximum negative friction on a single pile could with satisfactory accuracy be predicted by multiplying the effective pressure by a constant K tan.φ' which in the two cases were 0.20 and 0.25 respectively.

2. On two jobs it has been demonstrated that it is technically and economically feasible to reduce the negative friction on the piles. In both cases a 1 mm thick coating of bitumen reduced the negative friction to values of the order of 10-15 tons which, actually, is less than 10% of the values observed on unprotected piles.

3. It has been demonstrated by full-scale experiments that it is possible to develop methods which permits a pile coated with bitumen to be driven through a fill without damaging the coating. In sandy gravelly type of fills this was accomplished by driving the piles with an enlarged point and by stabilizing the annular hole between fill and pile shaft with a bentonite slurry. In coarser and more pervious fill a casing through the fill was used to protect the pile coating.

It should finally be mentioned that the observations described above are made either on individual piles or on piles driven at considerable distances apart. The experiences do thus not allow an evaluation of the group action.

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