Negative Skin Friction and Safety Analysis of Piles

Frottement Nègatif et Analyse de Sècuritè sur Pieux

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SYNOPSIS The magnitude of negative skin friction is larger to much larger than was generally assumed, but in spite of this underestimation its influence was allowable for the constructions: the settlements and differences of settlements were tolerable.
In this paper a safety analysis and calculation method is discussed as it is applied in Rotterdam nowadays, thereby taking into account the max. value of the negative skin friction. The recommended safety coefficient is 1,1 on the max. value of the load caused by negative skin friction and 1,7 to 2 on the working load. Stresses in the pile material up to 100 kgf/cm2 for wooden piles and 120 kgf/cm2 for concrete piles can be accepted.

INTRODUCTION

The opinion on the negative skin friction is strongly in alteration the last few years due to:

- the acquaintance with the results of a number of measurements in several countries (ref. 1, 2, 3) and
- the aim at a higher efficiency in foundation design.

While 10 years ago it was in complete accordance with every recommendation in Rotterdam to take into account a load caused by negative skin friction of 15 tons (for a prefabricated concrete pile sq. 40 cm), one now knows that it, depending on the subsoil conditions, can be 65 to 120 tons. On the other hand it may be stated that, proved by experiences, the foundations made during the past 40 years are in accordance with the demands: the settlements and differences in settlements are tolerable for the constructions (ref. 4). The fact that, in spite of the serious underestimation of the negative skin friction, the foundations made these past 40 years, may be qualified as good, implies the following:

a. The influence of the negative skin friction is of secondary importance, it is in the first instance a settlement problem and not a failure problem.

b. The bearing capacity is larger than calculated ("hidden safety") while the real safety coefficient is less than was assumed.

MEASUREMENTS IN ROTTERDAM

In a joint operation of Nederhorst Contractors and Public Works Rotterdam measurements were performed in Rotterdam on the negative skin friction and the influence thereof on the behaviour of piles. Three piles - normal construction piles - were provided with measurement instruments, whereby two of the three piles were treated with respectively bitumen and bentonite in the negative skin friction zone in order to reduce the load caused by negative skin friction. The three piles were located next to each other, below the same wall. The results of the measurements with all informations are given on fig. 1. The most remarkable points of these measurements are:

1. In a short period of time a considerable negative skin friction developed in spite of the very low settlement rate of the surface. The measured negative skin friction (for the pile without any coating in the negative skin friction zone) was about 70% of the calculated maximum value after 60 days during which period the surface settled around 10 millimetres. The calculated maximum value - full development of the shear resistance along the pile shaft in the negative skin friction zone - is about 95 tons for the pile without any coating in the negative skin friction zone.
2. The increasement of the negative skin friction was very rapid in the beginning (an increasement up to about 55% of the calculated max. value in 25 days, in which period the settlement of the surface was not more than 4 millimetres) which was most probably caused by the reconsolidation of the remolded soil around the pile (ref. 1.).
3. The loading of the piles (applied on the pile head) resulted in the first instance in a reduction of the negative skin friction (of about 25%), which reduction was eliminated after some time due to a further development of the negative skin friction.

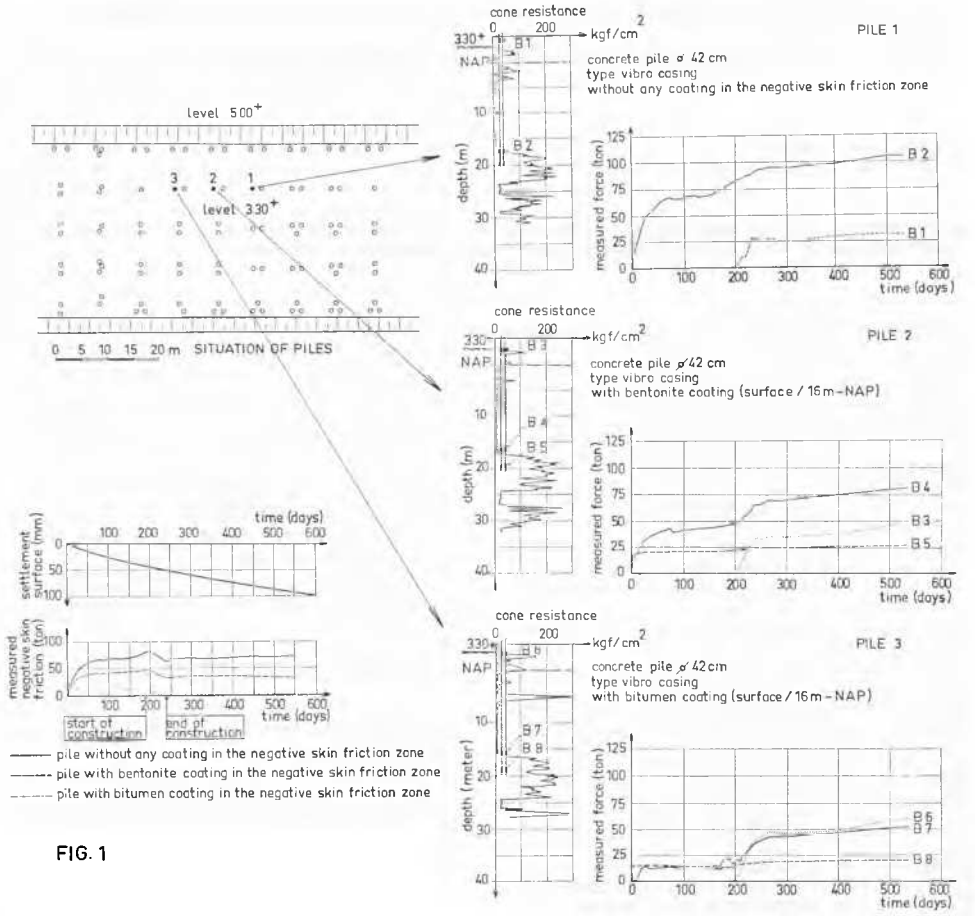

FIG. 1

4. Although the calculated point bearing capacity is twice as large as the calculated friction bearing capacity (the positive skin friction, developed in the deep sand formation) the measured bearing capacity is delivered for about 60% by the positive skin friction. The developed positive skin friction is about 45% of the calculated ultimate value.
5. The load-deformation character of the piles is remarkably influenced by the negative skin friction. The pile with bitumen coating (where the negative skin friction is strongly reduced) is for the given "load-range" twice as stiff as the pile without any coating, due to which the effective load on the pile with bitumen coating is twice as large (about 60 tons) as on the pile without any coating (about 35 tons).

THE NEGATIVE SKIN FRICTION IN GENERAL

In view of the theory of the phenomenon (ref. 5) and the result of measurements in general (also ref. 1) the following can be stated:

1. The magnitude of the negative skin friction is much larger than was assumed in the past. A development of the maximum value (:full development of the shear resistance along the shaft in the negative skin friction zone) can easily take place.

2. Small settlements - of a few millimetres - may cause significant negative skin friction along the piles. Remolding of clay around driven piles and the subsequent reconsolidation may even result in the occurance of negative skin friction.
3. The method of Zeevaert (ref. 5), taking into account the possible higher horizontal earth pressure coefficient in sandy layers (up to 1 to 1,5 instead of the coefficient of the earth pressure at rest) and the cohesion in clays, is a very realiable method for the calculation of the maximum value of the negative skin friction.
4. The phenomenon of the negative skin friction is a settlement problem and not a failure problem, although the differences in settlement may be quite significant.
5. For the stresses in the pile material the maximum value must always be taken into account.
6. Although there are a number of possibilities for reduction (group working, limited relative deformation, shortening of the pile by loading, settlement of the pile, etc.) it is often "speculative" to take such a reduction into account. It would in any case mean an assumption which is far from accurate.
7. A reduction or neglection of the negative skin friction is only then fully justified when the consequences of the phenomenon, namely:
   a. settlements and differences in settlements of the piles, and
   b. the occurrance of high to very high material stresses in the pile material,

   are taken into account in the construction design.

THE BEARING CAPACITY OF DRIVEN PILES IN GENERAL

With respect to the bearing capacity of driven piles and its influence on the safety analysis the following remarks can be made.

1. The influence of the friction bearing capacity (positive skin friction) is often neglected or underestimated although it can be of great importance, especially when the negative skin friction is fully taken into account. The method published by B.B. Broms (ref. 7) appears to be very reliable as is proved by extensive experiences and a number of tests among others in Rotterdam (ref. 8.).
   This method is much more reliable than the method based on the local friction measurements.
2. It is very realiable to calculate the point bearing capacity from the result of the static cone penetration test (ref. 9.).The interpretation method may vary between the "1,5D/3,75D method" (the average cone resistance in a zone of 1,5 times the pile diameter below and 3,75 times the pile diameter above the pile point) and the "4D/8D method", whereby the "4D/8D method" clearly is too pessimistic.

In order to give an impression on the value of the two above mentioned methods, two examples will be given in short:

a. For the foundation of cokes silos prefabricated concrete piles, Ø 45 cm, were used. The piles were driven 4 metres into a deep sand formation (with an average cone resistance of 100 kgf/cm2) and provided with a bitumen coating in the whole negative skin friction zone.
   With the aid of the above mentioned calculation methods an ultimate bearing capacity of 320 tons (being 120 tons positive skin friction and 200 tons point bearing capacity) was calculated.
   The results of load tests showed that the deformation under the working load (165 ton) was around 12 millimetres (gross settlement) and 4 millimetres after reloading (net settlement).The load test was performed up to 300 tons, which load resulted in a gross settlement of 35 millimetres and a net settlement of 20 millimetres.
b. Below an existing 14-story building a new foundation must be made because of the excessive settlement of the existing foundation. The new foundation was made up by steel piles, Ø 475 millimetres, provided with a bitumen coating in the negative skin friction zone. The piles were brought to the foundation level with the aid of driving ("inward hammering"). Every pile (until today 75) of the new foundation is tested because the safety coefficient on the working load was only 1,5 (the influence of the negative skin friction is eliminated with the bitumen coating). The deformations of the piles under working load (120 tons) vary between 5 and 8 millimetres gross settlement.

THE SAFETY ANALYSIS

In the past in Rotterdam (and probably at more places) a low negative skin friction was assumed, while the positive skin friction was neglected or seriously underestimated. The point bearing capacity was generally calculated in a rather pessimistic way ("4D/8D method") and the safety coefficient (on the working load and the assumed negative skin friction)was 2 for driven piles without enlarged point and 2,5 for driven piles with enlarged point.
Example: - negative skin friction 15 ton (assumption);
- positive skin friction neglected;
- point bearing capacity (ultimate value) 130 ton;
- pile Ø 40 cm, without enlarged

point, driven 1,25 metres into a sand layer with an average cone resistance of 120 kgf/cm2;
- above the sand is 14 metres of soft clay and 2,5 metres of sand.

The allowable pile load is

$$P = \frac{130}{2} - 15 = 50 \text{ tons}$$

The calculation nowadays, with the methods as discussed in this paper, gives the following data:

- a negative skin friction of 65 tons maximum value instead of the 15 tons assumed in the past;
- a positive skin friction (ultimate value) of 20 tons;
- a point bearing capacity (ultimate value, calculated with the "1,5D/5D method") of 145 tons.

It would result in an allowable load of

$$P = \frac{145 + 20}{2} - 65 = 20 \text{ tons}$$

Since we know that the negative skin friction is only a settlement problem and not a failure problem and also that the calculated value is a maximum value which may perhaps be reduced, a safety coefficient of 1,1 on this load is justified. The allowable load with this assumption would be

$$P = \frac{145 + 20 - (1{,}1 \times 65)}{2} = 47 \text{ tons}$$

Experiences on load tests showed that, in the case of a thorough soil investigation and the interpretation thereof by an experienced foundation engineer, the safety coefficient on the working load (for driven piles!) may also be reduced to 1,7 for a pile without enlarged point (to 2,2 for a pile with enlarged point). In this case the pile of the example may be loaded by

$$P = \frac{145 + 20 - (1{,}1 \times 65)}{1{,}7} = 55 \text{ tons}$$

CONCLUSIONS

1. A development of a large value (nearly the maximum) of the negative skin friction can easily take place.
2. If the maximum value of the negative skin friction is taken into account, the safety coefficient on this load may be 1,1.
3. If the maximum value of the negative skin friction is taken into account the bearing capacity may be calculated without "hidden safety", while the safety coefficient on the working load can vary between 2 and 1,7. The use of a low safety coefficient (of 1,7) on the working load calls for a thorough soil investigation and the interpretation by an experienced foundation engineer. This applies only just to driven piles (without enlarged point).
4. For the stresses in the pile material, the maximum value of the negative skin friction must always be taken into account. Stresses up to 100 kgf/cm2 for wooden piles and 120 kgf/cm2 for concrete piles can be accepted since such stresses are acting in old piles without any serious consequences.
5. If the consequence of the negative skin friction - settlements and differences in settlements of the piles - is taken into account for the construction (by the construction designer!) the phenomenon of the negative skin friction may be neglected except for the stresses which can occur in the pile material.

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