The Bearing Capacity of a Pile

La force portante d'un pieu

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Summary

With the aid of some examples concerning a number of pile loading tests, performed by the Department of Public Works of Amsterdam, the author has tried to obtain a principal answer to the question when the ultimate bearing resistance of a pile is reached.

First of all the general character of the load settlement curve of a pile is thoroughly analysed. The influence of skin friction and the resistance of the pile point are separated. Considering the latter, there appears to exist a general relation between load and settlement of the pile point and the time during which every load increment is applied. This can be represented by a formula with aid of which the ultimate resistance of a pile can be determined in a more objective way.

A new element is introduced when a pile is subjected to repeated loading and unloading, which causes larger settlements.

The ultimate resistance being known, it is possible to define the actual bearing capacity of a pile as equal to the load which will give the pile—in the future—at a previously fixed moment a previously fixed settlement.

A factor of safety is introduced in order to take into account the incertainties involved in the methods to predetermine the ultimate resistance of a pile, the ignorance as to the loads which will actually occur and which settlement is allowable at which time in the future.

A numerical interpretation is given with aid of the Dutch method of deep-sounding.

Sommaire

Se basant sur quelques essais de charge exécutés par le Département des Travaux Publics de la Municipalité d'Amsterdam, Hollande, le problème de la charge limite d'un pieu est posé.

Tout d'abord le caractère général du diagramme de l'enfoncement en fonction de la charge d'appui du pieu est analysé de façon approfondie. Le frottement latéral entre le pieu et le sol, ainsi que la résistance à la pointe sont considérés séparément. Une certaine relation paraît exister entre la charge, l'enfoncement à la pointe du pieu et la durée d'application de chaque charge. Cette relation peut être représentée par une formule permettant de déterminer de façon plus objective la charge limite d'un pieu.

Un nouvel élément est introduit lorsque le pieu est soumise à des charges répétées, ce qui cause un tassement plus important.

On peut ainsi définir la force portante d'un pieu comme étant égale à la charge qui produira un enfoncement donné à un moment déterminé à l'avance.

Un coefficient de sécurité est introduit pour tenir compte des incertitudes liées: aux méthodes appliquées pour déterminer au préalable la charge limite d'un pieu, aux charges réelles, à l'enfoncement admissible à tout moment. Une interprétation numérique est donnée à l'aide de la méthode hollandaise des essais de pénétration en profondeur.

Introduction

As a rule the bearing capacity of an individual pile is composed of the point resistance and the skin friction. If the latter is of minor importance the pile is called a point-bearing pile. In this paper the bearing capacity of a point-bearing pile is analysed, such influences on it as the load, the time during which the load is exerted and the effect of repeated loading and unloading being taken into consideration.

The point of view developed here is the result of a series of loading tests on piles, performed by the Department of Public Works of Amsterdam. In these tests a steel frame was used which made it possible to exert a load of about 150 tons on the pile, the settlements being measured, with aid of dials, with an accuracy of 5.10^{-3} mm. The dials were fixed to a measuring rod with a length of about 15 m, its supports being extended far enough from the loaded pile to get readings absolutely independent of the settlements of the soil around the loading frame.

In order to illustrate the views, of a more or less theoretical character, expounded in this paper, a choice has been made from the available material.

Load-Settlement Curve of a Pile

In Fig. 1 example is given of a load-settlement curve of the toe of a concrete pile which formed part of the foundation of a factory in the harbour area of Amsterdam. The curve is gradually bending downward without showing anywhere a sharp break which could be an indication that "something has happened" to the pile or the surrounding soil. Therefore the ultimate resistance of a pile is usually defined as the load, of which an infinitely small increase causes a infinitely large settlement. The load-settlement curve then has reached a point where it moves downward vertically.

This definition is easily given but is not very satisfactory. As is illustrated in Fig. 1 it is very difficult to determine when the load-settlement curve is absolutely vertical; e.g. if the scale on which the settlement is plotted is changed, the load-settlement curve takes a different shape. Whereas in the drawing on the upperpart of Fig. 1 the ultimate resistance seems to be reached at about 100 tons, the curve on the lower part suggests that the ultimate resistance is not yet reached. Moreover the shape of the curve, as will be demonstrated later on in this paper, is influenced by the time during which each load has been maintained on the pile.

It is possible to plot the load-settlement curve in a slightly different manner, as is done in Fig. 2 for the result of a loading test of *Plantema* (1948). On the horizontal base the load on the pile toe is given as a percentage of the ultimate resistance, which in the case of the *Plantema* pile was fairly well known.

The shape of the curve recalls a wellknown function in the branch of biology which represents the growth of a living individual as a function of time. It is postulated here that, in the same way, the load-settlement curve can be represented by the formula:

$$P = P_{max}(1 - e^{-\alpha z}) \qquad (1)$$

if P = the load on the pile toe
z = the settlement of the pile toe caused by the load P
P_{max} = the ultimate resistance of the pile
α = a coefficient which influences the shape of the load-settlement curve.

If this formula is valid, the load-settlement curve has to become a straight line—if the settlement z is plotted against $\ln\left(1 - \frac{P}{P_{max}}\right)$. This is done for the *Plantema* curve in Fig. 3. There appears to be two straight lines; this means that the formula is valid, but that when a certain load has been reached, here $P = 0.7\,P_{max}$, the coefficient changes from α_1 into α_2. The physical meaning of this change is probably the exceeding of precompression to which the soil had already been subjected before the loading test was performed. Other load-settlement curves appear to comply with the same formula, be it for other values of α.

In this way a method seems to be found to determine the ultimate bearing resistance of a pile in a strictly normalised and unpersonal manner, which may be illustrated in Fig. 4. Here

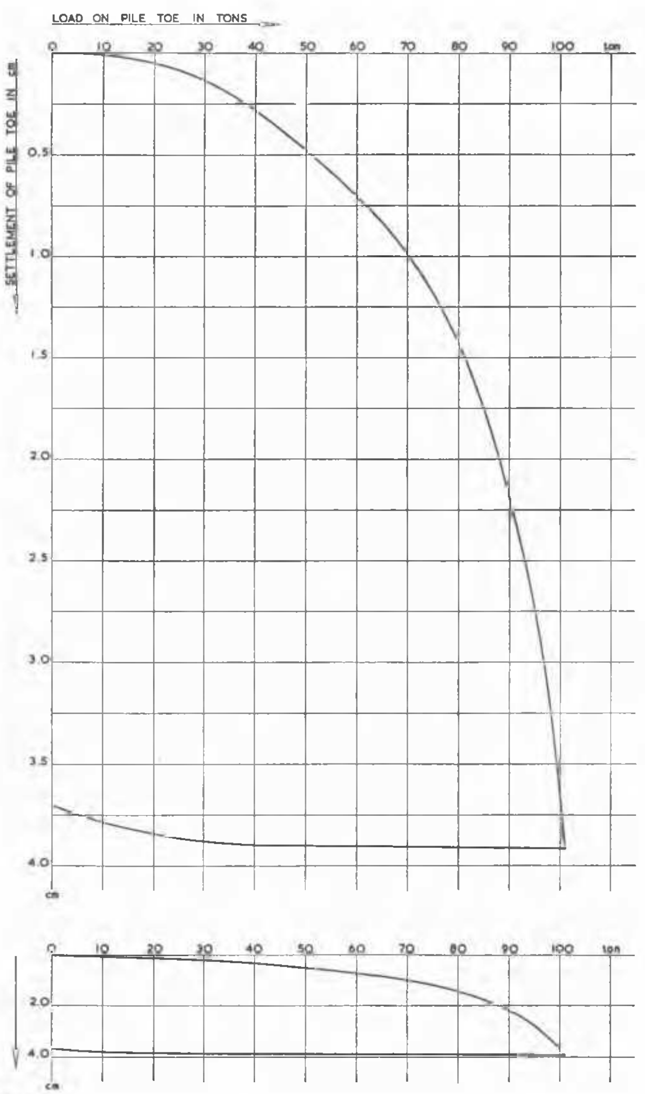

Fig. 1 Load-Settlement Curve of a Concrete Pile in the Harbour Area of Amsterdam
Diagramme de l'enfoncement en fonction de la charge d'un pieu en béton dans le port d'Amsterdam

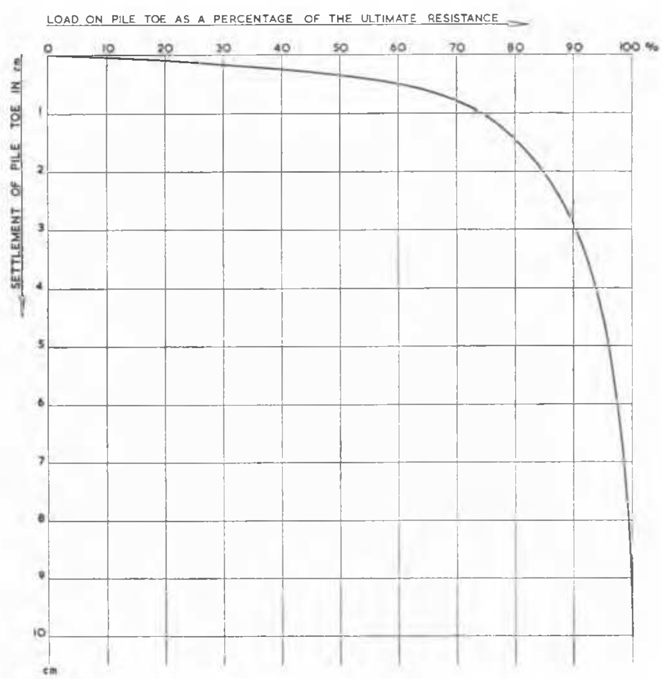

Fig. 2 Load-Settlement Curve of the *Plantema* Sounding Pile
Diagramme de l'enfoncement en fonction de la charge d'un pieu d'essai *Plantema*

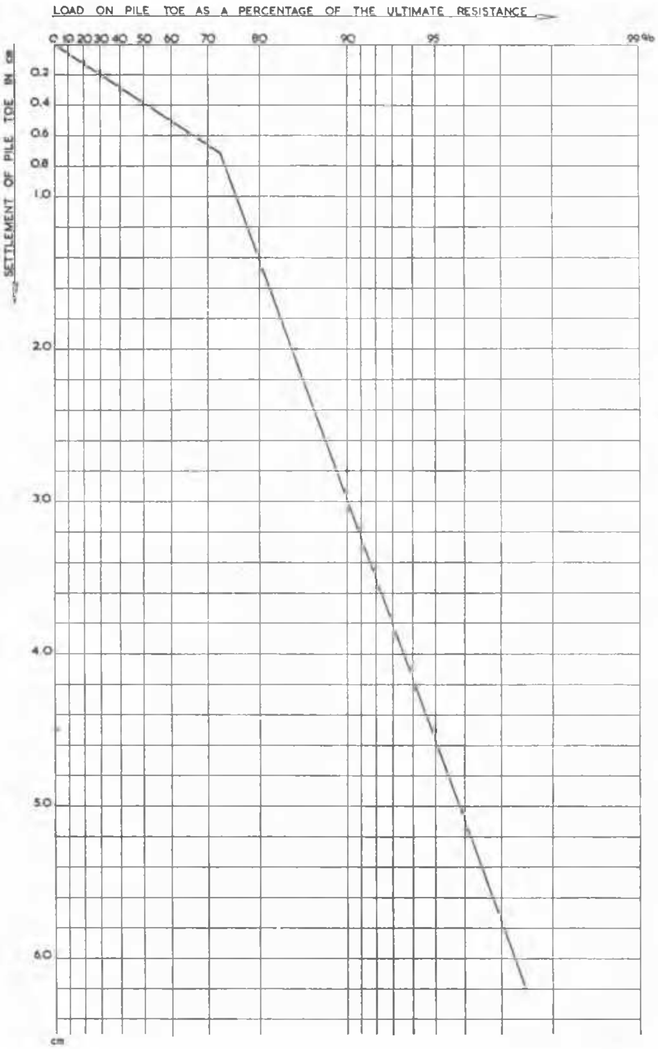

Fig. 3 Load-Settlement Curve of the *Plantema* Sounding Pile, plotted on a Semi-Logarithmic Scale
Représentation en coordonnées semi-logarithmiques du diagramme de l'enfoncement en fonction de la charge d'un pieu d'essai *Plantema*

for various supposed values of P_{max}, the ultimate resistance $\ln\left(1 - \frac{P}{P_{max}}\right)$ is plotted against the settlement z. Only for P_{max} approximately equal to 140 tons the curve appears to consist of two straight lines, that is, to comply with formula (1).

It may be clear that in this way it is possible to give to the conception—up to date somewhat vague—of the ultimate resistance of a pile a clearly defined meaning which can be interpreted only in one sense. However it must be emphasised that this conception has not yet got its most general expression; therefore it is necessary to introduce the time during which each load increment is maintained.

Time-Settlement Curve of a Pile

It is too simple a point of view to suppose that a given load P_1 on a pile causes a given settlement z_1. If doing so, the settlement of a pile is in no way defined, because there appears to be an immediate dependence of the time t during which the load P_1 is maintained. At different time intervals the settlement z for the same load P_1 differs. Fig. 5, which gives the time-settlement curve of a pile tested in 1952, demonstrates this clearly. If a logarithmic time scale is used, the nature of the dependence becomes more apparent as the time-settlement relation at different load increments becomes a set of straight lines, as is shown in Fig. 6. This can be represented in the formula:

$$z = \beta + \gamma \ln t \qquad (2)$$

if z is settlement of the pile toe, and β, γ coefficients.

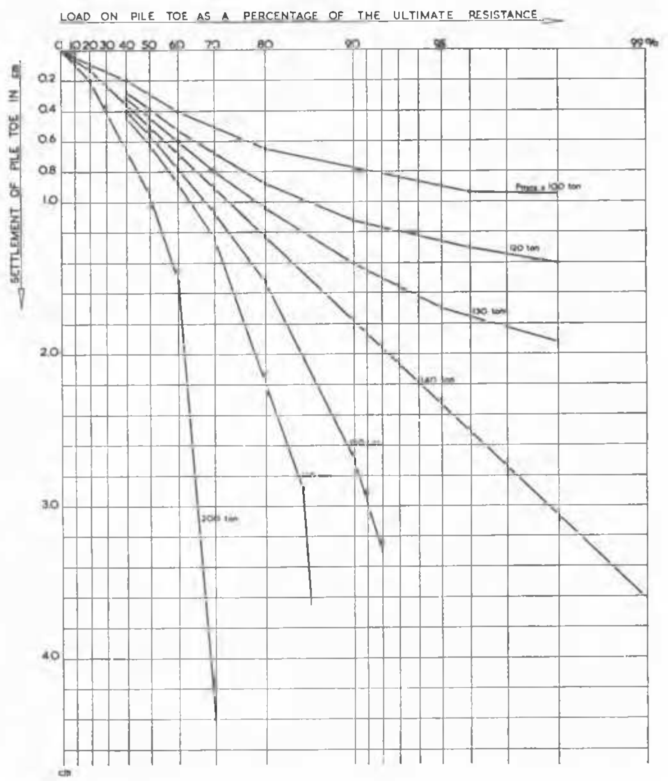

Fig. 4 Load-Settlement Curve of Concrete Pile No. 2, Slotermeer, Drawn for Various Supposed Ultimate Resistances at Failure of the Pile
Diagramme de l'enfoncement en fonction de la charge du pieu no 2, Slotermeer, dessiné pour diverses charges limites supposées

If the load P is small, there is as good as no increase of the settlement with time; gradually, P becoming larger and larger, the inclination of the time-settlement line grows. This makes clear why the rule that during a loading test the load has to be maintained until the settlement has come to an end is yet another vague and hazy notion in the philosophy of loading tests.

The general equation, which gives the settlement z as a function of the load P and of the time t during which P is applied, becomes:

$$z = -\left(\frac{1}{\chi} + \frac{1}{\lambda}\ln t\right) \ln \frac{P_{max} - P}{P_{max}} \qquad (3)$$

if χ, λ = coefficients.

If every load increment is taken to be maintained during a time $t = t_1$ the formula becomes:

$$z = -\left(\frac{1}{\chi} + \frac{1}{\lambda}\ln t_1\right) \ln \frac{P_{max} - P}{P_{max}} = -\alpha \ln \frac{P_{max} - P}{P_{max}}$$

which is equal to formula (1).

For a constant load $P = P_1$ the formula takes the form:

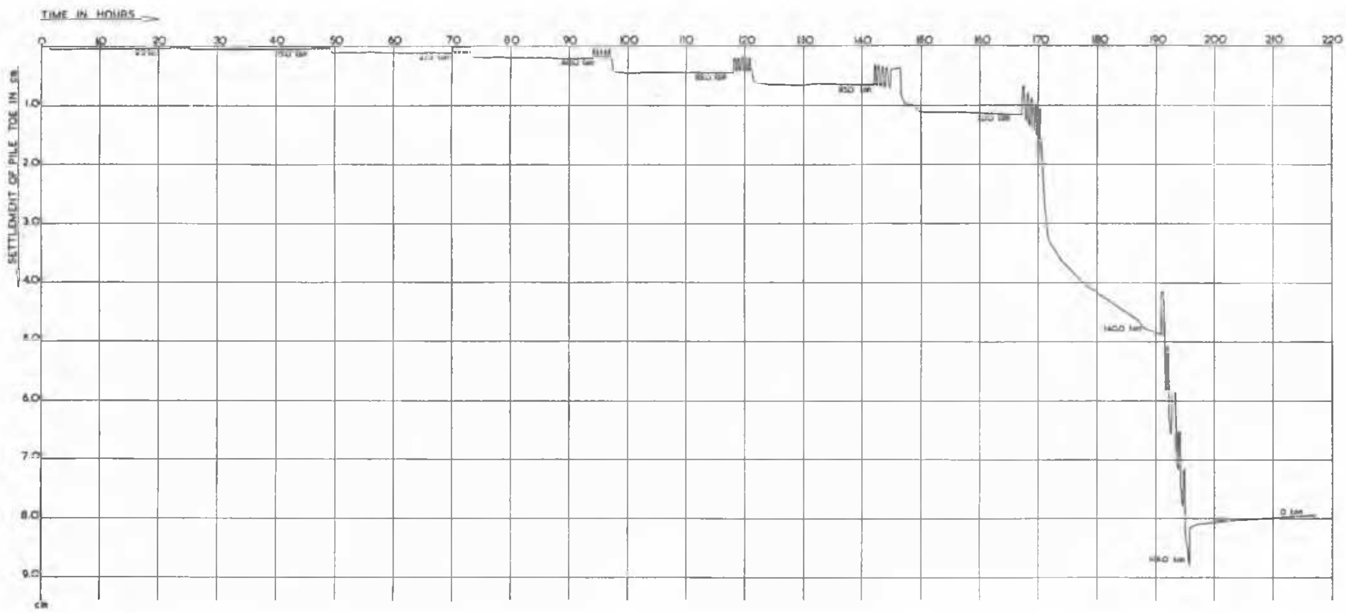

Fig. 5 Time-Settlement Curve of Concrete Pile No. 2, Slotermeer
Diagramme de l'enfoncement en fonction du temps de charge du pieu no 2, Slotermeer

$$z = -\left(\frac{1}{\chi} + \frac{1}{\lambda}\ln t\right)\ln\frac{P_{max} - P_1}{P_{max}} = \beta + \gamma \ln t$$

which is equal to formula (2).

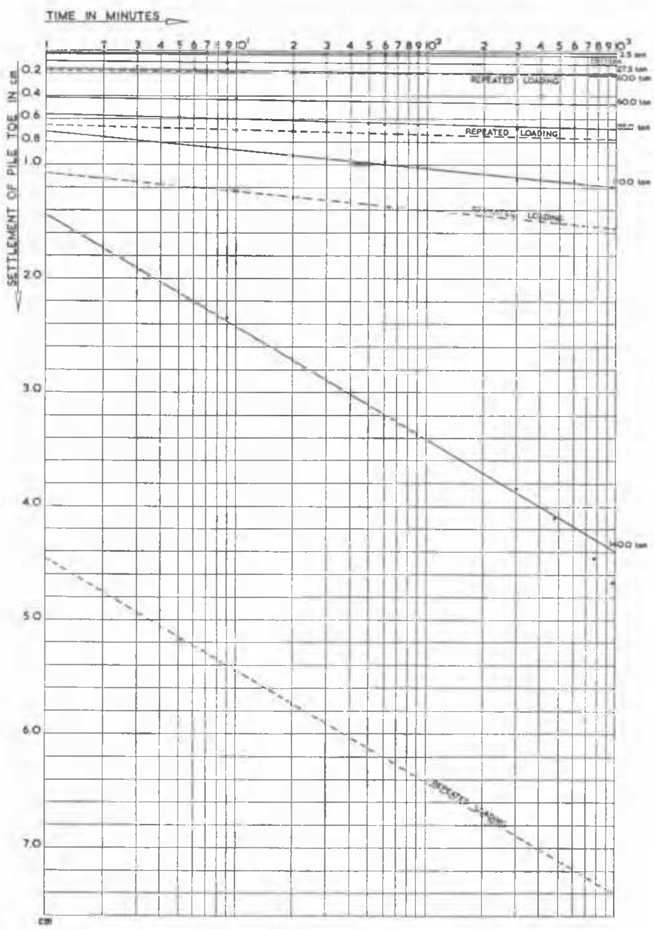

Fig. 6 Time-Settlement Curve of Concrete Pile No. 2, Slotermeer, Plotted on a Semi-Logarithmic Scale
Représentation en coordonnées semi-logarithmiques du diagramme de l'enfoncement en fonction du temps de la charge du pieu no 2, Slotermeer

Now it is possible to draw load-settlement curves for different time intervals, as is done in Fig. 7, and to compute the settlement caused by any load at any moment. If plotted on a semi-logarithmic scale, as was already done in Fig. 4 for a time interval of 10^3 minutes, which means that every load is supposed to be maintained during that time, the result for various time intervals becomes as demonstrated in Fig. 8.

However there still remains an influence which has not yet been mentioned: the influence of repeated loading and unloading.

Repeated Loading and Unloading

In the loading tests performed by the Department of Public Works Amsterdam every load was repeatedly applied after unloading. The behaviour of the pile under that repeated loading is to be seen in Fig. 5, and in Fig. 6 where the first repetition is plotted for some of the larger loads. It appears, as demonstrated in Fig. 9, that the settlement increases with the logarithm out of the number of repetitions of loading and unloading. Repeated loading has apparently the same effect as the time factor. It can be represented by the formula:

$$z = \delta + \varepsilon \ln n \quad .. \qquad (4)$$

in which n represents the number of repetitions and δ and ε are constant coefficients. Every time the load is supposed to be maintained during a constant time $t = t_1$.

A combination of the formulae (3) and (4) leads to the more general formula, in which the settlement z is given as a function of load P, time t and number of repetitions n:

$$z = -\left(\frac{1}{\chi} + \frac{1}{\mu}\ln n + \frac{1}{\lambda}\ln t\right)\ln\frac{P_{max} - P}{P_{max}} \qquad (5)$$

It is easy to see that the formulae (1) to (4) are special cases of formula (5).

It must be emphasised that this formula is valid only if the load increments are taken large enough to avoid any mutual influence. The coefficient μ can only be determined if the time during which each repeated loading is applied is maintained sufficiently long.

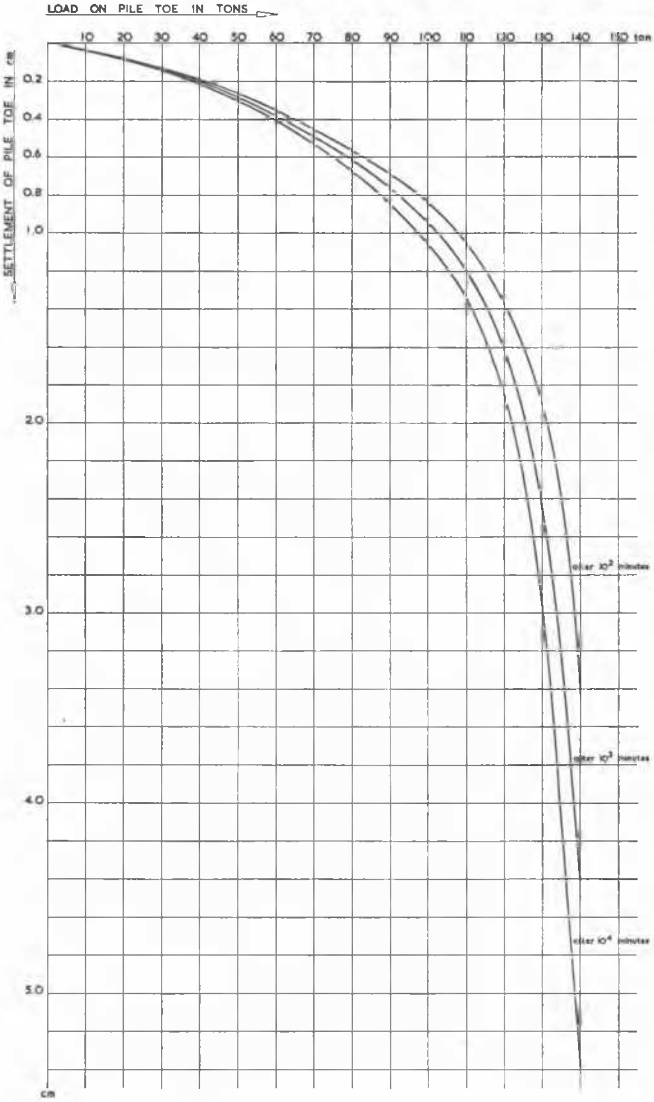

Fig. 7 Load-Settlement Curve of Concrete Pile No. 2, Slotermeer, at Different Time Intervals
Diagramme de l'enfoncement en fonction de la charge du pieu no 2, Slotermeer, pour divers temps de charge

The Theoretical Bearing Capacity of a Pile

It needs not to be underlined that the bearing capacity of a pile is not equal to the load which causes total loss of equilibrium. Only a certain part of the ultimate resistance can be allowed on a pile and considered as the real bearing capacity. The question rises as to which percentage of the ultimate resistance is to be taken as bearing capacity.

Usually this percentage is determined by the way of a certain feeling about which part of the ultimate resistance may safely be allowed on a pile. For instance the coefficient 2 is often used by which the load at failure has to be divided to get the bearing capacity. However, a more theoretical approach seems to be possible, which leads to a better insight into the problem.

What happens if a pile is loaded? It seems that three stages can be distinguished. At first the soil is liable to pure compression; the load-settlement curve is nearly rectilinear and the permanent settlement after the release of the load is very small. The second stage is characterized by the occurrence of local disturbances of equilibrium in the soil, which lead, at last, to total loss of equilibrium in stage three.

It may not be absolutely necessary to keep the bearing capacity within the limit of stage one, but it seems to be a wise policy not to allow too many local disturbances in the soil surrounding the pile toe. However, it is very difficult to deter-

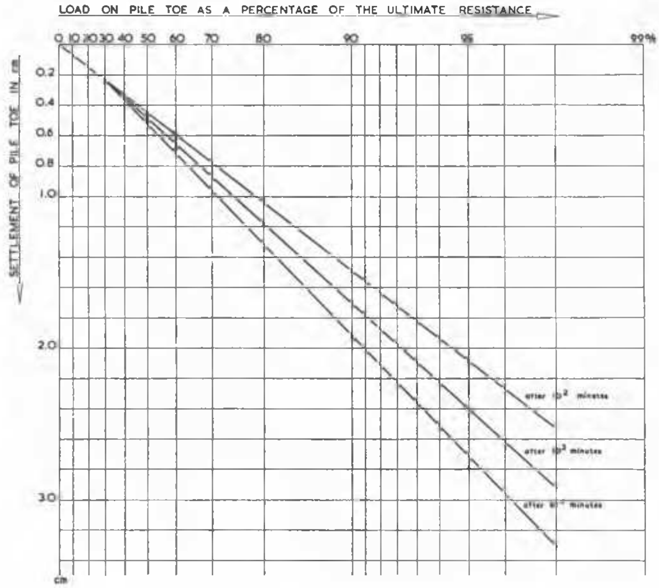

Fig. 8 Load-Settlement Curve of Concrete Pile No. 2, Slotermeer, at Different Time Intervals, Plotted on a Semi-Logarithmic Scale
Représentation en coordonnées semi-logarithmiques du diagramme de l'enfoncement en fonction de la charge du pieu no 2, Slotermeer, pour divers temps de charge

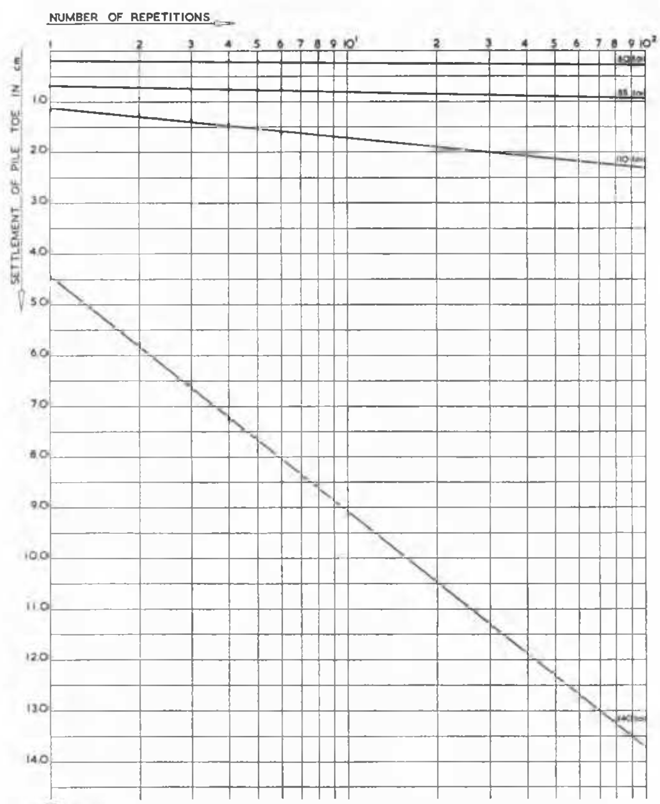

Fig. 9 Semi-Logarithmic Representation of the Influence of Repeated Loading and Unloading of Concrete Pile No. 2, Slotermeer
Représentation en coordonnées semi-logarithmiques de l'influence des charges répétées sur le pieu no 2, Slotermeer

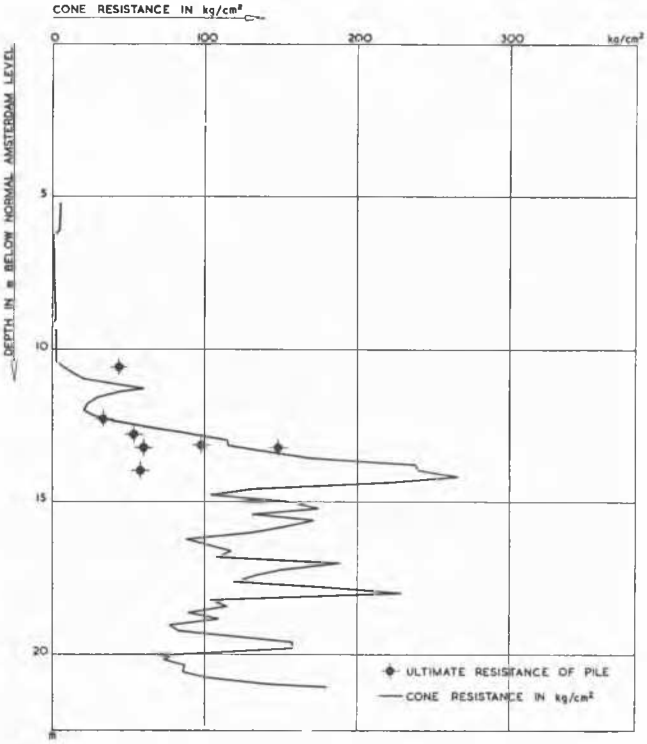

Fig. 10 Deep-sounding at Schiphol Airport, Amsterdam, with the Results of Some Loading-Tests
Diagramme d'un essai de pénétration en profondeur à l'aéroport de Schiphol, Amsterdam, avec résultats de quelques essais de charge

mine when stage two has been entered. The load-settlement curve, as plotted e.g. in Figs. 1 and 2, gives as good as no indication. A careful examination of the semi-logarithmic time-settlement curves gives more indication because, the load having passed a certain limit, discontinuities become now and then visible, which points to a temporarily larger increase of the settlement with time, probably caused by the occurrence of local disturbances. The load which marks the visible beginning of the local disturbances seems to be on an average about 70% of the ultimate resistance of the pile.

This does not mean that 70% of the ultimate resistance is to be allowed on a pile. The bearing capacity of the pile may be sufficient, the question rises as to which settlements can be allowed in the structure which is founded on the piles. These settlements have to remain within such limits that the stresses in the structure caused by those settlements, added to the stresses caused by forces on and in the structure, do not exceed the allowable stresses in the material of which the structure is built.

In a more simple way it can be put as follows: which are the allowable differences in the settlements of the various piles bearing a structure? If the lenght of the piles and the actual loads are about the same, all piles may be assumed to have the same elastic deformation. Then the requirement remains that the differences in the settlements of the pile toes have to remain within a certain limit. If a difference in settlement of about 2 mm is accepted, and it is supposed that the differences in settlement amount to 20% of the average settlement of the pile toes, a total settlement of about 5 mm results as the allowable settlement of the pile toe.

It must be emphasised that for special cases special requirements have to be drawn up; what is given here serves as an example, which however appears to serve as a good yardstick in the case of common buildings and structures.

If a total settlement of 5 mm is accepted, the allowable load can be determined if the relation between load and settlement is known. For various piles and soils the relations will differ; it can be roughly estimated that a settlement of 5 mm will be caused by a load which is about 60% of the ultimate resistance. This is for instance the case in the load-settlement curve of the *Plantema* sounding pile.

As has been demonstrated above the load-settlement curve is influenced by the time during which each load is applied and by repeated loading and unloading. If these two factors are also taken into account the theoretical bearing capacity of a pile can be defined as the load continuously or discontinuously applied, which at a previously fixed moment in the future has given the pile a previously fixed settlement. A numerical interpretation has to be given in view of experimentally determined data, to the effect that is explained in this chapter.

The Factor of Safety

A factor of safety is necessary in view of the uncertainties involved in the methods to predetermine the ultimate resistance of a pile, the ignorance of the loads which will actually occur, and what settlement is allowable at what time in the future.

The last problem has been treated above. As to the second part of the factor of safety it may be assumed that it is included in the loading scheme of the structure. How the first part of the factor of safety is to be determined will be demonstrated below, the Dutch method of deep-sounding is taken as an example.

This method consists of pressing a cone-shaped body, with a basis area of 10 cm², down into the earth by way of a rod, the resistance which offers the soil being measured. The friction between rod and soil is eliminated by a tube fixed round the rod. The result of a deep-sounding is plotted in a graph as represented by Fig. 10. Investigations in the laboratory as

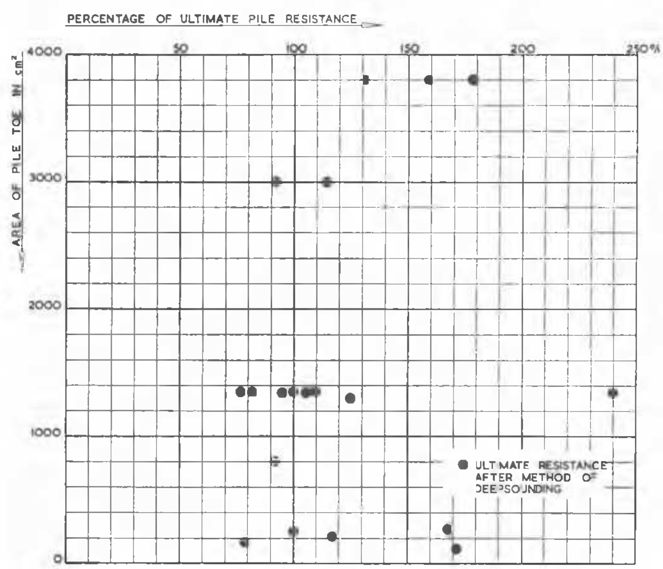

Fig. 11 Comparison of the Results of Loading-Tests and Deep-Soundings
Comparaison des résultats des essais de charge et des essais de pénétration en profondeur

well as theoretical considerations indicate that, in a homogeneous soil, the resistance of a cone-shaped body is directly proportional to the basis area. This gives an easy method, at least in principle, to compute the ultimate resistance of a point-bearing pile, the basis area of the pile toe being known.

In order to get a more definite idea of the reliability of the method of deep-sounding, several loading tests on piles were performed by the Department of Public Works, Amsterdam. The results were compared with the graphs of deep-soundings, which had been taken in the immediate neighbourhood. In Fig. 10 some of the results of loading tests are given by the round dots, which indicate depth and ultimate resistance of the pile toe in the same way as the deep-sounding graph is plotted, so that immediate comparison is possible.

The results of these tests and a number of other tests which were made in the Netherlands are represented in a more conveniently arranged way in Fig. 11. Every dot represents the result of a pile loading test. The area of the pile toe is to be read on the ordinate. The abscissa indicates the ultimate resistance, predicted by the deep-sounding graph, as a percentage of the actual ultimate resistance as determined by loading tests. If the abscissa is 100%, the results of deep-sounding and loading tests are in entire agreement.

It appears that nearly all dots are confined within the limits of 75% and 175%. This means that the ultimate resistance determined with the method of deep-sounding divided by 1.75 is less, or equal, to the real ultimate resistance. In the foregoing chapter it has been demonstrated that no more than 60% of the ultimate resistance is to be allowed in view of the structure settlement to be expected. The total factor of safety which has to be introduced is therefore $1.75 : 0.6 = 3$ if the method of deep-sounding is adopted.

Conclusion

In the above chapters a brief outline is given of a theory which may serve as a guide to a better understanding of the phenomena which figure in the problems concerning the bearing capacity of a pile. It must be emphasized that only the bearing capacity of the individual pile is referred to in this paper; the behaviour of a group of piles or the foundation as a whole has been left out of consideration.

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