

## NEGATIVE SKIN FRICTION AND SETTLEMENT OF PILES

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### **Introduction**

A relative movement between a pile and a soil produces shear stress along the interface of the pile and the soil. Such movement can be induced by a push-load on the pile pressing it down into the soil, or by a pull-load moving it upward. A relative movement can also be induced when the soil settles in relation to the pile, or, in swelling soils, when the soil moves upward in relation to the pile. By definition, if the movement of the pile is downward, i.e., the shear stress induced in the pile is upward, the direction of the shear is positive. If the movement of the pile is upward, the shear stress direction is negative; accordingly, the induced shear stress is called positive or negative.

In older terminology, the induced shear along a pile was called 'skin friction'. In modern terminology, the term 'shaft resistance' is used and a distinction is made between on the one hand, positive and negative shaft resistance by which is meant shear stress induced by load on the pile in the form of push-load and pull-load, respectively, and, on the other hand, negative and positive skin friction, which is shear stress induced by settling or swelling soil, respectively.

Negative skin friction produces (accumulates to) a dragload which can be very large for long piles. Johannessen and Bjerrum (1965), Bjerrum et al., (1969), and Bozozuk (1972) reported measurements of dragloads that exceed the allowable loads that ordinarily would have been applied to the piles. Bjerrum et al. (1969) also demonstrated the efficiency of coating the piles with bitumen to reduce the negative skin friction. Fellenius and Broms (1969) and Fellenius (1969) presented measurement showing that a dragload can develop alone from the reconsolidation following the disturbance caused by the pile driving. Walker and Darvall (1973) presented a comparison between bitumen coated and uncoated steel piles, and Clemente (1981) reported measurement of dragloads on coated and uncoated concrete piles. Fellenius (1975; 1979) discussed some practical aspects of bitumen coating of piles to reduce negative skin friction.

In all the papers referenced above, the emphasis is on the dragload. When the authors report observations of deformation and settlement, the main use of these is to calculate the loads in the pile. When the consequence of the negative skin friction for design are included, these are discussed in terms of reduction of pile bearing capacity of allowable load. In contrast, this paper suggests that the problem of negative skin friction is one of settlement and not of bearing capacity, i.e., the magnitude of the dragload is of no direct relevance to the geotechnical capacity of the pile, nor to the allowable load of the pile. Consequently, as recommended below, in the design for a downdrag condition, the calculation of the distribution of settlement is emphasized.

## **Movement Necessary for Negative Skin Friction to Develop**

The magnitude of the movement necessary for negative skin friction to develop has been reported in a few papers. Walker and Darvall (1973) reported that a 35 mm settlement of the ground surface due to a 3 metre high surcharge placed around single piles was sufficient to develop negative skin friction down to a depth of 18 metre. Settlement distribution with depth was not measured. Bjerin (1977) found that negative skin friction was fully mobilized to a depth of about 25 metre after a relative displacement of about 5 mm as measured at a short distance away from the pile (about 0.12 metre). At a distance of 5 metre, the relative displacement was about 8 mm. Bozozuk (1981) found that a reversal of direction of shear forces down to a depth of 20 metre occurred when loading a pile and generating a relative movement of about 5 mm at the pile head.

While Bjerrum et al. (1969) reported negative skin friction developing along piles at a site where the settlement under a recent fill amounted to 2 metre, they also reported that about the same magnitude of negative skin friction developed on the same type of piles driven under an adjacent, 70 year old fill of the same height in the same type of soil, which did not experience any new settlement after the pile installation.

The reported observations indicate that no "slip" between the pile and the soil takes place and that extremely small movement is all that is needed to generate shear stress or to reverse the direction of shear along the pile-soil interface.

The pile material is immensely more rigid than the soil and, with time, there will always be small settlement in a soil generating a small relative displacement between a pile and the soil that is large enough to develop shear forces along the pile. The inescapable conclusion is that all piles experience dragloads!

A consequence of the small displacement required to reverse the direction of shear forces in a pile is that live loads and dead load do not combine (Fellenius, 1972; Bozozuk, 1981).

## **Magnitude of Negative Skin Friction**

Johannessen and Bjerrum (1965) showed that negative skin friction is proportional to the effective overburden stress in the soil surrounding the pile. This was later confirmed by Bjerrum et al. (1969) and Bozozuk (1972). The constant of proportionality is called beta-coefficient,  $\beta$ , and it is a function of the earth pressure coefficient in the soil  $K_s$ , times the soil friction,  $\tan \phi'$ , times the ratio of the wall friction,  $M = \tan \delta' / \tan \phi'$ . (Bozozuk, 1972). Thus, the negative skin friction,  $q_n$ , follows the following relation.

$$q_n = \beta \sigma'_v = M K_s \tan \phi'$$

Bjerrum et al. (1969) found that the beta-coefficient in soft silty clay ranged between 0.2 and 0.3. Bjerin (1977) reported that in a clay of medium to firm consistency the beta-coefficient ranged between 0.20 and 0.25.

Zeevaert (1959; 1972) presented a method of calculating the negative skin friction based on the reduction of the effective overburden stress caused by the soil "hanging" on the pile. DeBeer (1966) developed design charts based on Zeevaert's method.

Axial pile-soil interaction is not simple. It is necessary to discuss it in some detail, as follows.

The above defined separation of the terms for shear stress along a pile on negative, or positive, skin friction as different from negative, or positive, shaft resistance is justified by the different behavior of a pile under different types of axial loading. In fact, as illustrated in Fig. 1, a pile can be loaded axially in six different ways.

Fig. 1 shows the upper portion of six piles marked **A** through **F**. The pile toes are at the elevation of a plane Z-Z. Pile **A**, or Mode **A**, indicates the behavior mode of a pile subjected to a push load applied at the pile head. The result is a downward deformation of the soil layers, as shown to the left of the pile, and an upward directed shaft resistance. As also indicated, the pile is in compression, which results, theoretically, in a Poisson's ratio effect—the pile diameter increases—and the result is that the earth pressure coefficient  $K_s$ , increases. Furthermore, the positive shaft resistance transfers load from the pile to the soil, and because of this, the effective overburden stress increases in the soil. Both the Poisson's ratio effect and the increase of effective overburden stress will have the result of increasing the shaft resistance.

Mode **B** indicates a pile subjected to a pull load applied at the pile head. The pull load results in an upward deformation of the soil layers and a negative shaft resistance. This mode is characterized by a decrease of lateral pressure and a decrease of effective stress.

Mode **B**, the uplift testing mode, is often thought representative for a dragload mode. However, while the resistance appears in the negative direction and the effective overburden stress is reducing, in contrast to the pile in the dragload mode, Mode **C**, Pile **B** is in tension not compression. Therefore, an attempt to predict the dragload from static uplift testing might underestimate the dragload.

Were one to run an uplift test to study the magnitude of dragload, the arrangement should be as shown in Mode **D**, where the pull load is applied at the pile toe and, therefore, all three aspects are similar to the dragload mode.

Mode **E** indicates a push test with the load applied to the pile toe. The purpose of such a test would be to simulate the behavior mode of Pile **F**, which is affected by swelling soil above Plane Z-Z.

To complete the modes of axial pile-soil interaction, a seventh mode, that of a pile subjected to a torque, could have been shown. However, this mode is of no practical significance.

## **Magnitude of Dragload**

Observations show that for piles bearing on very competent material, the negative skin friction along the pile surface can be the cause of very large dragloads. Bjerrum et al. (1969) measured dragloads of 4,000 KN on 0.5 metre diameter steel test piles installed to bedrock through 55 metre of soil settling under the influence of a recent surcharge. It is obvious that if a pile is long enough and/or if the ratio of its unit circumferential area to its cross sectional area is large enough, the induced stress could exceed the material strength, i.e., the structural capacity of the pile. In the field tests reported by Bjerrum et al. (1969), the piles were driven to rock, and the induced dragload forced the pile to penetrate into the rock. Obviously, the toe force developed in the pile by the pile driving hammer must have been smaller than the dragload.

Immediately after a pile is installed in the soil, the soil reconsolidates from the disturbance caused by the installation of the pile, whether the pile was driven or otherwise. For example, Fellenius and Broms (1969) and Fellenius (1972) reported load measurements in 300 mm diameter concrete piles driven into a 40 metre thick clay deposit and into an underlying sand layer. Immediately after the driving, the load in the pile was small, about equal to the free standing weight of the pile prior to the driving. The reconsolidation of the clay after the driving took about 5 months. During this time, negative skin friction developed and the dragload induced amounted to about 300 KN to 350 KN corresponding to a beta-coefficient of about 0.10 and to about one third of the maximum dragload measured later. The settlement of the ground surface associated with the reconsolidation was interpolated from measurements over a longer period of time and found to be about 1 mm. The distribution with depth of relative displacement between the pile and the clay was too small to be measured with the gages used in the test.

The pile test reported by Fellenius (1972) and Bjerin (1977) started in 1968 and measurements were taken until 1983, i.e., for 15 years. (The complete results are not yet published). The test is particularly interesting because it involves the effect of applying a static load to the pile head and not just observations of the development of the dragload in the pile. Applying a static load to the pile head caused the dragload in the pile to be reduced by the magnitude of the load applied. As the load was kept on, however, becoming a permanent load (dead load) from having been a temporary load (live load), the negative skin friction built up again and the end effect was that the load applied to the pile head was added to the dragload in the pile. At the end of the test, the dragload was fully developed and the maximum load was 1,750 KN consisting of 800 KN dead load and 950 KN dragload.

## **The Distribution of Load in a Pile and the Neutral Plane**

There must always be an equilibrium between the sum of the dead load applied to the pile head and the dragload, and the sum of the positive shaft resistance and the toe resistance. The depth where the shear stress along the pile changes over from negative skin friction into positive shaft resistance is called the neutral plane. This plane is where there is no relative displacement between the pile and the soil.

Provided the shear stress along the pile does not diminish with depth, the neutral plane lies below the mid-point of a pile. If the soil below the neutral plane is strong, the neutral plane lies near the pile toe. The extreme case is for a pile on rock, where the location of the neutral plane is at the bedrock elevation. For a pile with embedment length  $D$  floating in a homogeneous soil with linearly increasing shear resistance, the neutral point lies about the lower third point (assuming the negative skin friction is equal to the positive shaft resistance, that the toe resistance is zero, and that there is no load applied to the pile head). If the soil strength increases with depth, for instance, due to a transition from soft compressible soil to a dense competent soil, and if a toe resistance is present, the neutral plane moves deeper into the soil. If a dead load is applied to the pile head, the neutral plane moves up.

Fig. 2 illustrates the distribution of load in a pile subjected to a service load,  $Q_d$ , and installed in a relatively homogeneous soil deposit, where the shear stress along the pile induced by a relative displacement is a function of the effective overburden stress. It is assumed that any excess pore pressure in the soil has dissipated and the pore pressure is hydrostatically distributed. For reasons of simplicity, the shear stress along the pile is assumed to be independent of the direction of the displacement, i.e., the negative skin friction,  $q_n$ , is equal to the unit positive shaft resistance,  $r_s$ . Assume, also, that a toe resistance,  $R_t$ , is available. The dragload,  $Q_n$ , is the sum of the negative skin friction along the pile, and the total shaft resistance  $R_s$ , is the sum of the unit shaft resistance. These conditions determine the location of the neutral plane as shown in the diagram.

### Settlement of a Pile

The neutral plane is, as mentioned, the location where there is no relative displacement between the pile and the soil. Consequently, whatever the settlement in the soil is as to magnitude and distribution, the settlement of the pile head is equal to the settlement of the neutral plane plus the compression of the pile caused by the applied dead load plus the dragload.

The left hand side diagram in Fig. 3 illustrates how the location of the neutral plane for the pile in Fig. 2 changes with a variation of the load applied to the pile head. Notice also how the magnitude of the dragload changes as the service load,  $Q_d$ , increases.

Assume that the distribution of settlement in the soil around the pile is known and follows the diagram on the right hand side in Fig. 3. As illustrated in the diagram for the case of the middle service load, by drawing a horizontal line from the neutral plane to intersection with the settlement curve, the settlement of the pile at the neutral plane can be determined. The settlement of the pile head is this settlement value plus the compression of the pile under the load. The construction in the figure is made both for a small settlement that reduces quickly with depth and for a large settlement. If the settlement is small, it is possible that the toe movement is not large enough to mobilize the full toe resistance. In such a case, the neutral plane moves to a high location as determined by the particular equilibrium condition.

For a driven pile, the toe movement necessary to mobilize the toe resistance is about 1 % to 2 % of the pile-toe diameter. For bored piles, the movement is larger. However, in cases where the

toe movement is too small for the full toe resistance to be mobilized, the settlement is normally not an issue.

Blanchet et al. (19870) reported measurements on a group of 27 shaft bearing piles supporting a bridge pier. The soil consisted of a firm silty clay and the pile embedment depth was 15 metre. The piles were of wood, had an average diameter of 280 mm, and were installed at a 5 diameter center-to-center spacing. During 260 days of observation, 40 mm settlement occurred in the soil outside the pile group. The pile cap settled 22 mm during the same time. Settlement observations with depth are given in Fig. 4 and show that a neutral plane developed at a depth of about 12 metre. The observations confirm the qualitative behavior outlined in the foregoing.

## **Design of Piles Considering Negative Skin Friction**

### **Fundamentals**

The design principle outlined in the following is essentially the same for all piles, whether single or in a group, whether installed in a soil that settles significantly under the influence of a surcharge, groundwater lowering, or other cause, or installed in a soil that does not experience appreciable settlement, and whether they are essentially toe bearing, shaft bearing, or both toe and shaft bearing.

To understand the design principle, it is important to realize that the live load and the dragload do not combine and that two separate loading cases must be considered dead load plus dragload, but no live load and dead load and live load, but no dragload. Furthermore, a rigid, high capacity pile will experience a large dragload, but small settlement, whereas a less rigid smaller capacity pile will experience a smaller dragload, but larger settlement. Moreover, the dragload is caused by settlement, or, rather, relative displacement, but the dragload does not generate settlement, and no pile will settle more than the ground surface nearest the pile, indeed no more than the soil settlement at the location of the neutral plane.

The design has to consider three aspects separately: The structural strength of the pile, the settlement, and the geotechnical capacity (the bearing capacity).

### **Neutral Plane**

As a first step in the design, the neutral plane must be determined. The neutral plane is located where the negative skin friction changes over to positive shaft resistance (the point of equilibrium). Its location is determined by the requirement that the sum of the applied dead load plus the dragload is in equilibrium with the sum of the positive shaft resistance and the toe resistance of the pile. It can be found at the intersection of two load distribution curves construed as follows. First, as illustrated in Fig. 2, above, a load distribution curve (forcing load curve) is drawn from the pile head and down with the load value starting with the applied dead load and increasing with the load due to negative skin friction taken as acting along the entire length of pile. Second, a load distribution curve (resistance curve) is drawn from the pile toe up

starting with the value of the ultimate toe resistance and increasing with the positive shaft resistance.

The determination of the load distribution in a pile is subject to large uncertainty. To correctly determine the distribution requires reliable information on the soil strength parameters. The theoretical analysis using the above mentioned method of beta-coefficient on the effective overburden stress is preferred over any total stress method. The analysis should be supplemented with information from static cone penetrometer tests. For driven piles, the analysis should be combined with results from analysis of dynamic monitoring data aimed toward the calculation the distribution of resistance along the pile.

### **Structural Strength**

The structural capacity is the structural strength of the pile material at the neutral plane for the combination of dead load plus dragload - live load is not be included. (At or below the pile cap, the structural strength of the embedded pile is determined as a short column subjected to dead load plus live load, but dragload is not included).

At the neutral plane, the pile is confined and it is suggested that the limiting value of maximum combined load be determined by applying a safety factor of 1.5 on the pile material strength (steel yield and/or concrete 28-day strength and long term crushing strength of wood).

It should be realized that if both the negative skin friction and the positive shaft resistance as well as the toe resistance values are determined assuming soil strength values "erring" on the strong side, the calculated maximum load in the pile will be on the conservative side (and the neutral plane located deep down in to the soil).

As illustrated in Fig. 3, above, a reduction of the dead load on the pile will result in a lowering of the location of the neutral plane, but have proportionally smaller effect on the magnitude of the maximum load in the pile.

### **Settlement**

As demonstrated in Fig. 3, above, the settlement of the pile head is determined by first calculating the distribution of settlement and, then, drawing a horizontal line from the neutral plane to intersection with the settlement curve. The settlement of the pile is equal to the settlement of the soil at the elevation of the neutral plane plus the elastic compression of the pile due to the dead load and the dragload in combination.

A condition for the analysis is that the movement at the pile toe must be equal to or exceed the movement required to mobilize the ultimate toe resistance of the pile. In most soils, this required movement is about 1 % to 2 % of the pile toe diameter of driven piles and about 5 % to 10 % of the toe diameter for bored piles. If the movement is smaller than this, the toe resistance will not be fully mobilized and the neutral plane will move to a higher location in the settlement diagram. In a design case where the toe resistance value is difficult to estimate or where it is variable, for

instance, in the case of toe-jettted piles, a conservative estimate of the settlement is obtained by disregarding the toe resistance when construing the neutral plane.

The settlement calculation is carried out according to conventional methods for the effective stress increase caused by the dead load on the pile(s), surcharge, groundwater lowering, and/or any other aspect influencing the stress in the soil. The settlement calculations must include the compression of silt and sand layers in the soil profile, in particular, those located below the neutral plane. This makes it important to carry the investigation of the soil conditions at a site to a sufficiently large depth and to include a representative amount of sampling and laboratory testing of the soils located below the pile toe. As a minimum, an investigation should include static cone penetrometer tests and sampling of all layers encountered with undisturbed samples taken of all cohesive soils.

The settlement calculation of non-cohesive soils should not be based on the use of a constant 'elastic' modulus, but on the tangent modulus approach, which considers that the compression of soil is not linearly increasing with the increase of stress. The Canadian Foundation Engineering Manual (1985) details the use of the Janbu unified theory for both cohesive and non-cohesive soils and gives reference values of moduli to use.

It should be realized that if both the negative skin friction and the positive shaft resistance as well as the toe resistance are determined assuming soil strength values "erring" on the weak side, the calculated location of the neutral plane will be located higher up in the settlement diagram, i.e., the settlement of the pile will be calculated on the conservative side.

As illustrated in Fig. 3, a reduction of the dead load on the pile, will result in a lowering of the neutral plane, and, therefore, a reduction of the settlement of the pile.

### **Geotechnical Capacity**

In opposition to what the author has recommended in the past, the dragload must not be included in the consideration of the geotechnical capacity. Consequently, it is incorrect to reduce the dead load by any portion of the dragload (unless required by insufficient structural strength of the pile at the location of the neutral plane).

Consideration of the geotechnical capacity in the design of a pile, or of a group of piles, amounts to making a check of the safety against plunging failure of the pile. In such a case, the pile moves down along its entire length and the negative skin friction is eliminated. Therefore, the load applied on the pile in the design effort is the combination of the dead and live loads. The dragload must not be included.

When the pile capacity has been determined by static loading test or by the analysis of data from dynamic monitoring, a factor of safety of 2 or larger ensures that the neutral plane is located below the mid-point of the pile. When the capacity is calculated from soil strength values, the factor of safety should not be smaller than 3.



## **Special Considerations**

All piles will be subjected to negative skin friction and experience dragload. However, unless the structural strength of the pile is exceeded, piles where the soil settlement is small will not constitute a problem. Where the settlement is large, the maximum dragload induced in a straight and vertical pile is not going to be significantly different to the dragload where the settlement are small. However, large settlement will cause an inclined pile to bend. For this reason, it is advisable to avoid inclined piles in the foundation, or, at least, to limit the inclination of the piles to values which can follow the settlement without excessive bending being induced in the piles.

Piles which are bent, doglegged or damaged during the installation will have a reduced ability to support the service load in a downdrag condition. Therefore, the design according to the above approach postulates that the pile installation is subjected to stringent quality control directed toward ensuring that the installation is sound and that bending, cracking, and local buckling does not occur.

## **Means for Reducing Negative Skin Friction**

When the design calculations indicate that the pile settlement could be excessive, solutions such as increasing the pile length or decreasing the pile diameter, could improve the situation. When the calculations indicate that the pile structural capacity is insufficient, solutions such as increasing the pile section, or increasing the strength of the pile material could improve the situation. When such methods are not practical or economical, the negative skin friction can be reduced by the application of bituminous coating or other viscous coatings to the pile surfaces before the installation (Fellenius, 1975; 1979, and Clemente, 1981). For cast-in-place piles, floating sleeves have been used successfully.

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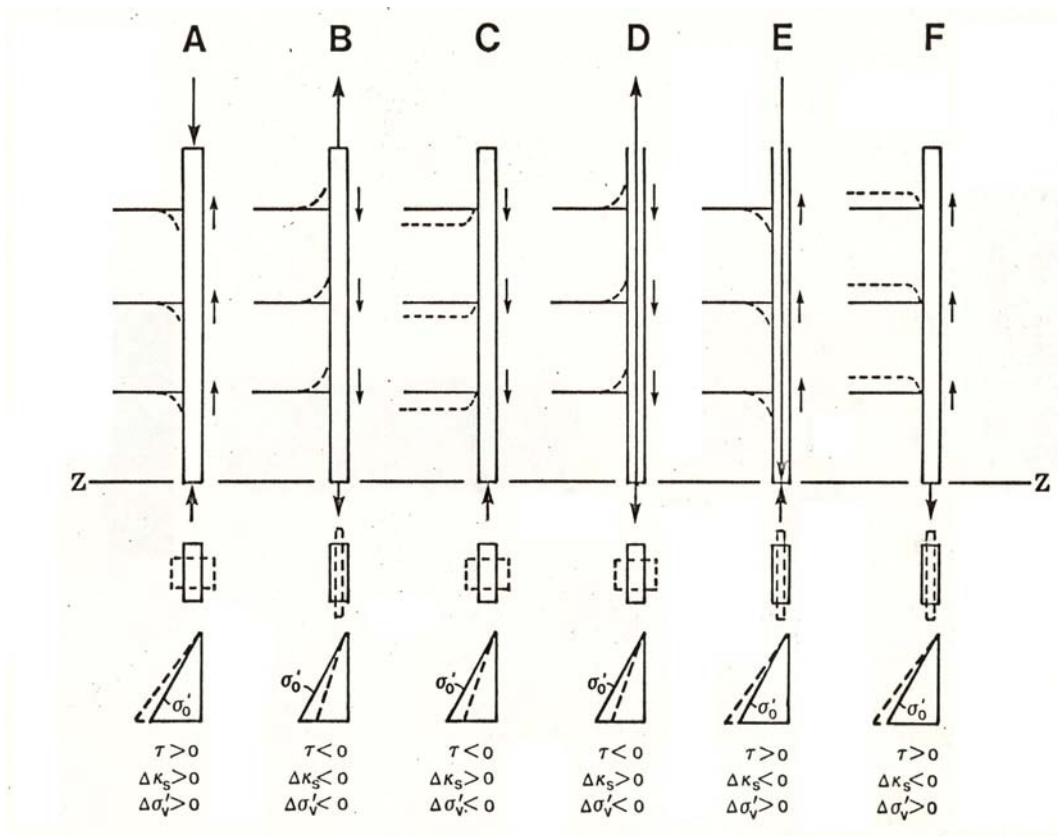


Fig. 1 Behavior modes of a pile subjected to different loading conditions

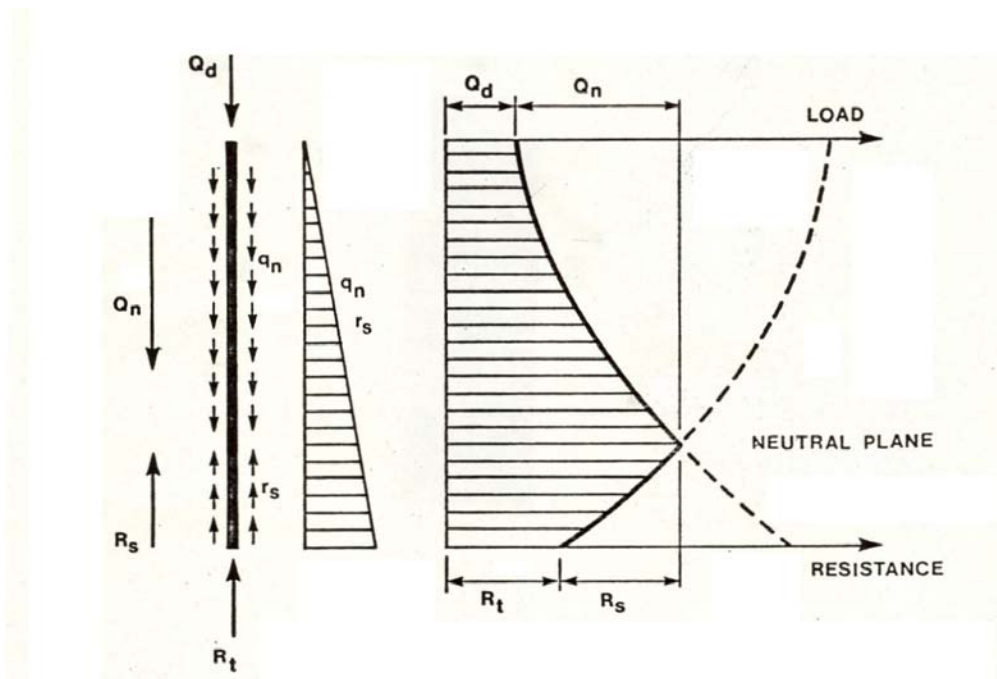


Fig. 2 Definition and construction of the neutral plane

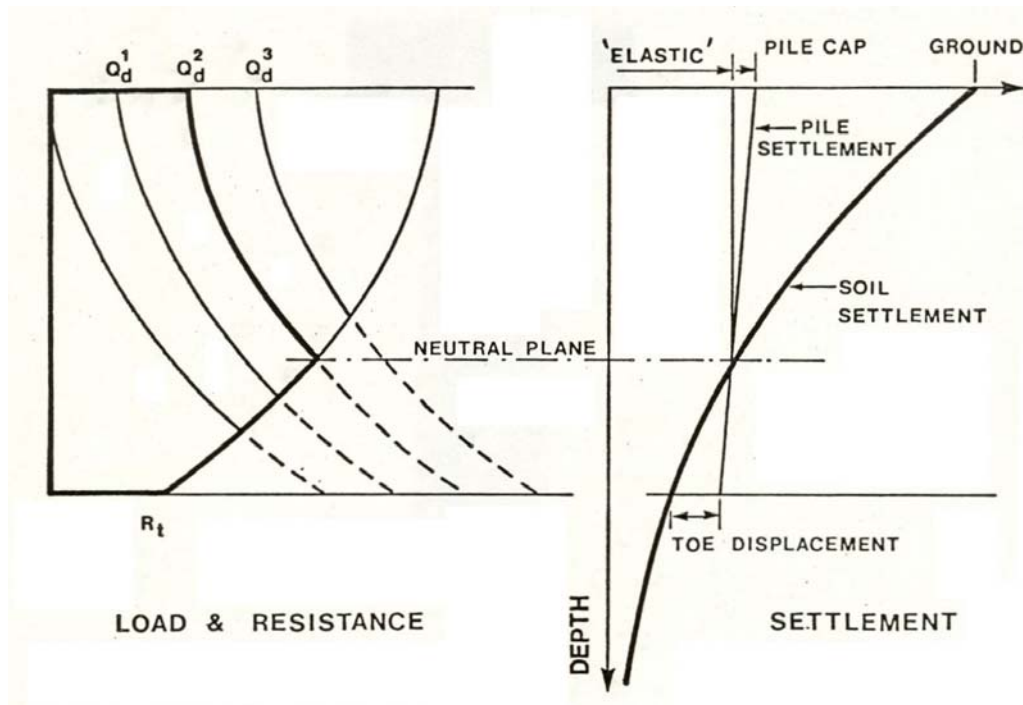


Fig. 3 Determination of the settlement of a pile

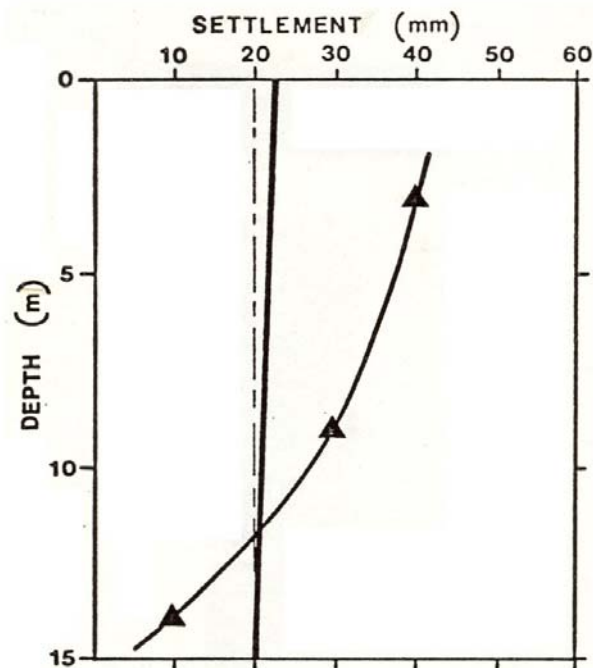


Fig. 4 Distribution with depth of settlement during reconsolidation of the clay for the instrumented pier at Riviere du Loup Bridge, Quebec. (after Blanchet et al, 1980)