Economical Design for NSF Piles in Soft Clays using Soil-Structure Interaction

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ABSTRACT: Code based design of piles with NSF consider the NSF force as a dragload to be imposed on the pile as an unfavourable design action. These codes like Singapore CP4, UK BS 8004 and the recent EC7 would indirectly factor up the value of the dragload while at the same time factor down the positive shaft friction below the neutral plane. Thus the pile design in very deep soft clays typical of Singapore and Asean coastal plains will lead to very conservative pile lengths to meet the code requirements. The Unified pile design method of Fellenius recognized this deficiency and it allows for better pile design with NSF taking into account the need for both force and settlement equilibrium between pile and soil. Fortunately, EC7 also allows for interactive pile/soil analysis using modern FEM tools that can optimise pile design for NSF, particularly when the remaining consolidation settlements around the piles are relatively small. This paper will compare these methods and provide insights into the proper understanding of NSF effects on pile behaviour, and recommend the way forward for rational and economical pile design in settling soils.

KEYWORDS: Geotechnical Design Codes, CP4, BS8004, EC7, NSF piles, and Consolidation of soft clays

1. INTRODUCTION

The current state of practice for design of piles is to place emphasis on pile as a capacity determination problem. This entails the determination of the pile bearing capacity (or resistance) by means of rational theory and verified by a maintained static load test to failure. Once the capacity is determined, the pile allowable design load can be estimated as the available resistance divided by some form of factor of safety to ensure that at working stress conditions, the pile is not loaded to a level anywhere near its capacity, so that the pile settlements remain small within acceptable limits (usually taken as < 25mm).

Prior to EC7, the BS8004 as well as CP4 used a lump global factor of safety approach for pile design. With EC7, the limit state approach with the use of partial factors on both the action, as well as the resistance side of the equations are employed, to factor up the unfavorable actions, and factor down the favorable resistance in one of the three design approaches (DA1, DA2 or DA3). For Singapore we have adopted in DA1, Combinations 1 and 2 in line with the UK practice.

2. DEFICIENCY OF CURRENT CODES ON PILE DESIGN WITH NSF

When design codes treat pile design as a capacity problem, it leads to the definition of NSF as an unfavourable load to be imposed on the pile. For example, BS8004 (as well as CP4) defines NSF as a downwards frictional force applied to the shaft of a pile caused by the consolidation of compressible strata, e.g. under recently placed fill. It adds the note that Downdrag has the effect of adding load to the pile and reducing the factor of safety. Thus it is implied that the NSF can act in such a way as to reduce the factor of safety of a pile to less than unity, thus causing a bearing failure of the pile. Clearly, this is a faulty incorrect concept that is contrary to reality. The reason is that whenever additional loads are place on the head of the pile the downward pile shaft displacements relative to the soil will only cause more of the shaft resistance to convert from NSF to positive shaft friction.

2.1 Typical Example of using CP4

The code used in Singapore prior to 1 April 2015 is CP4, which is a near copy of BS8004 with some modifications. The key equation in CP4 governing NSF pile design is in Cl.7.3.6 as below.

The allowable geotechnical capacity of a pile subject to negative skin friction in the long term (Q_{al}) is given by the following general equation:

$$Q_{al} = \frac{Q_b + Q_{sp}}{F_s} \geq P_c + \eta\, Q_{sn} \tag{1}$$

Where,
Q_b is the ultimate end bearing resistance
Q_{sp} is the ultimate positive shaft resistance below the neutral plane
F_s is the geotechnical factor of safety (usually taken as 2.5)
P_c is the dead load (DL) plus sustained live load to be carried by each pile
Q_{sn} is the negative skin friction load
η is the degree of mobilization typically 0.67, although 1.0 may be used in specific cases

Clearly the inequality in Eqn. 1 presents a challenging situation when we have a case of very thick soft clays of more than 20m thickness above the stiffer founding soils below the soft clays. Worst still is the common Singapore situation where we have very thick reclamation sand fill of more than 20 m thickness on top of a still consolidating layer of soft marine clays. In such situations, it is not uncommon to have very long piles socketed several more metres below the soft clays in order to satisfy Eqn. (1), even for the case of carrying a small permanent load of < 300 kN for each pile. This is especially so, because in the inequality, we reduced the positive shaft friction needed to resist the Dead load (DL) plus the NSF load by a factor of 2.5 (ie. multiply by 0.4), while we at most reducing the NSF load by 0.67, if we allow for the smallest mobilization factor in the equation. This implies that for soils of equal skin friction, we need 67% more pile lengths in positive shaft friction to balance the same length of pile in NSF.

3. UNIFIED PILE DESIGN

To the credit of Bengt Fellenius (1988), he was one of the early pioneers who recognised the fallacy of treating NSF as an unfavourable action on a pile in settling soils. The Unified Pile Design concept was proposed by him back in 1988 in TRB Record 1169, and was further refined over the years with the support of many high quality field research data based on instrumented piles from around the world. Much of these publications are summarised and discussed in the online E-book by Fellenius (2015) titled the Red Book – Basics of Foundation Design readily available at www.fellenius.net.

The most important contribution of Fellenius in this subject is his recognition that NSF issue is not a pile capacity problem, but it is really an issue of pile movements and settlements with respect to a settling soil.

Loads placed on a pile causes downward movements of the pile head due to:

1. 'Elastic' compression (shortening) of the pile.
2. Load transfer movement - the movement response of the soil at the pile toe.
3. Settlement below the pile toe due to the increase of stress in the soil. This is only of importance for large pile groups, and where there are soil layers below the piles that are relatively compressible.

A dragload will only directly cause movement due to Point 1 (the elastic compression), While it may be argued that Point 2 also is at play, because the stiffness of the soil at the pile toe is an important factor here, it is mostly the downdrag (pile settlement due to the dragload) that governs (a) the pile toe movement, (b) the pile toe load, and (c) the location of the neutral plane in an interactive "unified" process, to achieve both force and settlement equilibrium in the pile/soil system. The drag load cannot cause settlement due to Point 3, because there has been no stress change in the soil below the pile toe due to drag load itself.

Therefore, NSF (negative-skin-friction) or dragload cannot and does not diminish geotechnical capacity in piles. Drag load (plus dead load, DL) is a matter for the pile structural strength design. The main issue or question is “will excessive settlements occur around the piles that can cause downdrag.” The approach is expressed in “The Unified Pile Design Method”, which is a method based on the interaction between forces and pile movements.

The Unified Pile Design method is a three step approach involving the following ideas.

1. The dead load (DL) plus live load must be smaller than the pile capacity divided by an appropriate code factor of safety. The drag load is not included when designing against the bearing capacity.
2. The dead load (DL) plus the drag load must be smaller than the structural strength divided with appropriate structure factor of safety. The live load is not included because live load and drag load cannot coexist.
3. The settlement of the pile (pile group) must be smaller than the acceptable limiting value. The live load and drag load are not included in this analysis. The load from the structure does not normally cause much settlement, but the settlements due to other causes that cause large stress changes below pile toe can be large.

The principles of the mechanism that demonstrate the above concepts are illustrated in Figure 1 below. The distribution of load at the pile cap is governed by the load-transfer behavior of the piles. The “design pile” can be said to be the average pile. However, the loads can differ considerably between the piles depending on toe resistance, length of piles, etc.

The location of the neutral plane is the point along the pile shaft where the pile movement and the soil settlement is the same value (no relative movement between pile and soil). Above the neutral plane, the soil settles with respect to the pile so we get NSF. Below the neutral plane, the pile moves downwards relative to the soil thus developing PSF (positive shaft friction). The neutral plane is the result of Nature’s interactions to find the force and settlement equilibrium.

At equilibrium, the neutral plane (NP) will be in such a position that the dead load, DL plus NSF will balance the PSF below the NP plus the mobilized toe resistance Rt. The mobilized toe resistance is a function of the net pile toe movement (or penetration) into the base soil such that it develops sufficient toe resistance to provide the required force equilibrium. If the end result - by design or by mistake - is that the neutral plane lies in or above a compressible soil layer, the pile group will settle even if the total factor of safety appears to be acceptable by design.

Therefore, it is not difficult to realize that any fictitious force equilibrium equations that introduce unequal partial factors on negative and positive shaft resistance on either side of the action/resistance equations will contradict nature and end up with a conservative design that is not economically sensible.

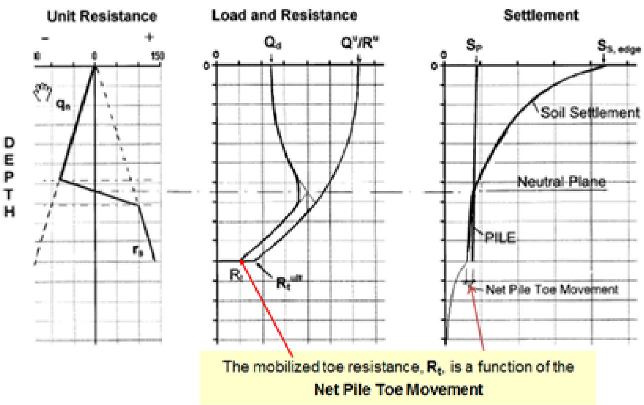

Figure 1 Diagrams to illustrate the Unified Pile/Soil Interaction

4. EC7 ALLOWS FOR PILE/SOIL INTERACTION IN NSF DESIGN

The introduction of EC7 for pile design using limit state analysis with partial factors of safety for actions, materials (soils strengths), and resistances appears to also suffer the pitfallS of the unbalance force equilibrium equations when applied to pile design with large NSF.

Realising that NSF pile design is a settlement rather than a capacity issue should lead designers to tackle the problem from a pile movement/settlement viewpoint. Surprisingly, the relevant clauses for pile design in the UK version of EC7- Part 1, as adopted in Singapore appears to be more liberal than either BS8004 or CP4 of the past. The relevant Clause is 7.3.2.2 as below.

4.1 Cl.7.3.2.2 Downdrag (negative skin friction)

(1) P If ultimate limit state design calculations are carried out with ***the downdrag load as an action (called the dragload)***, its value shall be maximum, which could be generated by the downward movement of the ground relative to the pile.

(2) Calculation of maximum downdrag loads should take account of the shear resistance at the interface between the soil and the pile shaft and downward movement of the ground due to self-weight compression and any surface load around the pile.

(3) *An upper bound to the downdrag load* on a group of piles may be calculated from the weight of the surcharge causing the movement and taking into account any changes in ground-water pressure due to ground-water lowering, consolidation or pile driving.

(4) ***Where settlement of the ground after pile installation is expected to be small, an economic design may be obtained by treating the settlement of the ground as the action and carrying out an interaction analysis.***

(5) P The design value of settlement of the ground shall be derived taking account of material weight densities and compressibility in accordance with Cl.2.4.3.

(6) Interaction calculations should *take account of the displacement of the pile relative to the surrounding moving ground,* the shear resistance of the soil along the shaft of the pile, the weight of the soil and the expected surface loads around each pile, which are the cause of the downdrag.

(7) Normally, downdrag and transient loading need not be considred simultaneously in load combinations.

Clearly, Clause sections (4) and (6) showed that the Code writers are fully aware that when ongoing ground settlements are small, NSF developed will be quite small, and so it allows for pile/soil interaction analysis that will enable the pile design to treat the settlement of the ground as the action (instead of dragload as the action) and determining a more appropriate value of NSF load to be used in the pile structural design.

This served as an indirect recognition that pile geotechnical capacity is not the primary focus; instead, pile settlement is the focus of the design. Also, sub-clause section (7) correctly recognized that NSF and transient live load cannot co-exist and should not be considered simultaneously in any load combinations in the design analysis.

5. VALIDATION OF UNIFIED DESIGN BY FEM STUDY

The Unified Pile Design concept is now validated by FEM model studies of piles subject to settling soils, allowing for proper accounting of soil/structure interactions. The first set of study concern a single pile using an axisymmetric PLAXIS 2D FEM model. The second set of studies concern a pile group using PLAXIS 3D FEM software.

5.1 PLAXIS FEM Model of Single Pile with NSF loadings

The FEM analysis provides a very effective tool to study the pile/soil interaction behaviour with piles subjected to NSF conditions of settling soils after the pile had been installed.

The hypothetical model of such a pile in a typical soft clay site is shown in Figure 2. The pile is a solid cylindrical concrete elements with a soft dummy beam element (with EA one million times less than actual pile EA) embedded in it to allow for easy determination of the force distributions in the pile. The interaction between the pile and soil is modelled by a line interface element that adopts the linear elastic perfectly-plastic Mohr Coulomb model. The pile is installed by a wish in place replacement of soil by concrete material within the pile radius after the initial phase. The ground settlement is induced by applying a ground surcharge loads of 10, 20 and 40 kPa for three cases studied under drained conditions. For each case, loads of 2, 4 and 6 MN are applied on the pile head to simulate external loads on the pile, as in a simulated Static Load Test of piles.

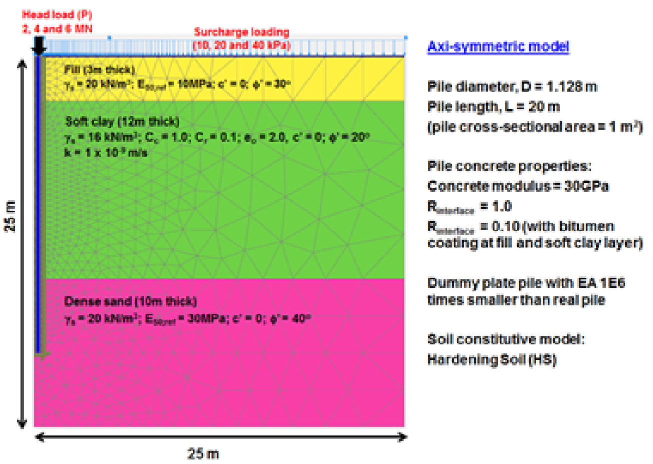

Figure 2 Plaxis 2D Axisymmetric FEM model of Single Pile in Settling Ground

The pile responses for the various cases studied are discussed as follows. The typical case of pile dead load (DL) of 4MN with and without ground settlement is shown in Figure 3.

The figure illustrates the effects of NSF, where force equilibrium is achieved by a natural self-balancing process, where the neutral plane (NP) is the point somewhere along the pile such that the pile and soil moved together, with NSF above the NP point and PSF below the NP point. The force equilibrium is obtained as the DL plus the NSF will equilibrate with the PSF and mobilized toe resistance. The toe resistance needed to achieve this balance will determine the amount of toe penetration of the pile. Clearly there is an interdependence of the pile settlement, load transfer, and load-movement response to achieve both the force and settlement equilibrium of the pile/soil system, simultaneously.

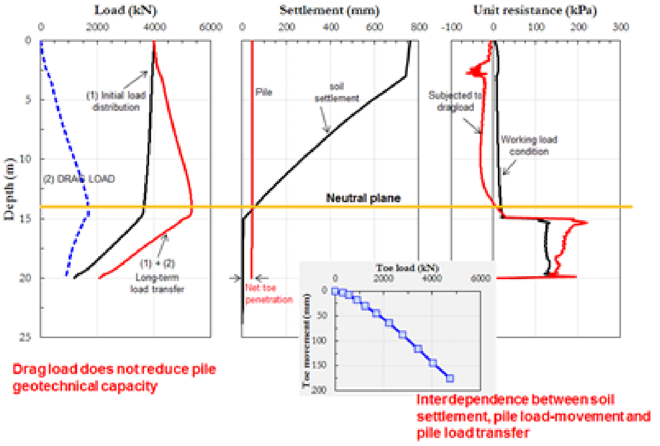

Figure 3 Typical Case of 4MN DL with ground load of 40 kPa (settles 800 mm)

Figure 4 showed the results of the same pile subjected to different amounts of long-term ground settlements (approximately 200, 400 and 800 mm) induced by varied surface loads under drained conditions. The plots showed that for the same DL, larger ground settlements resulted in a deeper NP, with larger NSF dragload and increasing mobilized toe resistance. Also the transition zone from full NSF to PSF is sharper and smaller as the ground settlements become larger.

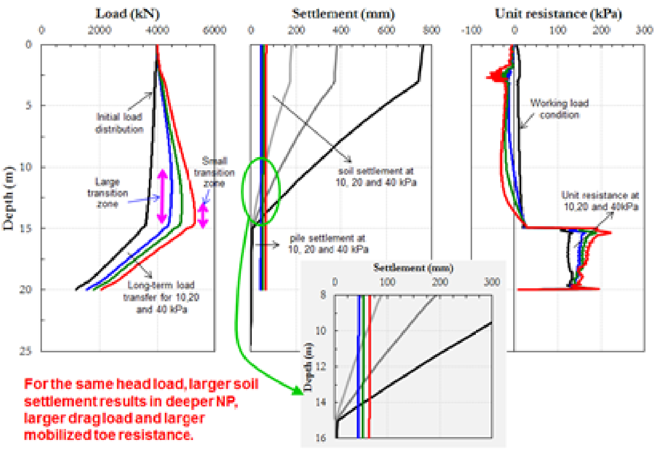

Figure 4 Cases of 4MN DL with ground loads of 10, 20, 40 kPa (settles 200, 400 and 800mm, respectively)

Figure 5 showed three cases of varied DL with the same grounds settlements of about 800 mm. It appears that for the same ground settlements, the larger DL will result in shallower NP with smaller NSF dragload, larger mobilized toe resistance, and hence larger toe penetration resulting in larger pile settlements.

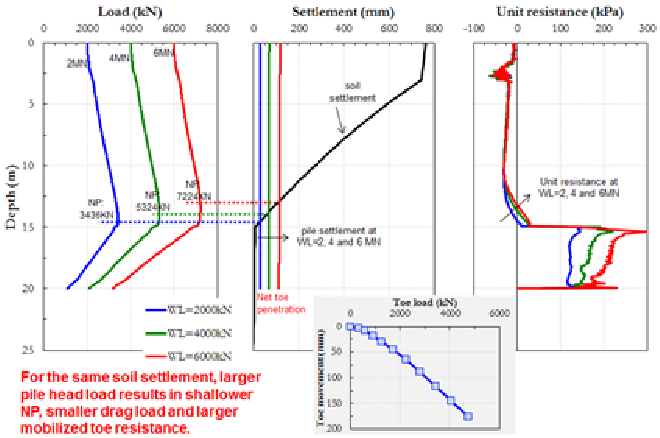

Figure 5 Cases of 2, 4, 6 MN DL with ground loads 40 kPa (settles 800mm)

One very significant finding of these studies is shown in Figure 6. The results suggests that the toe penetration load movement response is unique and that it can be obtained from either applying various DL on the pile head like in a short-term pile load test, or alternatively, it is also the same response in an "impossible" to perform long-term loading test by inducing different amount of ground settlements around the pile.

But this very important data can actually be easily obtained from short-term instrumented load pile tests using GloStrExt (Global Strain Extensometer) system of measuring both the toe loads as well as the toe movements in the load test under various amounts of head loads.

Variable working load cases

Head Load [kN]	Toe Load [kN]	Toe Penetration [mm]
2000	1180	27.99
4000	2241	65.27
6000	3431	111.58

Variable surcharge load cases

Surcharge [kPa]	Toe Load [kN]	Toe Penetration [mm]
10 kPa	1704	44.38
20 kPa	1951	53.42
40 kPa	2241	65.27

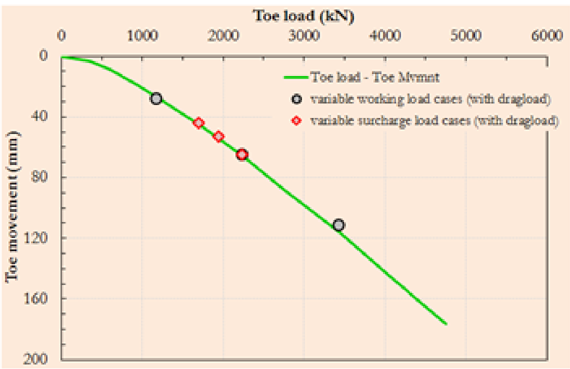

Figure 6 Toe Penetration Resistances obtained from Variable Head Loads cases as well as Variable Ground Settlements cases

For the case of slow consolidation settlements of soft clays with time, the typical development of NSF over time is shown in Figure 7. It is observed that as the NP moves downwards, NSF dragloads and mobilized toe resistances increases, and pile settlements also increases over time as soft clay consolidation and ground surface settlements progresses over time.

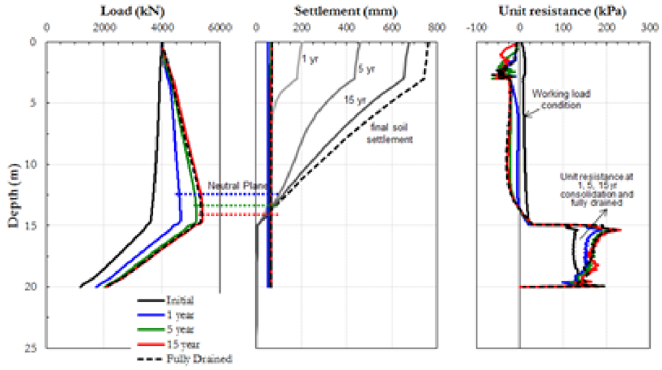

Figure 7 Pile subjected to increasing NSF over time as soil consolidates

Simulated load tests of the same pile subjected to varied amounts of NSF dragloads by different amounts of ground settlements are shown in Figure 8. The results showed clearly that NSF dragloads do not affect the geotechnical capacity of the piles.

All the load tests converged to a limiting value of about 6.8 MN after about 50 mm pile settlements. Larger ground settlements resulted in larger dragloads and produced a softer pile response after load levels of 3.5MN. However, the geotechnical capacity of the pile remained the same when pile is pushed down to about 50mm head vertical displacement.

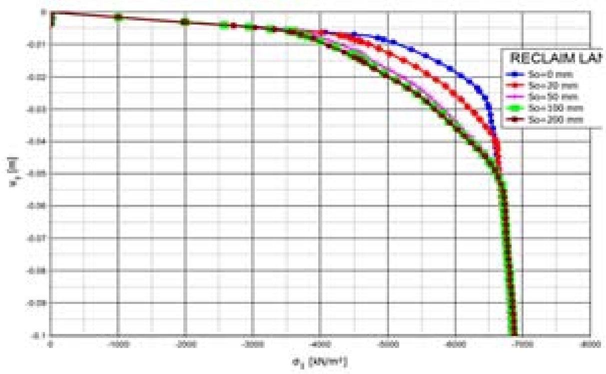

Figure 8 Load Tests on Same Pile with Varied NSF dragloads from increasing amount of ground settlements

If the piles were coated with bitumen to nullify the dragloads above the soft clay base, the piles would respond in slow load tests as in Figure 9.

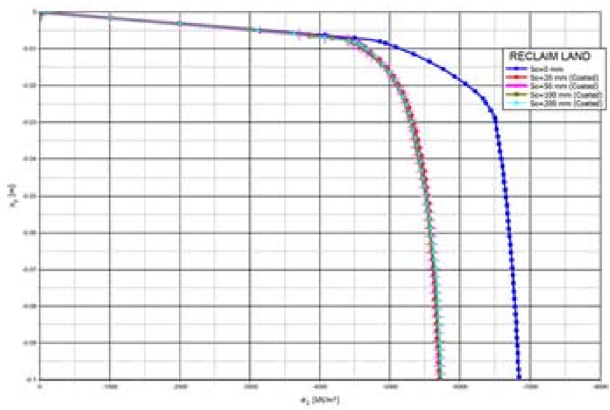

Figure 9 Load Tests on Bitumen Coated Pile with Varied amount of ground settlements (NSF dragload is eliminated)

This is modelled by setting the interface friction factor to 0.1 (10% of soil shear strengths) along the fill and the soft clay layers in the FEM model. The effects of the bitumen coating is to eliminate the NSF dragloads, but it also reduced the geotechnical capacity of the pile from 6.8 MN to 5.6 MN.

5.2 PLAXIS FEM Model of Pile Groups with NSF loadings

It has been reported that NSF dragloads in pile groups is somewhat reduced due to the shielding effects of the outer piles on the inner piles. A field experiment is reported by Okabe (1973) showing the measured response of these piles as in Figure 10.

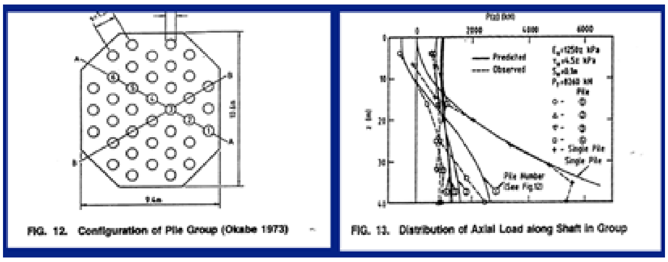

Figure 10 Field experiments of pile group subjected to NSF (Okabe, 1973)

Similar findings had been observed in centrifuge tests reported by SY Lam et. al. (2013), with measured shielded responses on piles at different locations of a pile group is shown to occur for the inner piles, with reduced dragloads in a consolidating ground.

Such shielding of inner piles results can also be replicated in a 3D-FEM model study of pile groups similar to the single pile study as shown in Figure 11. It is obvious that the pile group with a rigid pile cap must settle as an entity. Thus the NP for the pile group must be nearly at the same level somewhere above the pile toes.

The FEM pile group behaviour agrees well with the observed results in the field experiment as well as the centrifuge tests. In general the centre piles experienced the largest shielding effects that are lesser for the piles located towards the edge of the group. The corner piles will experience the largest NSF dragloads. These effects can be exploited for an economical design of large pile groups and pile rafts in settling grounds, when the amount of shielding can be well determined approximately in a 3D-FEM model, using coupled flow deformation analysis.

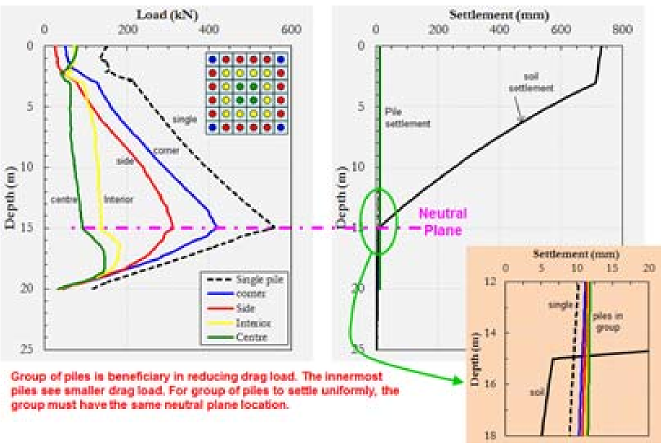

Figure 11 PLAXIS 3D-FEM Results of a Large Pile Group in Settling Ground

6. CONCLUSIONS

A review of the design of piles with NSF when subjected to settling ground conditions from the consolidation of soft clays had been presented.

The following conclusions are inferred.

1. CODES like BS8004 and CP4 incorrectly treated NSF dragloads as an external unfavourable actions acting on the pile that reduces the pile geotechnical capacity.
2. The new code like EC7 also treats NSF dragloads as an external unfavourable action. However, it also recognized that when the remaining ground settlement is relatively small as in a matured or treated reclaimed land, this approach will be too conservative for pile design. Therefore, it allows the designer to treat the ground settlement as the geotechnical action, and design for much smaller dragloads to be determined by a soil/pile interaction analysis. Such analysis is described in the Fellenius Unified Design method.
3. The alternative is to use full FEM models to include the effects of settling soil on the pile response to obtain a more realistic estimate of the NSF dragloads and the settlements of the pile and the ground.
4. In the case of large pile groups in settling ground, the added benefits of the shielding of the inner piles may be estimated properly by a 3D-FEM model analysis of the group. Thus, the reduced dragloads on the inner piles can be computed and used for a more economical design of the pile groups.
5. It should be well noted that NSF problem is not one of geotechnical capacity, as this cannot be reduced by soil settlements. Rather it is one of a serviceability limit state, where after establishing the neutral plane, the pertinent question is will the pile foundation settlements remain small within acceptable limits.

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