Three-dimensional finite element analysis of a single pile subjected to negative skin friction

Analyse par éléments finis en trois dimensions d'une pile unique soumise à un frottement cutané négatif

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ABSTRACT: Pile foundations encounter the negative skin friction (NSF) when the soil surrounding the pile settles more than the pile itself, causing an increase in compressive dragload on the pile, which reduces the final shaft resistance of the pile. Three-dimensional finite element (FE) analysis was performed using PLAXIS 3D to investigate the behavior of a single pile subjected to downdrag. Based on the load applied on the pile and its surrounding region, the settlement of the pile and the surrounding soil layer is estimated. Depending on the relative settlement, the negative skin friction generated at the periphery of the pile is computed and the location of the neutral plane is identified. The FE models were validated against the benchmark cases from the literature. The influence of soil type, surcharge conditions and the pile tip location were investigated for the variation of skin friction and axial load of the pile. The migration of the neutral plane for all the different cases was captured. Depending on the distance of the pile tip from the bearing layer, the neutral plane of a single floating pile migrates between $0.4L$-$0.7L$, where L is the embedded length of the pile. Further, a comparative of negative skin friction profile, arising from two conditions leading to soil settlement, is also presented.

RÉSUMÉ: La fondation sur pieux subit un frottement cutané négatif lorsque le sol environnant se dépose plus que le pieu, ce qui induit une charge de traînée de compression accrue sur le pieu, ce qui réduit la capacité de résistance ultime du pieu. Une analyse par éléments finis (FE) tridimensionnelle a été réalisée à l'aide de PLAXIS 3D pour étudier le comportement d'un seul pieu soumis à un downdrag. Sur la base de la charge appliquée sur le pieu et sa région environnante, le tassement du pieu et de la couche de sol environnante est estimé. En fonction du tassement relatif, le frottement cutané négatif généré à la périphérie du pieu est calculé et l'emplacement du plan neutre est identifié. Les modèles FE ont été validés par rapport aux cas de référence des études expérimentales et numériques de la littérature. L'influence du type de sol, des conditions de surcharge et de l'emplacement de l'extrémité du pieu a été étudiée pour la distribution du frottement cutané et de la charge axiale du pieu. La migration du plan neutre pour tous les différents cas a été capturée. On constate qu'avec une augmentation de l'angle de frottement, la traînée augmente dans le cas des sols à gros grains, alors qu'elle diminue dans le cas des sols à grains fins. En fonction de la distance entre la pointe du pieu et la couche porteuse, le plan neutre d'un pieu flottant unique migre entre 0,4 et 0,7 L, où L est la longueur enfoncée du pieu. En outre, un comparatif du profil de frottement cutané négatif, résultant de diverses conditions menant au tassement du sol, est également présenté.

KEYWORDS: Negative skin friction, Dragload, Embedded Pile, 3D finite element analysis, Neutral plane

1 INTRODUCTION

Pile foundation has a vast application in the domain of the construction industry because it helps in transferring the heavy load from the superstructure to a larger depth in the soil. When surrounding soil around the pile is subjected to a greater settlement as compared to the settlement of the corresponding pile, the pile experience an effect known as negative skin friction (NSF). This effect causes an additional downward force on the pile known as dragload and the constituting settlement of pile is known as downdrag (Lam et al. 2013). The engineers while evaluating the ultimate capacity of pile often neglect this behaviour of piles that can lead to construction and maintenance failure for supporting structures (Fellenius, 1999). Several studies have been investigated in different directions to evaluate the complex behavior of negative skin friction in piles (Koerner & Mukhopadhyay 1972, Poorooshasb et al. 1996, Leung et al. 2004, Lam et al. 2013, Wu et al. 2014, Huang et al. 2015, Lv et al. 2017). These studies were aimed to analyze the behavior of negative skin friction in different conditions such as investigation of its variable nature at the soil-pile interface, effects of different types of loading on surrounding soil and pile head. Various strategies were also developed in the past to shield the pile from negative skin friction. Responses of dragload and down drag were also analyzed for different pile tip locations under axial loads. However, three-dimensional finite element studies focusing on negative skin friction are still limited in the literature. Hence, in this study, an attempt is made to understand the effect of negative skin friction with the change in soil conditions. Dragload on pile shaft is also studied for the initial days of construction under the simultaneous effect of surcharge loading and consolidation.

The dragload and downdrag on piles were investigated for three different types of soils using three-dimensional finite element analysis PLAXIS 3D. The negative skin friction conditions were developed by providing a surcharge load on the surrounding soil.

2 FINITE ELEMENT MODELLING

Finite Element Method (FEM) is an approach used to approximate solution of a complex problem that consists of a piecewise-continuous simple solution (Nazir et al. 2013).

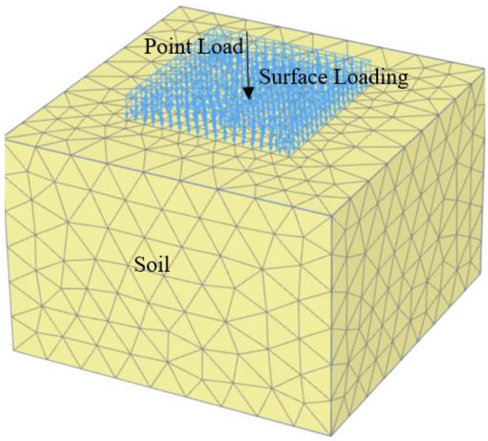

Figure 1 Embedded pile with surcharge on surrounding soil and axial load on pile head

Influence of dragload and downdrag due to negative skin friction on a single pile is studied using the FEM platform PLAXIS 3D. The concrete pile was considered as linear elastic material with a radius of 1 m and having an embedded depth of 6 m. The concrete pile is an embedded beam model. A detailed exercise was conducted to fix the model dimensions by eliminating the boundary effects. A soil model of dimension of 15m x 15m is considered. The soil profile used is a single homogenous, isotropic layer. The constitutive model used for defining soil behaviour is the Standard Hardening Soil Model due to its ability to consider the effect of stress path on soil stiffness and soil behaviour. Pile-soil interface value is chosen as 1.0 as it helps in evaluating the stress behaviour at rough surface-soil interaction. Ground water table is available at 2 m depth from ground surface. Near the soil pile interface, a fine mesh is considered and it becomes coarser as it proceeds away from the pile. Dragload and downdrag on the pile are investigated in three different types of soil – soft clay, medium dense sand, and dense sand. The model parameters considered for pile and soil are shown in Tables 1 and 2 respectively.

Table 1 Pile Properties considered in the analysis

Constitutive Model	**Elastic Modulus (E) (kN/m^2)**	**Unit Weight (γ_t) (kN/m^3)**	**Poisson's Ration(ν)**
Linear Elastic	3000000	27	0.3

Table 2 Soil Properties considered in the analysis

Material	**Soft Clay**	**Medium Dense Sand**	**Dense Sand**
Unit weight γ (kN/m^3)	17	20	20
Void Ratio (e_o)	0.5	0.5	0.5
Friction Angle (ϕ)	25	31	33
Dilatancy Angle (ψ)	0	3	3
Cohesion (kPa)	5	0	0
K_o^{nc}	0.5774	0.46	0.46
K_o	0.7411	0.46	0.46

K_o Lateral earth pressure coefficient
K_o^{nc} – Lateral earth pressure coefficient for normal consolidation

3 VALIDATION FOR THE NUMERICAL MODELLING

The behaviour of negative skin friction on the periphery of the pile is verified by comparing the results of the present study with the results of Lee et al. (2002). The dimension for the soil model used is 30 m x 30m and 25 m in depth as shown in Figure. 2. The model consists of 2-layered soil with a concrete pile placed at the centre. 15 nodded triangular element mesh is considered for the pile and soil. Comparatively fine mesh is considered near soil pile interface and it becomes coarser as it moves away from the pile. The upper strata of soil are soft clay, which is of 20 m deep, and the lower strata of soil is sand, and is of 5 m deep. The concrete pile rests on the top surface of the sand. Table 3 represents the design parameters used for the validation study.

Table 3 Material properties used for the analysis (Lee et al. (2002))

Material	**Concrete Pile**	**Soft Clay**	**Bearing Sand**
Model	Isotropic Elastic	Mohr-Coulomb	Mohr-Coulomb
Elastic Modulus (E) (kN/m^2)	2000000	5000	50000
Cohesion (c) (kN/m^2)		3	0.1
Poisson's ratio (ν)	0.3	0.3	0.3
Friction Angle (ϕ_c) (°)		20	35
Dilatancy Angle (ψ) (°)		0.1	10
K_o	1	0.65	0.5
Unit Weight (γ_t) (kN/m^3)	25	18	20

Note:
Groundwater table is considered at surface.
Hydrostatic water pressure distribution is assumed.

The shear stress distributions along end bearing (Figure 3) and friction piles (Figure 4) were compared with shear stress distributions obtained by Lee at al. (2002). Theses distributions are obtained when a surcharge load of 50 kPa is applied on the surrounding soil. A very good agreement between the shear stress distributions obtained by the present study and the study of Lee et al. (2002) can be noticed from Figs. 2 and 3. Hence, the numerical model considered in the present study is validated.

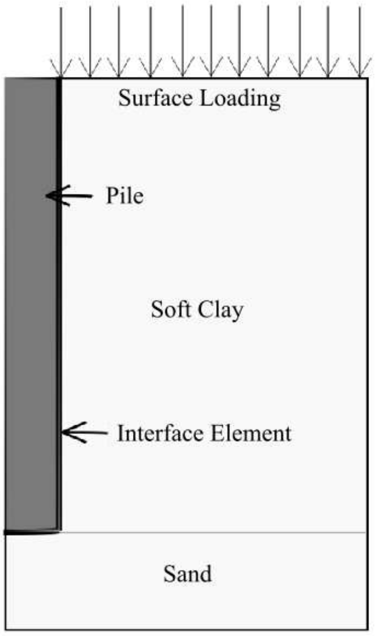

Figure 2. Finite element model of single vertical pile in soil

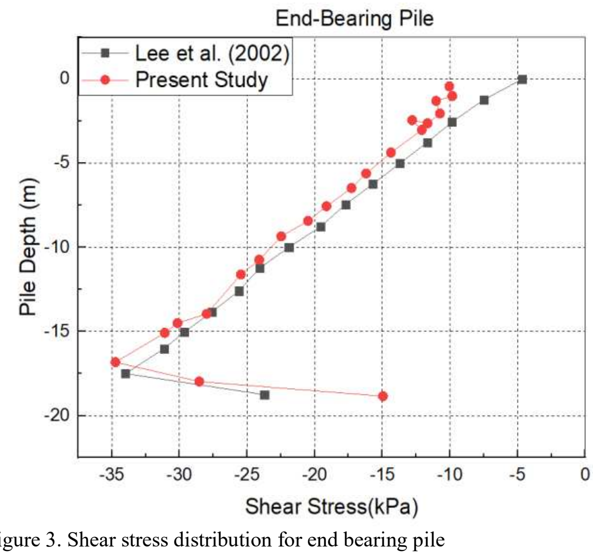

Figure 3. Shear stress distribution for end bearing pile

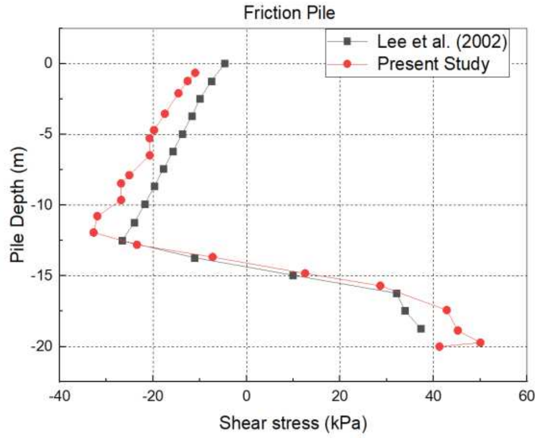

Figure 4. Shear stress distribution for friction Pile

4 RESULTS AND DISCUSSIONS

After validating the numerical model considered, a detailed parametric study was conducted. The effect of type of soil, surcharge loading, axial loading, pile tip locations and methods of generating NSF on dragload and downdrag were studied. The outcomes of the same are shown in the following sections.

4.1 *Influence of surcharge loading and soil type on NSF*

The behavior of stress developed due to NSF is analyzed along a single pile under different surcharge loadings. The surcharge loadings ranging from 10 kPa to 100 kPa were considered. The properties of three different soils considered are summarized in Table 2. Along with the surcharge load, an axial load of 50 kN is also placed on the pile head to consider the service load conditions.

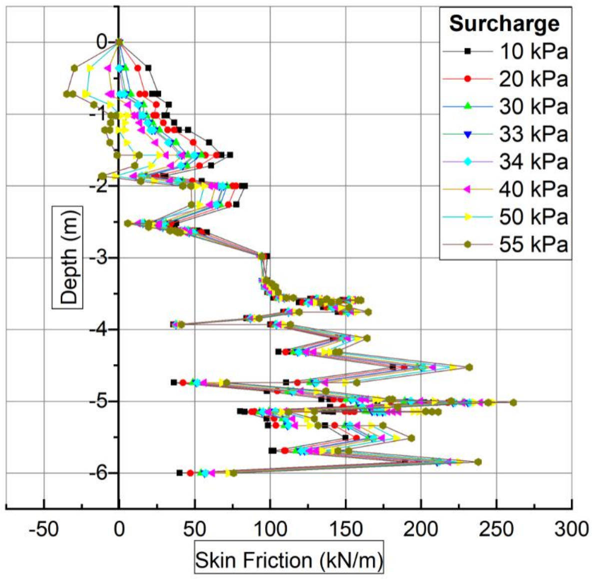

Figure 4(a) Skin friction distribution for soft clay

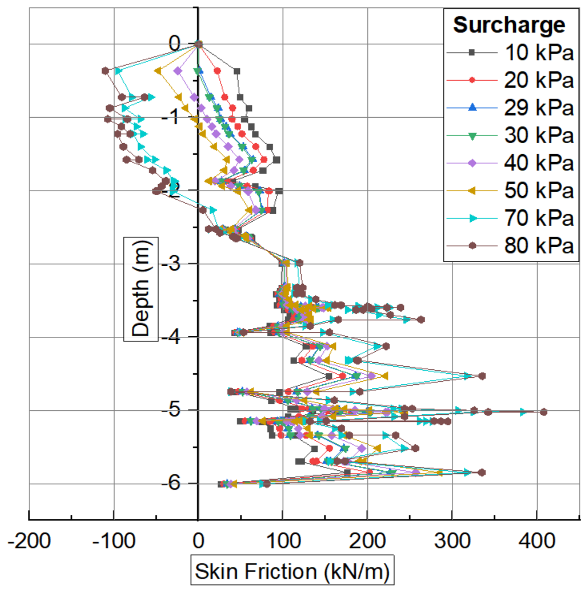

Figure 4(b) Skin friction distribution for medium dense sand

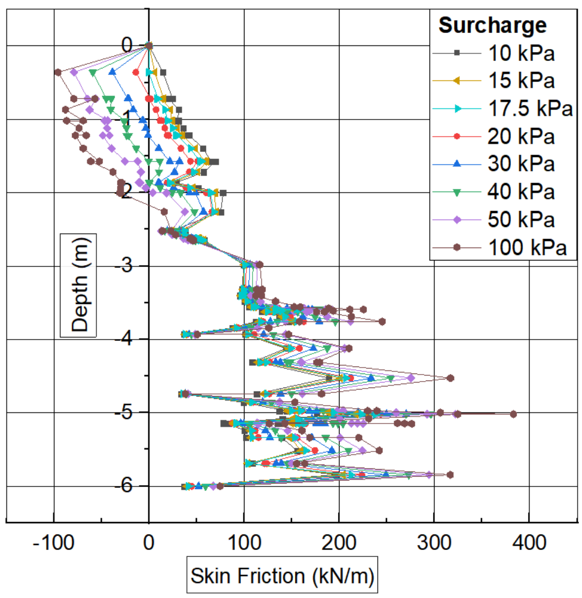

Figure 4(c) Skin friction distribution for dense sand

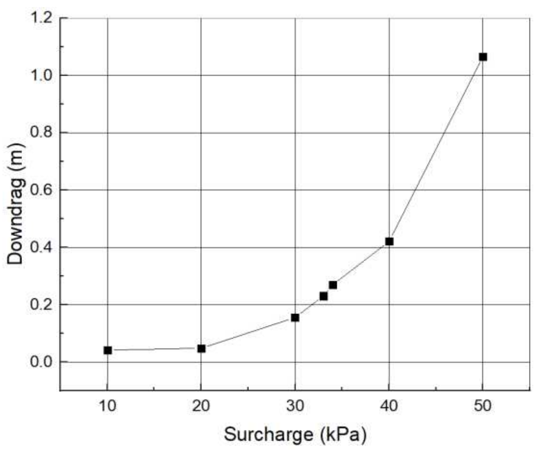

Figure 5(a) Downdrag distribution for soft clay

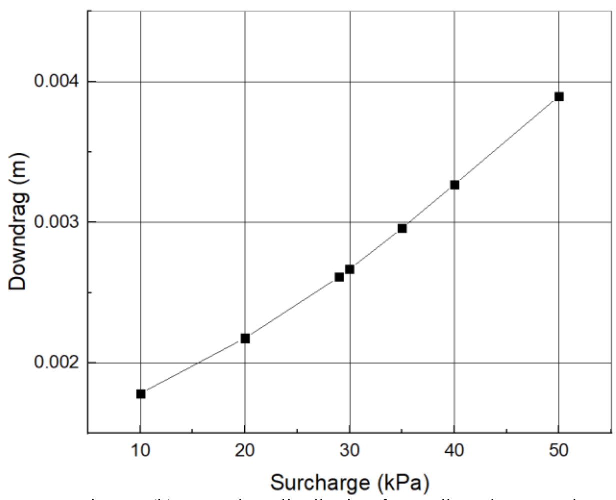

Figure 5(b) Downdrag distribution for medium dense sand

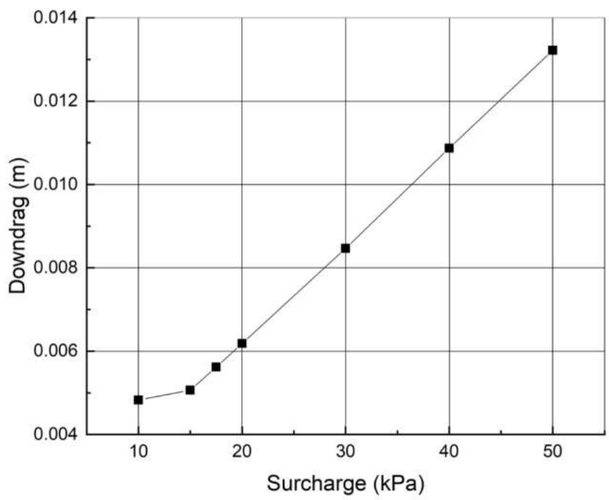

Figure 5(c) Downdrag distribution for dense sand

Figure 4 presents the distribution of skin friction along the depth of the pile for different values of surcharge loadings. For soft clay (Figure 4 (a)), the initial values of the surcharge loading i.e., up to 34 kPa, there is only positive skin friction acting along the pile shaft. However, with the further increment of surcharge loading, there is a rise in negative skin friction, which keeps on gaining its magnitude with the further addition of surcharge loading. Therefore, 34 kPa is considered as threshold value for surcharge load to generate NSF in soft clay. Figure 4 (b) and Figure 4 (c) represents the skin friction distribution for medium dense sand and dense sand respectively having threshold values as 29 kPa and 17.5 kPa respectively. A similar result can be observed through the values of downdrag in pile for different surcharge values. Figure 5 represents maximum downdrag occurred across the pile for particular values of surcharge. A sudden uptrend can be observed in the value of downdrag for all soils at their threshold value. Threshold values indicates the surface load value below which it is insufficient to mobilize the NSF on pile shaft. As expected the coarser soil is having faster mobilization of negative skin friction as compared to fine soil.

4.2 *Impact of NSF on the distribution of axial load in different soil types*

Axial load on pile is increased due to action of dragload on pile surface. Figure 6 shows the axial load distribution along the pile shaft for different soil types. It is observed that dragload at pile shaft increases with pile depth and maximum value is occurred at a depth of 0.45L, and then it decreases as the depth is increased. Therefore, the position of the neutral plane is obtained at 45% of the pile depth below the ground surface. The neutral plane is that location at the pile shaft, which signifies that there is no relative settlement between pile and soil. Above the neutral plane, relative soil pile displacement is downward and below the neutral plane, relative soil pile displacement is upward. Dragload is mobilised at depth above the neutral plane whereas upward friction load is mobilised below the neutral plane along the soil-pile interface. The maximum axial load values for soft clay and medium dense sand are 230.837 kN and 224.875 kN respectively. Among the three soils, dense sand is having the highest value of axial load with a magnitude of 310 kN which can be explained on the basis of their friction angles.

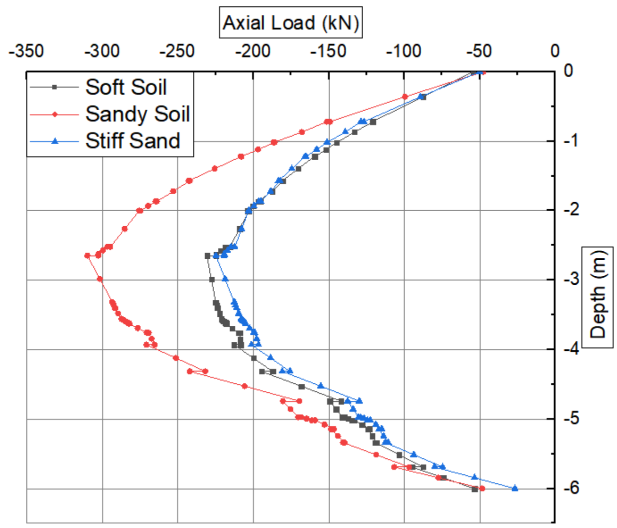

Figure 6 Axial load distribution along the pile depth for different soil types

4.3 *Influence of axial load on the position of neutral plane*

Location of the neutral plane is studied for all three types of soil where surrounding soil is subjected to a particular surcharge load of 40 kN/m^2. Figure 7 presents the axial load distribution along the pile depth for soft clay. Axial loads of 50, 100, 200, 300, 500 and 800 kN with a uniform surcharge condition of 40kN/m^2 is considered. It was observed that when axial load on pile head is increased six times there is 33% reduction in depth of neutral plane. This can be explained as the locked in negative skin friction at the neutral plane is decreasing because there is reduction in relative settlement between pile head and surrounding soil. This is the reason that when axial load on pile head is increases there is relative movement of neutral plane.

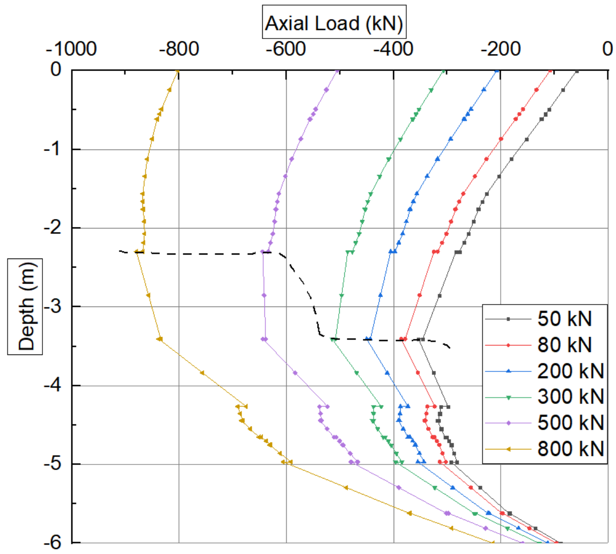

Figure 7 Transition of neutral plane with change in axial load

4.4 *Influence of pile tip locations on dragload*

Distance between the tip of the pile and bearing layer plays a major role in the resulting relative displacement between the soil and head of the pile. Hence, it also influences the dragload load on floating piles and end-bearing piles. Seven cases were studied for different pile tip locations with D’ = 0.25D, 0.5D, 1.00D, 0.00D, -1.00D, -0.5D, -0.25D, where D is diameter of pile and D’ = distance between pile tip and bearing soil. Surrounding soil is considered as soft clay and surcharge load is considered as 40kN/m^2. From Figure 8, it can be observed that for a floating pile, the positions of neutral plane are rising above with the increase in pile tip locations. Also, for pile at surface the dragload is maximum. In case of end bearing piles, the dragload is increasing with the increase in embedment depth. This is because for floating pile, the relative soil-pile displacement will be decreasing with an increase in distance between pile tip and bearing soil. For the end bearing pile, if the pile tip is having higher embedment depth in the bearing soil, then it better controls the relative soil pile displacement. Therefore, for both the cases, neutral plane depth decreases with the increase in distance between pile tip and bearing soil and it is maximum when pile tip is at surface of bearing soil.

4.5 *Dragload distributions along the pile for different prevailing field conditions*

Dragload distribution across the pile is investigated for the various possible prevailing conditions in the field (Fig. 4.9). The three possible conditions considered in the study are: pile under surcharge load, under consolidation and under both surcharge and consolidation. For surcharge conditions, 50 kPa was considered over the surrounding soil and a consolidation period for 30 days in considered. Soil considered in the model is soft clay.

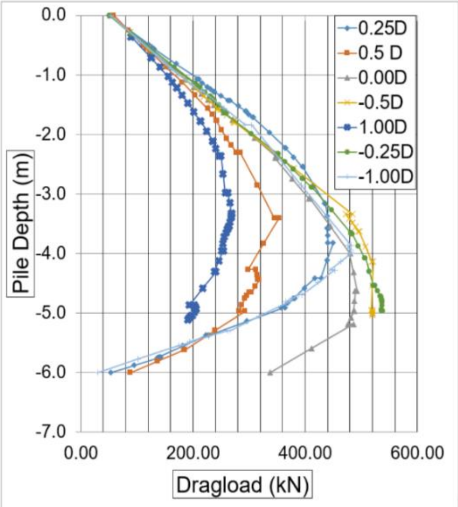

Figure 8 Distribution of dragload for various pile tip locations

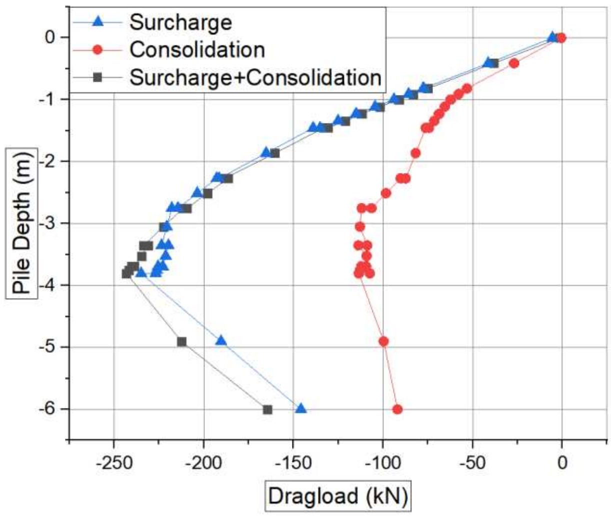

Figure 9 Comparison of NSF distributions for different possible conditions

Figure 9 shows that dragload under surcharge is almost 100% more as compare to consolidation condition. It also shows that dragload for both surcharge and consolidation is not directly the superposition of their individual effects which signifies that under surcharge conditions, consolidation is having very little contribution for NSF. This can be explained as the consolidation here is considered only for 30 days and there is no significant dissipation of excess pore water pressure. Therefore, for the initial days of construction, there is very little participation by consolidation for NSF generation as compare to the surcharge loading.

5 CONCLUSIONS

In this study, the behaviour of negative skin friction is assessed for a single pile for different possible conditions. The negative skin friction effect is simulated along the pile shaft for three different types of soils. It is observed that for the majority of the cases neutral plane lies between 0.4 L – 0.7 L. It is also observed that coarser soil is having faster mobilization of negative skin friction as compared to the fine soil and again within the coarser soil sand with a higher friction angle is having faster mobilization of negative skin friction. The axial load distribution is also studied for these soils along the pile length, where the dense sand has shown the maximum value of the axial load. It is found that the soil with a higher friction angle has a higher value of the axial load at the neutral plane. Migration of neutral plane is studied with the change in pile head loads, from which it is inferred that the axial loads can act as a great aid in the reduction of negative skin friction. It is also observed that by increasing the pile head load by six times, there is a 33% reduction in the depth of the neutral plane. The dragload along the pile shaft is examined for different pile tip locations. For both floating and end-bearing pile, there is a reduction in neutral plane depth with an increase in distance between pile tip and bearing soil. A comparative study is done for three possible negative skin friction cases. Dragload on the pile shaft is analyzed for the initial days of construction where the pile is subjected to both surcharge loading on surrounding soil and consolidation effect. It is observed that for the initial days of construction there is very little participation by consolidation in the generation of negative skin friction as compared to surcharge loading on the surrounding soil.

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