Effect of Swelling Soil on Load Carrying Capacity of a Single Pile

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ABSTRACT

Expansive soils are recognized by their swelling potential upon wetting due to the existence of some clay minerals such as montmorillonite. An effective solution was found to avoid the danger of such soils by using piles. A single pile embedded in an elasto-plastic expansive soil has been analyzed by using one of the available software which is ABAQUS to investigate the effect of applied loads on pile's top and investigate the effect of swelling soils on load carrying capacity of the pile. The result shows that as the pile is axially loaded at its top, the axial force along the pile gradually changes from (tension) to (compression) and the pile tends to move downward. The applied load needed to initiate pile's settlement depends on pile's embedment depth and the depth of active zone. The ultimate carrying capacity of a single pile for no swelling conditions is greater than that of with swelling conditions.

Keywords: Pile-Swelling soil-Load carrying capacity-ABAQUS-Axially loaded pile

تأثير الترب اللأنتفاخيه على قابليه تحمل الركيزه

الخلاصه

تعرف الترب الانتفاخيه بخاصيه التغير الحجمي عند تعرضها للماء حيث يزداد حجمها نتيجة لوجود بعض المعادن مثل Montmorolonite. حيث تم ايجاد حل لغرص تفادي المشاكل الناتجه من هذه الترب وذلك بأستخدام الركائز. ولغرض معرفة مقدار تحمل الركائز ومدى تأثرها بالأحمال المسلطه عليها تم تحليل ركيزة مفردة ممتدة في تربة إنتفاخية (Elasto-plastic soils) بأستخدام طريقة العناصر المحددة Finite Elements Method وتم ذلك بأستخدام برنامج ABAQUS. و أظهرت النتائج عند تحميل الركيزه فأن القوى المحوريه تتغير تدريجيا من قوى شد لى قوى ضغط على طول الركيزه والقوه اللازمه لبدأ نزول الركيزه يعتمد على طول الركيزه وعمق الطبقه الانتفاخيه. أما بالنسبه لمقدار تحمل ركيزه مفرده في تربه اعتياديه يكون اكبر من مقدار تحمل ركيزه مفرده ممتده في تربه انتفاخيه.

INTRODUCTION

Expansive soils are generally found in arid and semi arid region such as United State of America, China, Canada, Turkish, and others. The problem of these soils appears when water reaches the soil particles and causes them to separate. Foundations of lightly weight structure subjected to sever structure damage due to swelling pressure. The cost associated with damage due to swelling soils is more than twice as much as the cost associated with damages from flooding, hurricanes, tornados, earthquakes, and others. In order to avoid the dangerous from the swelling soil pile foundations used to anchor down the structure at a depth where the change in moisture content is negligible. Poulos and Davis (1980) reviewed Donaldson (1965) classification of moisture migration, which was:

1. A primary phase caused by the erection of the structure, resulting in a change in moisture regime until an equilibrium state is reached under the new circumstances.
2. The fluctuation caused by seasonal climate change, and
3. The results of extraneous influence, such as broken drains, leaking water pipes, local concentrations of storm water, and gardening operations.

LITERATURE REVIEW

There are two approaches to calculate the ultimate load carrying capacity of a single pile in clay; the first one is the static method which uses normal soil mechanics to calculate load capacity from measured soil properties, the second one is the dynamic method, which utilizes the pile-driven data to estimate load carrying capacity (Poulos and Davis, 1980).

The net ultimate load capacity of a single pile is the summation of ultimate shaft resistance and the base resistance, in other words:

$$Q_{ult} = Q_s + Q_b - W \tag{1}$$

Where

Q_{ult} = Ultimate load carrying capacity of the pile,
Q_b = End bearing resistance of the pile,
Q_s = Shaft skin frictional resistance, and
W = Pile's weight.

Pile's shaft-resistance can be computed by integrating pile-soil shear strength, τ_a, over the surface area of pile shaft as follows:

$$\tau_a = c_a + \sigma_n \tan \varphi_a \tag{2}$$

Where

τ_a = pile-soil shear strength,
c_a = Adhesion of the soil,
σ_n = Normal stress between pile and soil, and
φ_a = Angle of friction between the pile and soil, degree.

The most commonly used formula to determine the bearing capacity of the foundation was developed by Terzaghi (1943) which is (Poulus and Davis 1980):

$$Q_{ult} = cN_c + \gamma DN_q + 0.5\, B\gamma N_\gamma \tag{3}$$

and from Terzaghi's theory (Poulus and Davis, 1980), ultimate base resistance can be evaluated as follows:

$$Q_b = A_b\left(cN_c + \gamma DN_q + 0.5\, B\gamma N_\gamma\right) \tag{4}$$

Where

c = The cohesion of the soil,
B = Width of the footing or pile's diameter,
N_c, N_q, and N_γ = Dimensionless bearing capacity factors,
D = Vertical distance from ground surface to the bottom of the footing, and
A_b = Cross-sectional area of the pile at the base.

Aljorany (2001) presented a mathematical solution to the displacement problem of an axially loaded pile. The solution which was based on the weighted residual method, considered the nonlinear mechanical behavior of the surrounding soil. The proposed solution indicated a good correspondence with field measurements especially for loading levels below the pile's working load.
Gan and Nicholas (2004) developed a finite-element model to simulate the nonlinear response of pile or drilled piers axially loaded. The nonlinear stress-strain behaviors of soils were modeled by using Drucker-Prager and Von Mises type plasticity. Their study was carried out to address the influence of various factors such as soil friction, dialatancy, and interface element. They found that pile's response in cohesive soil was successfully simulated by using Von-Mises's type criterion and it is in excellent agreement with field test data; also they found that the predicted load capacity was greatly underestimated, only up to 70% of actual capacity.

SOIL PROPERTIES

In this research, the lightly brown, dry soil samples brought from Al-Falujaa about 50 km west of Baghdad and tested to obtain the various parameters needed to complete the theoretical analysis. The conducted tests included consistency, compaction, permeability, one dimensional consolidation test, unconfined compression test, soil properties shown in table (1).

PROBLEM MODELING WITH ABAQUS

Parts Model

The building block of ABAQUS/CAE models is composed of parts. An axi-symmetric analysis was adopted throughout this research work since both geometry and loading are symmetrical around the vertical axis of the pile. The analysis of a single pile embedded in an expansive soil was divided into three parts, namely the pile, lower soil, and the swelling zone.

The Pile

The pile is assumed to be a linear, elastic material throughout the analysis. The pile properties which are assumed and used in this analysis are as follows: Unit weight of the pile, γ, is 24 kN/m^3; elastic modulus of the pile, E_p, is $2*10^7$ kPa; pile's diameter, D, 0.4 m; Poisson's ratio, υ, is 0.18, and pile's length, L, ranged from 10 m.

The Soil

The soil was assumed to behave as an elasto-plastic material throughout this analysis. The soil properties used in the modeling were obtained experimentally and these values are as follows:
Dry unit weight of the soil, γ_d, is 13.9 kN/m^3; elastic modulus of the soil, E, is 17000 kPa; Poisson's ratio, υ, is 0.4; coefficient of permeability, k_w, is 1.27 $*10^{-10}$ m/sec; initial void ratio, e_o , is 1.04, undrained shear strength, c_u, is 103 kPa; angle of internal friction, φ, is 4^o. The assumed data is as follows: cap eccentricity is 0.4; flow stress ratio is 1; initial cap yield surface position is 0; transition surface radius parameter is 0.05; and other parameters are shown in table (2).

The Swelling Zone

The swelling zone was assumed to behave as an elasto-plastic material and its yield function is defined by Cap plasticity models. The parameters used in this analysis were obtained experimentally these values are as follows:
Dry unit weight of the soil, γ_d , is 13.9 kN/m^3; elastic modulus of the soil, E, is17000 kPa; Poisson's ratio, υ , 0.3; coefficient of permeability, k_w, is 1.27 $*10^{-10}$ m/sec; initial void ratio, e_o , is 1.04; undrained shear strength, c_u, is 103 kPa; angle of internal friction, φ, is 4^o. The assumed data is as follows: cap eccentricity is 0.4; flow stress ratio is 1; initial cap yield surface position is 0; transition surface radius parameter is 0.05; and other parameters are shown in tables (2) and (3).

MODELING SWELLING BEHAVIOR WITH ABAQUS

In order to model swelling behavior with ABAQUS there are several parameters that should be defined such as: moisture swelling, permeability, and soil suction-saturation relationship. Volumetric moisture swelling of the porous-medium, solid skeleton is a function of degree of saturation of the wetting liquid in partially - saturated flow conditions. The swelling behavior is assumed to be reversible; where the swelling strain is calculated logarithmically with respect to the initial saturation.

MODELING ELASTO-PLASTIC BEHAVIOR WITH ABAQUS

In order to model elasto-plastic material by using ABAQUS either linear elasticity or nonlinear porous elasticity ought to be used with the plasticity models, where linear elastic is defined by Young modulus and Poisson's ratio, while porous elasticity is a nonlinear, elasticity model in which the pressure stress variation can be expressed as a function of the volumetric strain. In order to define the plastic behavior of a material there are several models that can be used such us; Cam-Clay, Cap model, Drucker-Prager, and Mohr-Coulumb model. Through this research Modified Drucker-Prager (Cap model) was used (ABAQUS manual, 2009).

DEFINITION OF BOUNDARY CONDITIONS IN ABAQUS

The boundary conditions should be chosen and identified carefully to represent the actual entire domain in terms of in-situ stresses and displacements. The boundary conditions are assumed to be hinged at the end of the lower soil to prevent horizontal and vertical movements, and a roller is placed at a distance r_m, which is the maximum effective radius of the pile on the surrounding soil, to allow a vertical movement and prevent horizontal movement, and symmetry /antisymmetry / encastre for the pile's side.

TYPE OF THE ELEMENT USED

The swelling zone and the lower soil layers were assumed to be eight-nodded pore pressure/stress quadrilateral elements, while the pile was assumed to be eight-nodded axi-symmetrical stress quadrilateral elements. Eight-nodded elements were adopted to get more accurate results since the problem focuses on the stress and settlement of the swelling layer and soil below the pile.

STEPS FOR ANALYZING SWELLING BEHAVIOR IN PARTIALLY SATURATED SOILS

In this research, four steps were used to analyze the behavior of a single pile in partially saturated soil which is: initial, geostatic, swelling, and loading steps. The initial step of the analysis involved specifying the initial boundary conditions such as: initial void ratio, permeability, degree of saturation, and pore water pressure, while geostatic step involved specifying the initial geostatic stresses. The influence of gravity should also be included in this step also. Geostatic step makes sure that equilibrium is satisfied within the clay layer and that the initial stress conditions in any element within the clay layer falls within the initial yield surface of the cap model. The swelling step included specifying the swelling boundary conditions such as pore- water pressure at top and end of the swelling zone, and the loading step of the analysis involved specifying the loading conditions such as pressure exerted on pile's top.

EQUIVALENT EFFECTIVE STRESS CONCEPT

For soil deformation, effective stress is the corresponding equivalent stress to generate the same volumetric strain, $d\varepsilon_v$, caused by the mechanical stress variation, $d\sigma_m$, together with the matric suction variation $d\,(u_a - u_w)$.

First of all, the initial stress should be computed and inserted in ABAQUS in the geostatic step where ABAQUS uses the initial stresses specified as an initial guess. This initial stress specification has a great impact on the subsequent steps. ABAQUS calculates the total stresses which are in equilibrium with the external loading, i.e., the gravity and boundary conditions. The initial stress should be computed as follows:

$$\sigma' = (\sigma - u_w) + \chi(u_a - u_w) \qquad (5)$$

In this research, u_a, is the atmospheric pressure, the air phase is assumed to be continuous and the excess pore air pressure will dissipated instantly.

MODELING OF LOADING IN ABAQUS

ABAQUS/Standard provides several options for the applied loads such as concentrated load, pressure, gravity, and body forces. Loading conditions may differ from step to another depending on the case to be analyzed. For instance, in geostatic step the influence of gravity is included by using the gravity options, where the acceleration is specified to be 9.81m/sec^2 in the vertical direction and zero in other directions, and the pressure options are used in the loading step to represent the load on the pile's top.

RESULTS AND DISCUSSIONS

Effect of applied load on pile's head

Figures (1) and (2) show the influence of a load applied on the pile's top on axial displacement and axial force along the pile. It can be seen that upward movement decreases as the applied load on the pile's top increases up to a certain limit then pile's settlement starts. This increase in the applied load causes a decrease in the axial force along the pile and gradually changes from tension to compression. Increasing applied load increases the negative skin friction along the pile and helps the pile to resist the upward movement coming from soil heave.

EFFECT OF SWELLING SOIL ON LOAD CARRYING CAPACITY OF THE PILE

The load carrying capacity of a single pile that was obtained by using ABAQUS software was compared with the values obtained Alpha method and it was found that the results extracted from ABAQUS software were more conservative. Figure (3) shows load-settlement curves for a single pile embedded in an expansive soil before and after swelling for pile's top and tip, respectively. It is obvious that the load carrying capacity of the pile decreases after swelling and this reduction in pile's bearing capacity decrease as the pile's length increases. The reduction in the bearing capacity before and after swelling is due to the decrease in the strength properties of the soil after inundation (swelling). In 1974, Sorochan found that bearing capacity of a pile after inundation is about 1.5 - 2 times less than that of the soil at its natural water content, and with increasing pile's length the difference in its bearing capacity due to soil inundation decreases.

CONCLUSIONS

1. As the pile is axially loaded at its top, the axial force along the pile gradually changes from (tension) to (compression) and the pile tends to move downward. The applied load needed to initiate pile's settlement depends on pile's embedment depth and the depth of active zone.
2. The ultimate carrying capacity of a single pile for no swelling condition is greater than that of with swelling condition. This may be attributed to the inundation effect on the strength parameters of the soil. The difference diminishes as the pile's length increases. Thus, in order to keep the bearing capacity of the pile intact or to limit the reduction in its bearing capacity a long pile could be a convenient choice.

REFERANCE

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Sorochan, A., (1974): "*Use of Piles in Expansive Soils*", Soil Mechanics and Foundation Engineering, vol: 11, No. 1, pp: 33-38.

LIST OF SYMBOL

A_b = Cross-sectional area of the pile at the base.

B = Width of the footing or pile's diameter,

c = The cohesion of the soil,

c_a = Adhesion of the soil,

D = Vertical distance from ground surface to the bottom of the footing,

N_c, N_q, and N_γ = Dimensionless bearing capacity factors,

Q_{ult} = Ultimate load carrying capacity of the pile,

Q_b = End bearing resistance of the pile,

Q_s = Shaft skin frictional resistance,

W = Pile's weight.

τ_a = pile-soil shear strength,

σ_n = Normal stress between pile and soil, and

φ_a = Angle of friction between the pile and soil, degree.

Table (1). Soil Properties

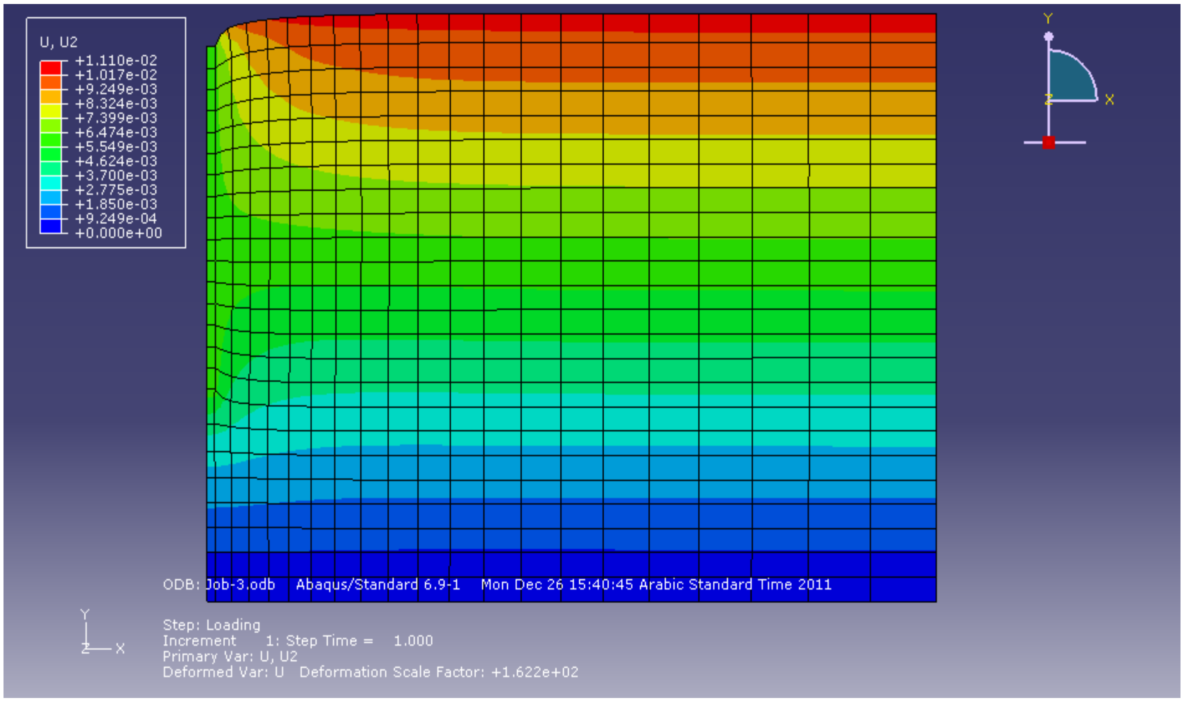
Parameters	**Value**
Liquid Limit, %	67
Plastic Limit, %	30
Specific Gravity	2.79
Percent finer 0.05, %	85
Percent finer 0.02, %	54
Maximum dry unit weight, kN/m^3	13.9
Optimum moisture content, %	29.2
Undrained shear strength, kPa	103
Coefficient of permeability, m/sec	$1.27*10^{-10}$

Table (2). Values of yield stresses and volumetric plastic strains used in the analysis.

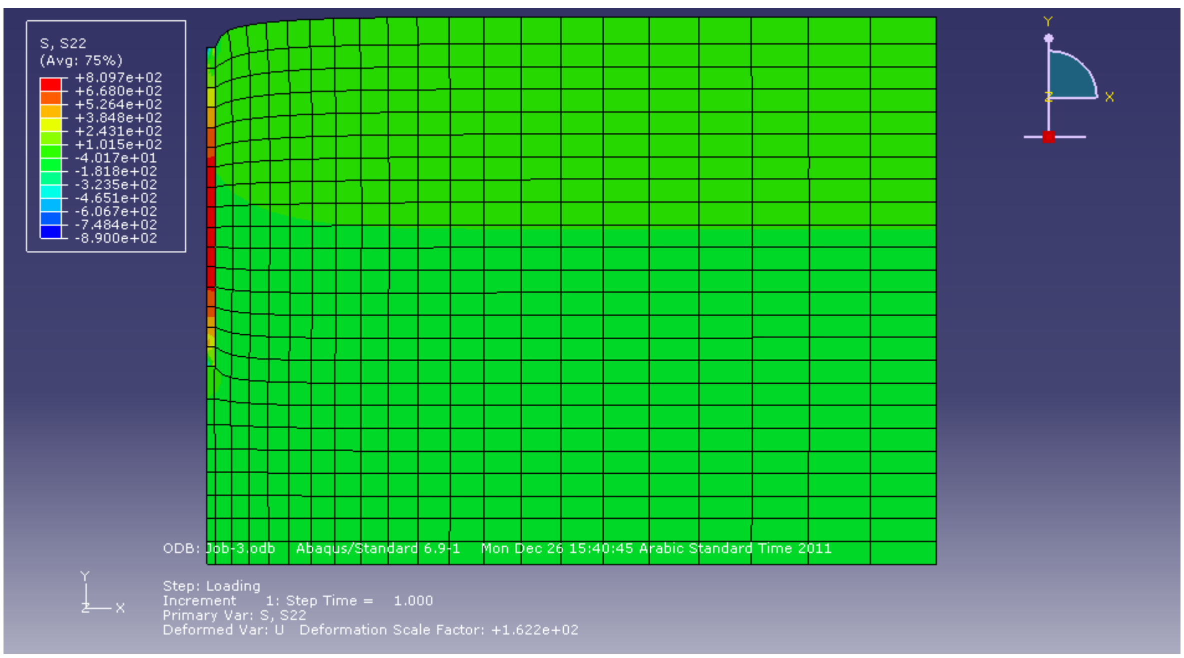
yield stress, kPa	volumetric plastic strain, %
200	0
400	0.16
600	0.2

Table(3). Values of the parameters used in the swelling models.

Water content %	Degree of saturation %	Swelling strain, %	Matric suction, kPa *(assumed)*
23	61.9	0.094	-
25	69	0.071	-
29.2	78	0.032	600
31.7	85	0.012	135
36	100	0	0

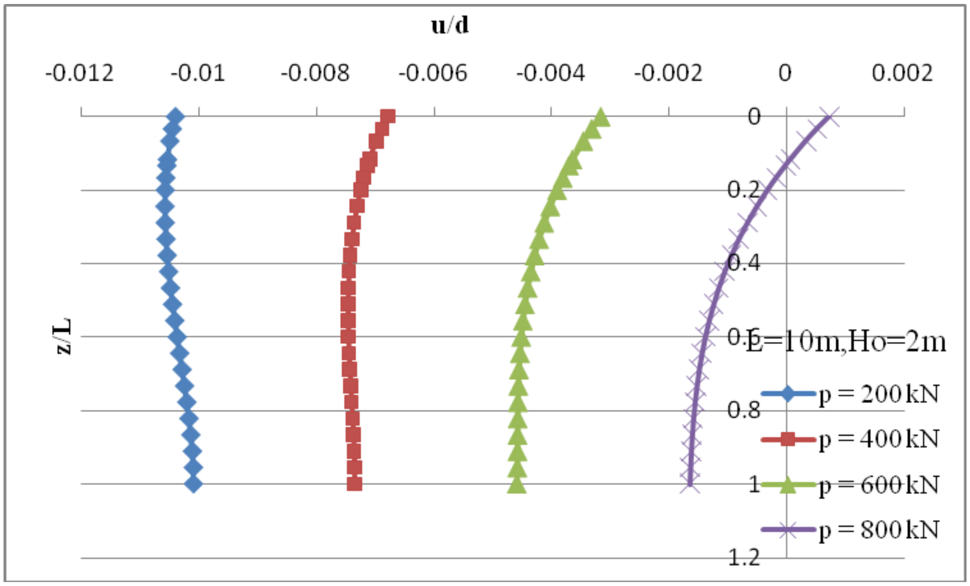


(a)



(b)

Figure(1). Longitudinal side view of the soil heaves and stress distribution for a pile's length of 8 m and depth of active zone 2 m, and applied load on pile's top 200 kPa.



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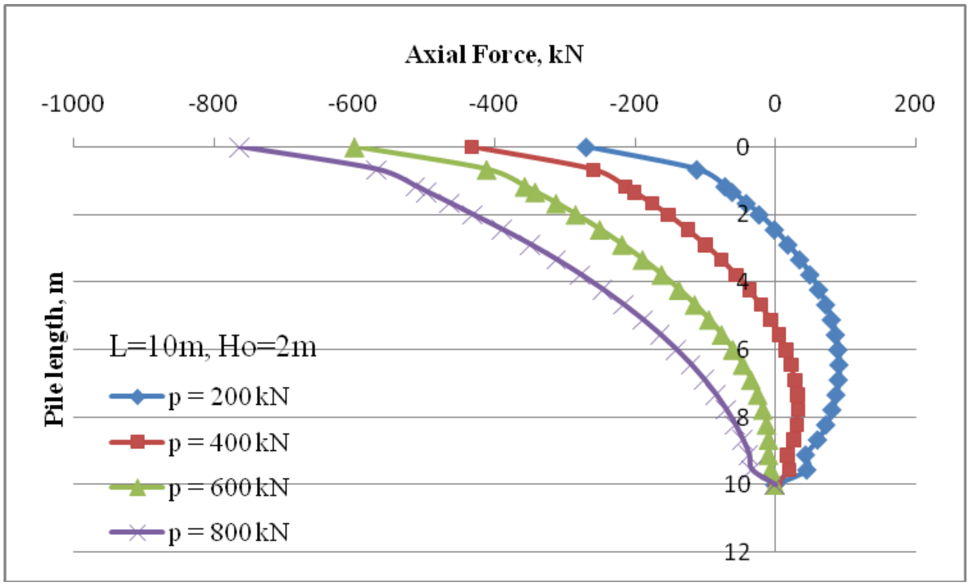
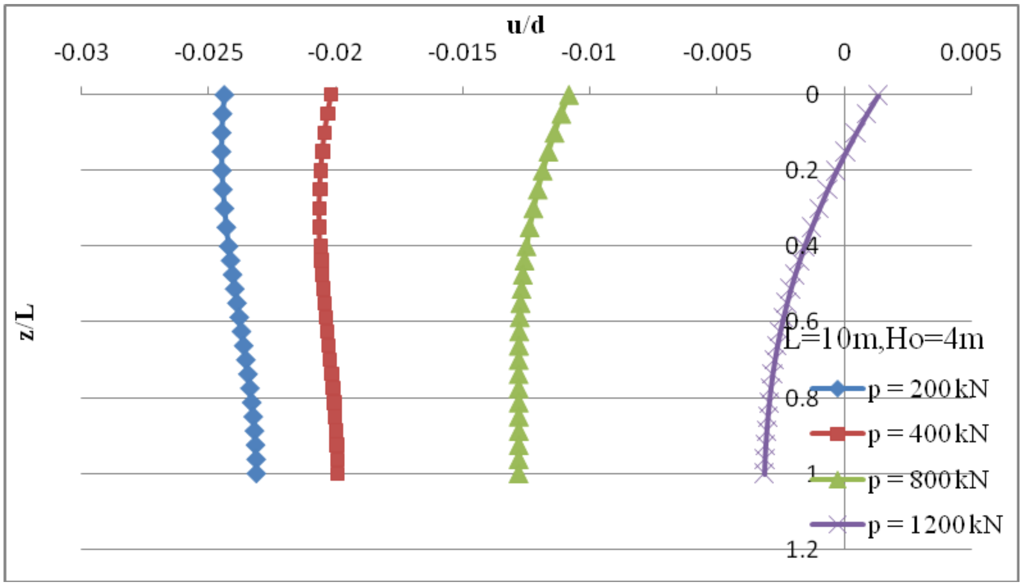


(b)

Figure(2). Effect of applied load on pile's top on: (a) upward movement and (b) Axial force.



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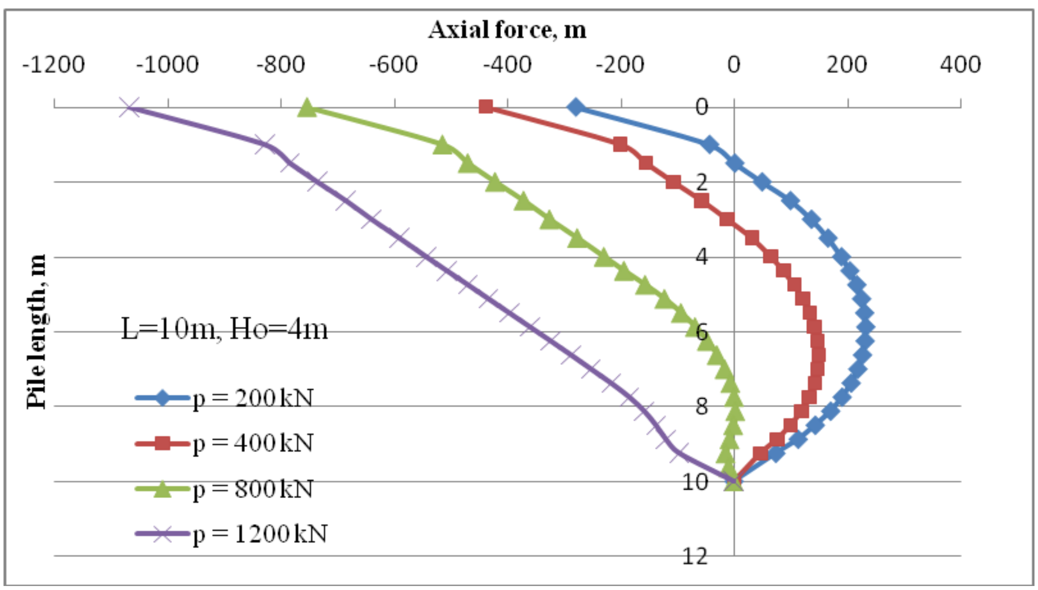
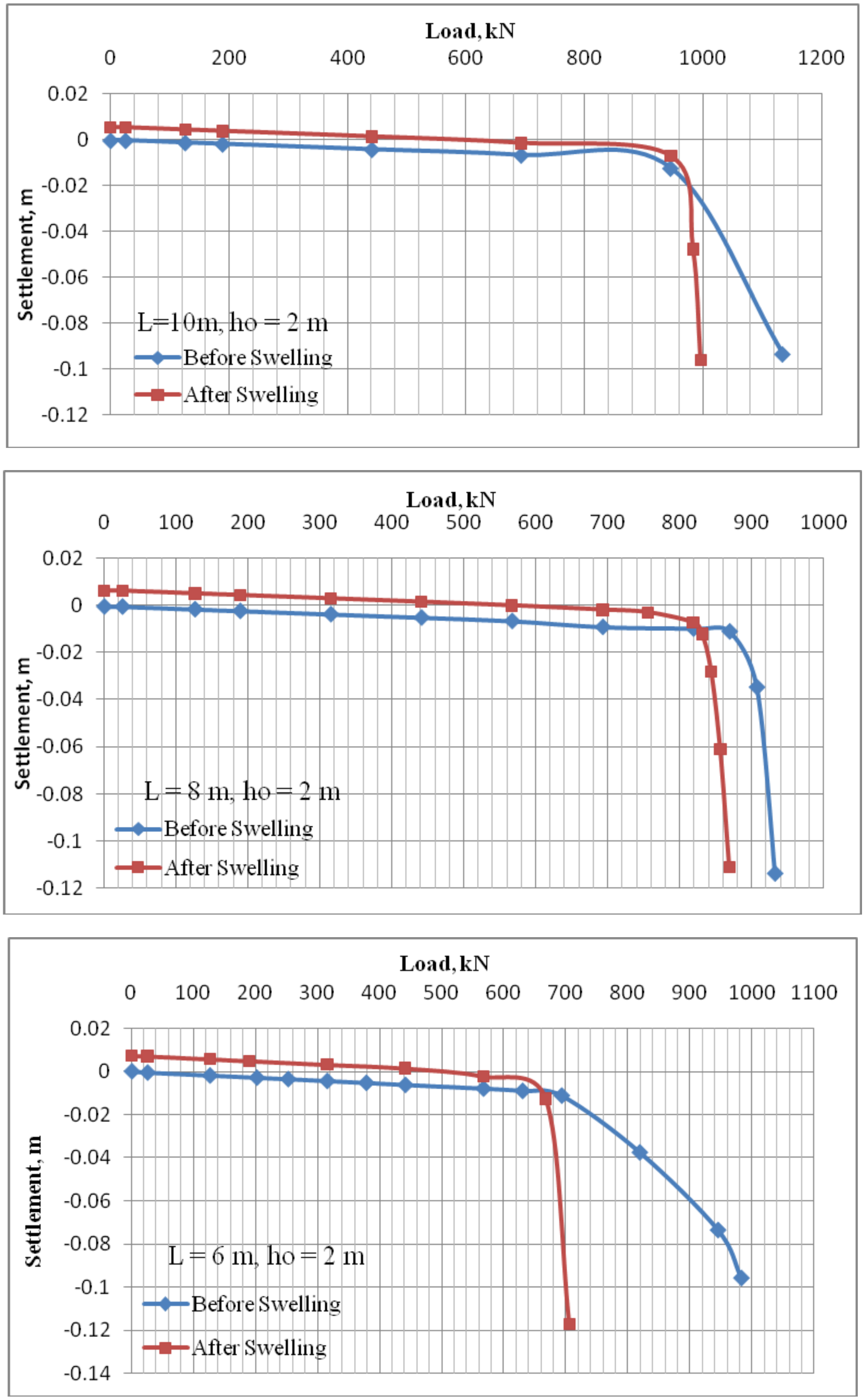


(b)

Figure (2). Continued.



Figure(3). Effect of swelling soils on loads carrying capacity of the pile.