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A NUMERICAL STUDY OF PILES IN SATURATED EXPANSIVE SOILS*

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ABSTRACT

Foundations on expansive soils are of great interest to geotechnical engineers. Piles foundations are used in expansive soils to resist the induced heave. Many factors can affect the pile heave in expansive soil. These factors include the pile length, diameter, and pile loading. The depth of active zone and depth of wetting can also affect the pile and surrounding soil heave. A numerical model of a single straight shaft pile constructed in an expansive soil is presented herein. The numerical study concerning pile and soil properties is set to clarify their effect on pile heave. The finite element software, ADINA is used to model the pile and surrounding soil domain and to compute the pile heave. The model is exposed to inundation with various depths of wettings, where net pile and free field heave are computed. The results show that pile length significantly affects the pile heave, while pile diameter has no noticeable effect on pile heave neither has the pile loading. Tracking of the pile movement shows that it begins to settle immediately after decreasing the depth of wetting, returning approximately to its initial state due to loading at zero depth of wetting.

KEY WORDS: Depth of Wetting, Expansive Soil, Pile Heave, Depth of Active Zone

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ÉTUDE NUMÉRIQUE DE PIEUX EN GRAS SATURÉS EXPANSIVE SOLS

RÉSUMÉ

Fondations sur sols gonflants sont d'un grand intérêt pour les ingénieurs en géotechnique. Fondations de pieux sont utilisées dans les sols gonflants pour résister à la houle induite. De nombreux facteurs peuvent influer sur le soulèvement de pile dans le sol expansif. Ces facteurs incluent la longueur de la pile, le diamètre et chargement du pieu. La profondeur de la zone active et la profondeur de mouillage peut également affecter la pile et entourant le soulèvement du sol. Un modèle numérique d'une seule pile arbre droit construit dans un sol expansif est présenté ici. L'étude numérique concernant poils et les propriétés du sol est de clarifier leur effet sur la pile soulèvement. Le logiciel d'éléments finis, Adina est utilisé pour modéliser la pile et ses environs domaine des sols et calculer le soulèvement de pile. Le modèle est exposé aux inondations avec différentes profondeurs de mouillages, où pile net et sans soulèvement de terrain sont calculés. Les résultats montrent que la longueur de pile affecte de manière significative le soulèvement de pile, tandis que le diamètre de la pile n'a pas d'effet notable sur la pile ni soulèvement est le chargement de la pile. La traçabilité des mouvements de pile montre qu'il a commencé à régler immédiatement après la diminution de la profondeur de mouillage, revenant à peu près à son état initial en raison de chargement, à zéro la profondeur de mouillage.

MOTS CLES: Profondeur De Mouillage, Sol Expansif, Pile Soulèvement, La Profondeur De La Zone Active

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1. INTRODUCTION

Pile foundations are recommended in many cases of highly expansive soils extending to large depths. However, full documentation of such cases including field measurements is very rare.

Nusier, et al. [7] studied the effectiveness of using micro-piles to control heave of light weight structures over expansive soils. He used smooth and artificially roughened steel piles, surrounded by dense sand inserted in highly expansive clay. The expansive clay was compacted in a steel box. Steel plates were used to model footings, where heads of the model micro-piles were fastened to the steel plate. Footings with 0, 1, 2, or 4 micro-piles were prepared. The compacted clay is then flooded with water, where heave of footings was measured with time. Results showed that roughened micro-piles are more effective in reducing the heave than the smooth ones. Also, increasing the number and diameters of micro-piles reduce the heave.

Mohamedzein, et al. [4] performed finite element analysis on short piles constructed in expansive soil in ELFAO, Sudan. Piles of one, two, three, and four meters length were constructed and exposed to inundation, with no loading, where heave was measured. Computed heave (by a computer program presented by the authors) was compared with the measured one. Results showed that heave decreases with increasing the pile length, and pile loading.

One of the most precisely documented case studies of full scale piles, constructed in expansive soil was the TRACON building in Colarado. Chao [2] tracked the pile heave continuously for six years under the TRACON building in Colorado. This Case study was reproduced in Salem [8], using the finite element software ADINA. Results show the ability of ADINA software in modeling the behavior of piles in expansive soil.

One of the powerful numerical analysis techniques is the finite element method. A comprehensive numerical analysis is performed in this research using ADINA finite element software package. The numerical model presents a pile having different lengths, diameters, and loading in an expansive clay soil layer of thickness extending down to 15 m followed by dense sand. The effect of depth of wetting and depth of the expansive soil are also accounted for.

2. NUMERICAL MODELING OF PILES IN EXPANSIVE SOIL

ADINA is a finite element analysis package capable of modeling structures, fluids, heat transfer, electro-magnetics and multi-physics. It is used for displacement and stress analysis. ADINA presents modeling of two-dimensional (plane strain, plane stress and axi-symmetric), and full three-dimensional analyses. In this research, ADINA structure is the used module, with two-dimensional axi-symmetric conditions.

Elastic Isotropic model is used to model the pile. Mohr Columb model is applied to present soil where no heave is expected i.e., sand soil. Cam Clay model is used to present the saturated expansive soil, to account for the expected heave.

Cam Clay parameters can be conducted from an isotropic compression test in a triaxial cell. An extensive research was performed to collect a documented data base on Cam Clay parameters, presenting expansive clay soil. Four sets of Cam Clay parameters of expansive clay were employed in reproduction the TRACON Case Study, Table (1). The so-called Weald Clay set showed the best agreement between measured and computed heave. This set of parameters is chosen and used in the current numerical model. A detailed description, reproduction of TRACON Case Study, and the used sets of Cam Clay, are presented in Salem, [8].

3. NUMERICAL MODEL PRESENTATION

The numerical model presents a pile in expansive soil clay of 15-m thickness layer underlain by a 15-m thick dense sand layer. The numerical study includes pile parameters such as; pile diameter, pile length, and pile loading. Depth of wetting and thickness of

expansive soil are also included.

Pile and soil are modeled as axi-symmetric two dimensional condition, with specifically porous media for soil. 4-nodel element with quadrilateral pattern was specified for cell shape. Table (2) presents the model and soil parameters used in the numerical model.

Rollers are set on left and right side boundaries of the soil domain to allow vertical movement (settlement). Hinged ones are at lower base of model to prevent any movement in both directions. The proposed model presents a soil domain extends in depth to 1.8 times the pile length, and 10 times the pile diameter in width.

Net heave is calculated at two points. The first point is chosen at the pile head, and the second one is chosen on soil surface to track the free field heave. "Free-Field" heave is the amount of heave that the ground surface will experience due to wetting of the sub-soils with no surface load applied (Chao, [2]). Fig. (1) shows the finite element mesh of the basic proposed numerical model with these two noted points.

Table (1): Referenced Cam Clay Parameters Applied in TRACON Case Study

Soil	Cam clay Parameters				**Reference**
	M	*Λ*	*K*	*Γ*	
- London clay	0.888	0.161	0.062	2.448	Parry, 1958*
- Wiener Tegel V	1.01	0.122	0.026	2.130	Hvorslev, 1937*
- Weald Clay	0.95	0.093	0.035	1.88	Parry, 1958*
4- Silty clay (CH)	1.02	0.049	0.018	2.01	Abdl Mofez and Nurul Islam, 2010

* *cited by* Schofield, and Wroth, 1968

3.1 Modeling of Wetting Due to Inundation

Herein, soil and pile are exposed to inundation, where pore pressure is induced within the expansive layer(s). The pore pressure is related to the depth of wetting. Depth of wetting is the depth to which water contents have increased due to the introduction of water from external sources, or due to capillarity after the elimination of evapo-transpiration. The external sources can include irrigation, seepage from ponds or ditches, broken water lines, and others (Nelson, et al., [6]).

Experience has shown that many sites exist where the depth of wetting has exceeded 6 meters (Nelson et al., [6]; Diewald, [3]). It is common practice to consider that the soil will be saturated to a certain depth for design of deep foundations along the depth of wetting (Chao, [2]). Hence, for the proposed model, soil is modeled as saturated along the depth of wetting, and dry beneath it. This assumption seemed to be conservative, and would overestimate the computed heave. Wetting due to inundation is modeled as classical ground water pressure profile, i.e., a triangle pattern, with base at end of the studied depth of wetting, Fig. (1).

Table (2): Parameters in Numerical Model

Parameter	***Expansive Clay*** Cam Clay Model	***Dense Sand*** Mohr Columb Model	***Pile*** Elastic Isotropic Model
Modulus of Elasticity, E M N/m^2	18	70	21000
Unit Wright, γ kN/m^3	18	19	25
Poisson ratio, ν	0.45	0.25	0.25
Other parameters	• *over consolidation ratio,* OCR= 3.5 • *coefficient of earth pressure,* k_0= 0.93 • *initial yield pressure,* P'_0=200 k N	• *Cohesion,* c= 10 k N/m^2 • *Angle of Friction,* $\Phi = 40^0$ • *Angle of* $\psi = 10^0$	

3.2 Phases of Numerical Modeling

Four Phases are presented to fulfill loading of soil and pile. The phases are placed to simulate the sequenced loading on soil and pile. Fig. (2) shows a schematic loading of soil and pile. These phases in sequence are:

- Settlement due to own weight (due to geo-static pressure),

- Pile installation process and its effect on the surrounding soils,
- Pile loading phase,
- Inundation phase in which the heave due to wetting of soil as a result of inundation is calculated

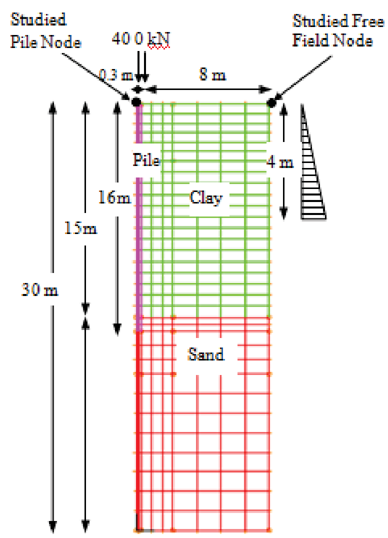

Fig. (1): Finite Element Mesh for the Proposed Numerical Model.

4. RESULTS AND DISCUSSION

The last phase of loading; inundation is of interest herein, where net pile and free field heave is numerically calculated. They are computed as the heave at each time step increment. Six years is the total time of the inundation, with three months calculation increment. An example of the heave plot for 8-meter pile length exposed to 4- meter depth of wetting is shown in Fig. (3). It can be noted that the minimum computed surface heave took place at the loaded pile head. The maximum one occurred at soil surface.

4.1 Effect of Wetting Depth

Depths of wetting of: 0, 1, 2, 3, 4, 5, and 6 m are considered in the analysis, where pore pressure is induced. For the model shown in Fig. (1), pile and free field heave are computed for all the depths of wetting.

The effect of depth of wetting on the net pile heave is presented in Fig. (4).

A linear increasing trend for the net pile heave is noticed with time for different depths of wettings. For 6-m depth of wetting, a slight shift of the net heave is noticed. The convergent values in heave can be explained by that for the shown model; Fig. (1), the pile is embedded in sand, which decreases the pile heave.

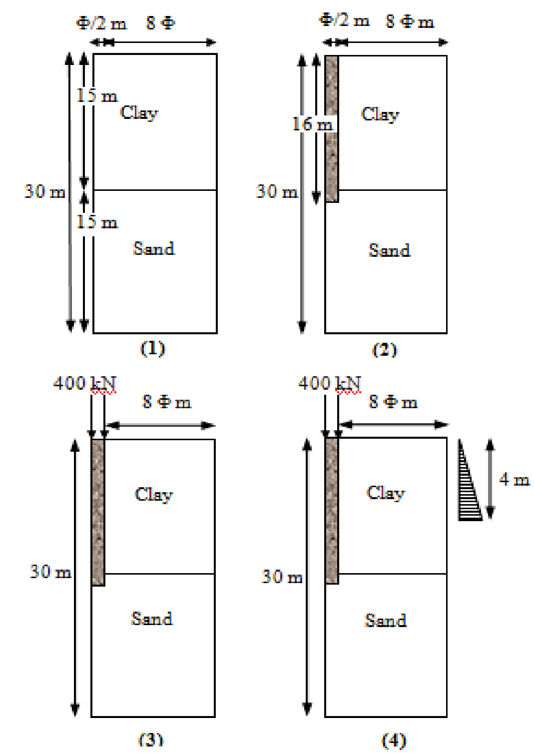

Fig. (2): Schematic Sequence of Soil and Pile Loading.

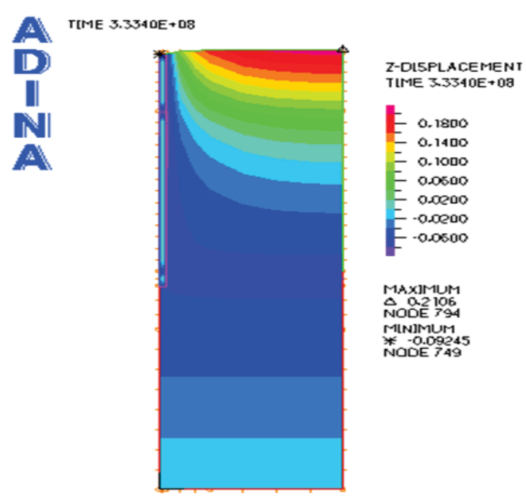

Fig. (3): Heave Plot for 8-m Pile Length and 4-m Depth of Wetting.

Free field (soil) heave for different depths of wetting is shown in Fig. (5). A slightly sagging increasing trend for net free heave with time is noticed for different depths.

The direct proportion between depth of wetting and pile heave, or free field heave can be explained by that as depth of wetting increases, volume of expansive soil exposed to change in water content changes, and then large swelling took place. A summary of the two last curves is shown in Fig. (6). Total net pile and free field heave at end of six years is depicted. It can be concluded that values of total net free heave are much higher than those of pile by about 39 times. This indicates the effectiveness of using piles in resisting heave.

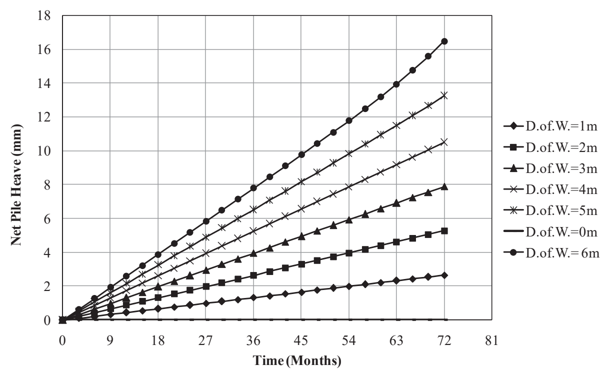

Fig. (4): Effect of Depth of Wetting on Net Pile Heave.

4.2 Effect of Active Zone Depth

The term "Active Zone" has been in common usage in the field of expansive soils. The active zone is defined as: the zone of soil that is contributing to heave due to soil expansion at a particular point in time, Nelson, et al., 2001. Herein, Depths of active zone of: 5, 10, 15, 20, 25, and 30 m are studied.

The effect of depth of the active zone on pile heave is depicted in Fig. (7). A linear increasing trend is noticed with time for all depths. For depths of 5, 10, and 15 m, curves of net pile heave are nearly coinciding, with a total pile heave less than 10 mm. The coinciding curves of heave, for these depths may be attributed to the embedment of pile in the underlying sand layer. In such case, the pile heave is restricted and the pile upward movement is minimum. Depths of 20, 25, and 30 m pose high values of heave, as the pile toe is embedded in expansive soil.

Net free field heave versus time for different depths of active zone is presented in Fig. (8). A slightly sagging increasing trend of the

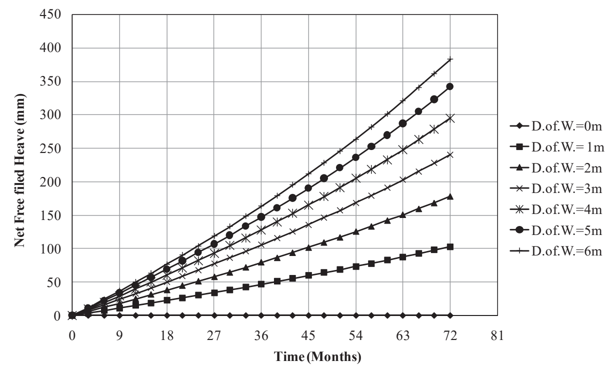

Fig. (5): Effect of Depth of Wetting on Free Field Heave.

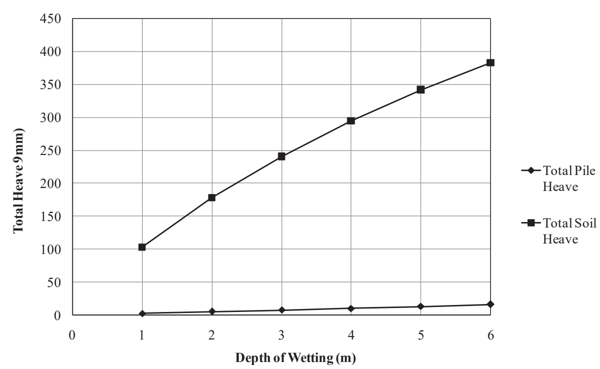

Fig. (6): Total Heave for Different Depths of Wetting.

free field heave is noticed with time, for all depths of the active zone. At 5m depth, the net free heave is significantly lower than the values at other depths.

Total net pile and free heave at end of the studied time period (six years) are shown in Fig. (9). The clear difference between free field and pile heave emphasizes the effectiveness of using piles in resisting heave.

4.3 Effect of Pile Length

Effect of pile lengths of: 8, 10, 12, 14, 16, 18, and 20m on pile heave are shown in.
Fig. (10). A linear increasing trend of net pile heave for different lengths is noticed with time. Also, net pile heave is inversely

proportional with the pile length. This can be explained by that as the pile length increases, surface area resisting the heave increases and consequently the heave decreases. For pile lengths of 16, 18, and 20m, curves of net heave are coinciding with a total heave value of about 10 mm. This may be attributed to that pile of these lengths, exceed the studied active zone of 15-m, and embedded in the sand layer, where heave strongly decreases.

Fig. (11) shows the final net pile heave for each pile length. The same findings from Fig. (10) can be stated here.

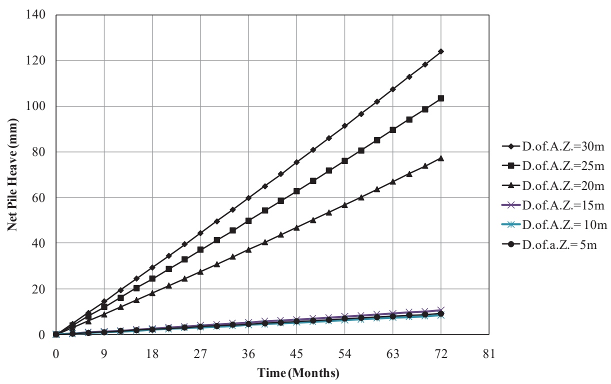

Fig. (7): Effect of Depth of Active Zone on Pile Heave.

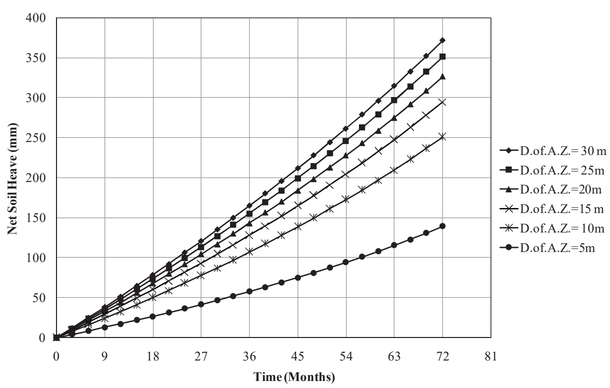

Fig. (8): Effect of Depth of Active Zone on Soil Heave.

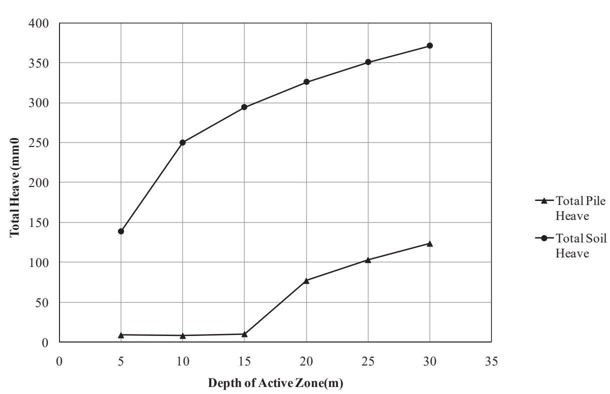

Fig. (9): Total Pile and Free Field Heave for Different Depths of Active Zone.

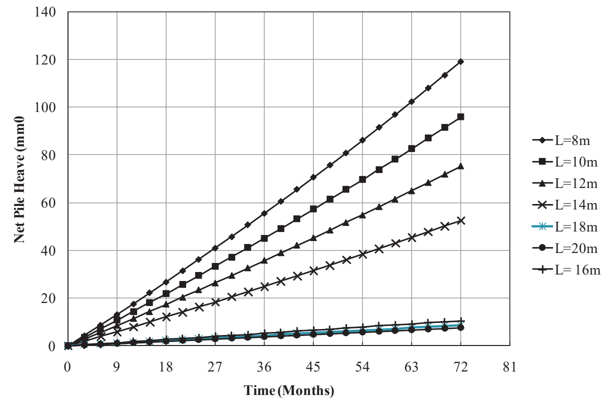

Fig. (10): Effect of Pile Length on Net Pile Heave

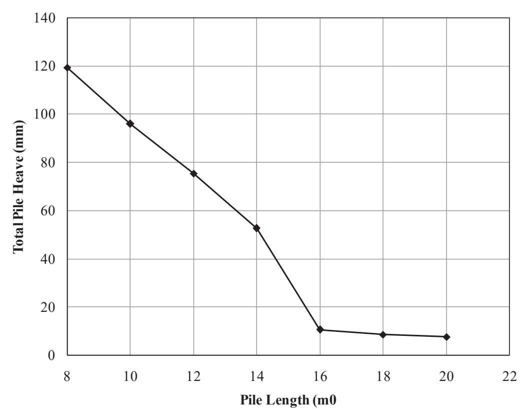

Fig. (11): Total Pile Heave for Different Pile Lengths.

4.4 Effect of Pile Diameter

The model shown in Fig. (1) is used to study the effect of pile diameter on the pile heave. Pile diameters are chosen within the practical range of 0.5, 0.6, 0.8, 1.0, and 1.2 m. Fig. (12) shows the effect of pile diameter on the net pile heave. A linear increasing trend for net pile heave is noticed with time for different pile diameters, with nearly coinciding curves for different pile diameters. The final net heave ranges between 9.5 and 10.9 mm. It seemed that pile diameter has no significant effect on the pile heave, within the same pile length. Fig. (13) presents the total net pile heave at

the end of the inundation phase for different pile diameters. The same result of Fig. (12) can be noted here.

The effect of pile diameter on piles constructed in uniform expansive soil (16-m pile length, and 30-m depth of active zone) is also studied. The results are presented in Fig. (14). From Fig. (14), it can be observed that net pile heave ranges from 123.6 mm for a 0.50 m pile diameter, to 119.7 mm with 1.20 m pile diameter. The same result of Fig. (12) can be observed here, that there is no considerable effect of pile diameter on the computed pile heave, within the same pile length.

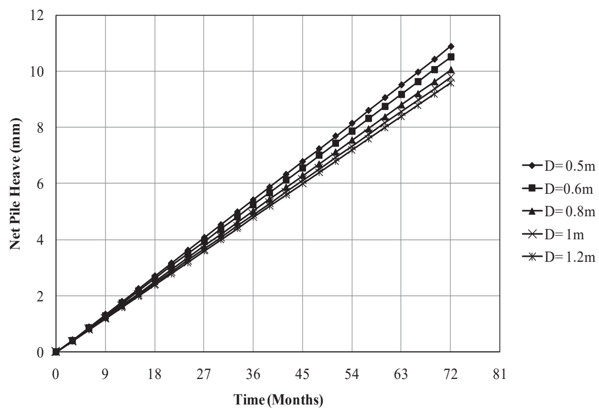

Fig. (12): Effect of Pile Diameter on Pile Heave (Piles Embedded in Sand).

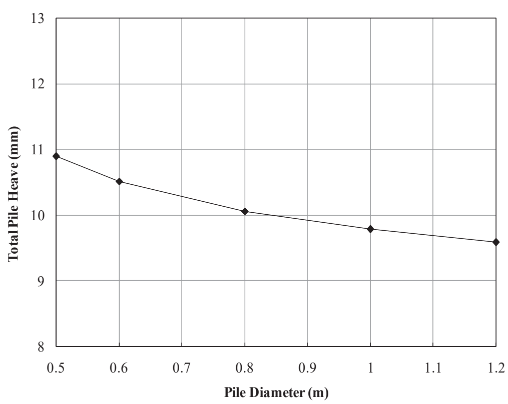

Fig. (13): Total Pile Heave for Different Pile Diameters (Piles Embedded in Sand).

4.5 Effect of Pile Loading

The model shown in Fig. (1) is used to study the effect of pile loading on net pile heave. Pile loading of 300, 400, 500, 600, 800, 900, 1000, 1100, 1200 kN are applied. As shown in Fig. (15), curves of net pile heave for different loading are coinciding. The total pile heave at the end of the computed heave time-period is depicted in Fig. (16). The same finding from Fig. (15) can be stated herein.

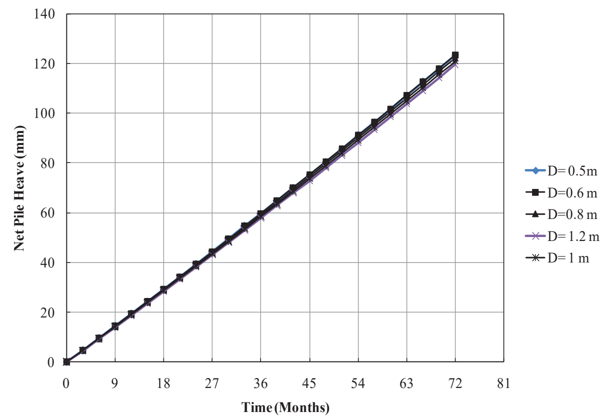

Fig. (14): Effect of Pile Diameter on Pile Heave (Piles Embedded in Expansive Clay).

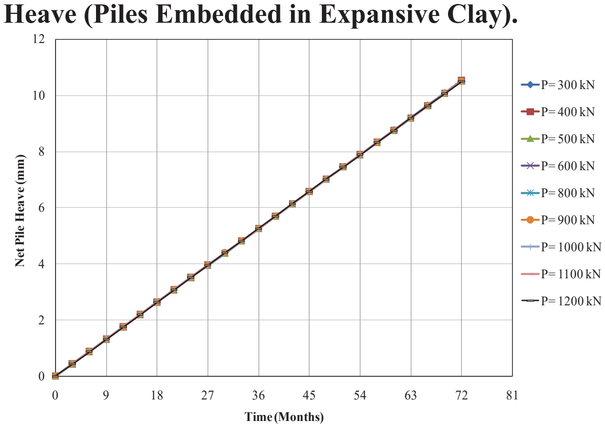

Fig. (15): Effect of Pile Loading on Pile Heave (Piles embedded in Sand).

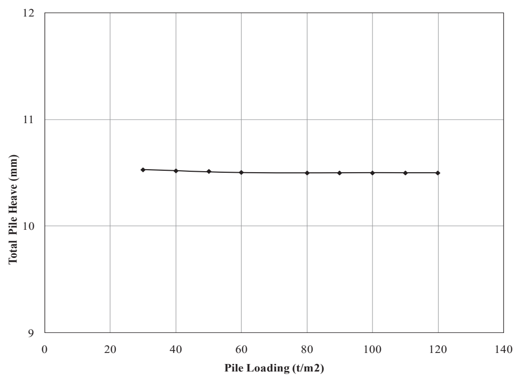

Fig. (16): Total Pile Heave for Different Pile Loading (Piles embedded in Sand).

Effect of Loading on net pile heave on piles constructed in uniform expansive soil is also studied as shown in Fig. (17). From Fig. (17), a slight reduction in heave due to increasing the pile loading is noticed. The total pile heave at the end of the computed heave time-period is depicted in Fig. (18). The same finding from Fig. (17) can be stated herein.

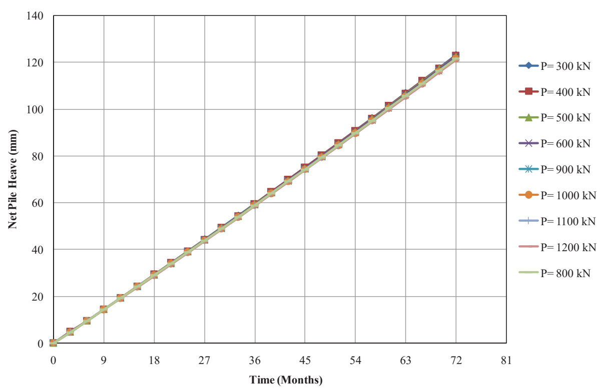

Fig. (17): Effect of Pile Loading on Pile Heave (Piles in Uniform Expansive Clay).

The result of inconsiderable effect of loading in reducing the heave may be attributed to the high depth of active zone. This depth is up to 15 m which causes high swelling pressure. This pressure in turn resists the settlement of the applied loading in such soil.

4.6 Effect of Soil Drying

Drying of the heaving soil is accounted for in the analysis, and consequently the related decrease in heave is computed. Depths of

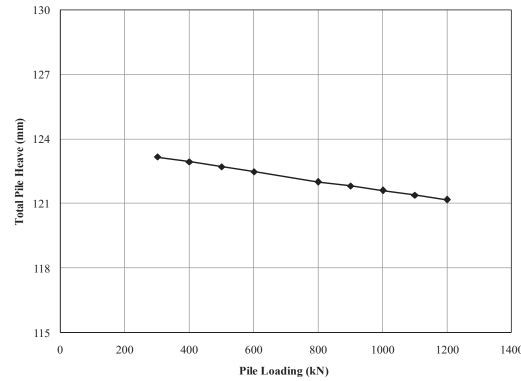

Fig. (18): Total Pile Heave for Different Pile Loading (Piles embedded in Expansive Clay).

wetting decreasing from 4, to 3, 2, 1, and zero meters are studied to identify the effect of pile

loading within the drying soils. For loading values of 50, 100, 300, 400, 600, 900, and 1200 kN, the net pile heave is computed for each depth of wetting.

Fig. (19) presents the computed heave for each depth of wetting. The same trend of decreasing heave is noticed for different loading values. Soil nearly settled with the same value, through drying from 4 to 3-m, and from 3 to 2-m depth of wetting. However, it settled through drying from 2 to 1-m depth of wetting, by nearly the double value resulted of drying from 4 to 3, or 3 to 2-m. A stable movement is noticed from 1-m depth of wetting, where no movement is concluded.

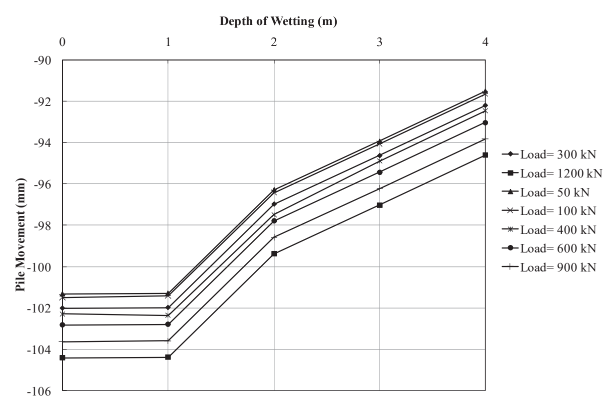

Fig. (19): Computed Heave for Decreasing Depth of Wetting.

4.7 Displacement/Heave History

Tracking of pile movement since the start of

pile loading, inundation, and drying in four stages was performed. Settlement/heave for each stage was computed, and then net difference in movement between every two sequenced stages was calculated. The basic model earlier shown in Fig. (1) is studied. The pile head movements for piles embedded in sand, as well as constructed in uniform expansive soil were tracked. The results are shown in Fig. (20).

From Fig. (20), it can be seen that pile settled due to loading. Then, after exposure to inundation, it is moved upward with a heave exceeding the ground surface. For the next four stages, decreasing the depth of wetting leads to drying in the soil, where pile begins to settle again. Through the four decreasing depths of wetting, pile nearly return to its original settlement that it gained earlier due to loading, with little gain in the heave side. Generally, pile movements in uniform expansive soil; either settlement or heave, are more obvious than for pile embedded in sand.

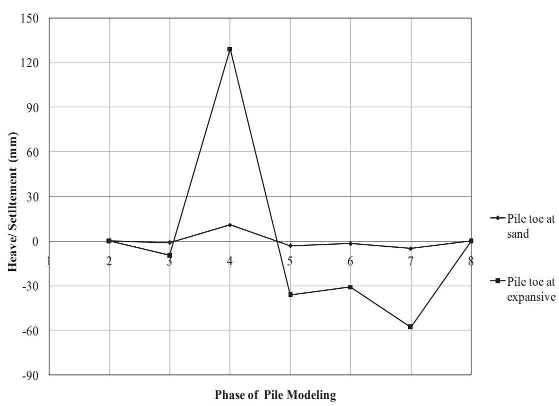

Fig. (20): Movement History of Model Pile

Phase No.	Phase
2	Pile Installation
3	Pile Loading
4	Inundation to 4m
5	Inundation to 3m
6	Inundation to 2m
7	Inundation to 1m
8	No Inundation

5. CONCLUSIONS

Based on the proposed model, depth of wetting

and depth of the active zone considerably affect the pile and the free field heaves in expansive soils. Pile and free field heave are directly proportional to the depth of wetting and the depth of the active zone. Embedding the piles in sand, even with 1.0m only, resulted in a dramatic reduction in the computed heave of piles constructed in expansive soil layers. For 5-m depth of the active zone, the free filed heave is significantly lower than the values at larger depths.

Pile diameter and pile loading seemed to have no significant effect on pile heave. However, pile length can restrict the pile heave. Pile heave is directly proportional to the pile length; whether the pile toe embedded in sand or in expansive soil.

Tracking of pile heave since pile loading, inundation, and drying the soil by decreasing the depth of wetting, showed that pile is losing the heaving movement. The pile returned to the settlement that resulted by loading, with slight heave remaining after drying.

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