ASSESSMENT OF THE UNDER-GROUND WATER LEVEL EFFECTS ON THE NONLINEAR BEHAVIOR OF SINGLE PILE SUBJECTED TO STATIC VERTICAL LOADS IN THE PRESENCE OF SOIL-PILE INTERACTION

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Abstract. *In this paper, an attempt to parametric investigation is performed to study the ground water level effects on the load-settlement behavior of large diameter pile which is subjected to vertical load at its head considering the existence of nonlinear soil-pile-interaction. A two-dimensional finite element model is used for this purpose. The soil-structure-interaction is modeled using an elastic-plastic model to describe the behavior of interfaces. Herein, five water levels (Hw=0, 3, 6, 9, 12 m) are used and also the diameter D=1m of pile is considered in two conditions as drained and undrained soil and compared with pile embedded in drained soil in absence of water. This study highlights the effects of the ground water table on the pile settlement with drained and undrained soil material; it is shown that the nonlinear required displacement to reach the ultimate bearing of the pile increases with increasing the load, and also raising the ground water level leads to increased settlement in undrained soil more than drained soil. Parametric study results shown that with decrease in the water level, the settlement of embedded pile decreased in undrained soil condition and with increasing diameter of the pile, the settlement decreased to arrive to allowable settlement in presence of water.*

1 INTRODUCTION

A pile is a structural member of timber, concrete or steel which is used to transmit surface loads to lower levels in the soil mass. This transfer may be done by vertical distribution of the load along the pile shaft or a direct application of load to a lower stratum through the pile point. A vertical distribution of the loads is made by a friction pile and a direct load application is made by a point, or end-bearing capacity of the pile. This distinction is purely one of convenience since all piles carry load as a combination of side resistance and point bearing except when the pile penetrates an extremely soft soil to a solid base [1]. Piles are deep foundations, necessary when the bearing capacity of shallow foundations is not enough to ensure the support of the superstructure. This superstructure results in vertical forces, due to its weight as well as additional loads, which are axially transferred to the pile, and through its shaft and base, to the soil, possibly reaching a stiffer layer. The analysis of the load transfer mechanism in single piles under axial loading is therefore an essential basis for deep foundation design. It is very important that the physical interaction between pile and soil is carefully studied. The settlement analysis is also fundamental, for the maximum allowable settlement of a foundation is often the most important criterion in its design. Thus, it should be estimated accurately [2]. Pile load test is a fundamental part of pile foundation design. An accurate interpretation of the pile test would be difficult unless some aspects such as whether the different types of load test or test set-up may have any side-effects on the test results is clearly understood.

Of the various numerical methods, the finite element technique allows more variables to be considered in the problem. Some researchers have considered a multi-linear soil stress-strain curve and have introduced special joint elements at the pile interface to allow for slip. The method involves discretizing of the pile and soil domains into a finite number of elements, the stiffness equations are formulated for each element and assembled together to give the global system. The appropriate constitutive models are selected to simulate the stress-strain behavior of soil so that soil in-homogeneity and nonlinearity can be studied in a rigorous manner. With the development of high performance PC, some powerful FEM programs such as CRISP and PLAXIS have been widely used in research, which made it possible that more factors can be taken into consideration so that more realistic situations can be simulated [3]. Laterally loaded piles are designed using a semi empirical technique the p-y method, which is used almost universally. The frame work of elastic–plasticity has been usually used for representing the mechanical behavior of interfaces. Relative movements between bodies in contact are described either by a local high velocity gradient or by a kinematic discontinuity. In both cases, the development of a nonlinear behavior within contact, inducing a very slow rate of convergence of the global solution except for models of thin layers. Two major kinds of constitutive equations are used for modeling the soil-structure interface behavior, often associated with the Finite Element method. The first one considers the soil-structure interface as a thin continuum [7], thus the thickness of the interface elements should then be specified.

In this paper, the finite element method (FEM) was used to carry out the research. A 2D-FEM code is developed for the numerical simulation of pile load test in the presence of soil-pile-interaction. This method has the advantage over traditional analysis techniques as more realistic test condition can be taken into account and displacements and stresses within the soil body and pile are coupled, thus more realistic pile-soil interaction behavior can be represented with more realistic assumptions. The load-settlement behavior and the ultimate load capacity of the pile are two main issues that are concerned about when conducting a pile load test. The relevant theoretical analysis of static pile load test is based on analysis of the single pile under the axial compression. With the advent of computers, more sophisticated methods of analysis have been developed to predict the settlement and load distribution in a single pile. Here, first a model of pile-soil is created regarding to the study which is mentioned in [4] and with comparing the results of the model and the field test [4], the model is calibrated and then the settlement of the pile is evaluated respect to various pile diameter, length and water level.

Figure 1. Single pile subjected to vertical load in the field test [4].

2 MODELING OF SOIL, PILE AND INTERFACE

In this paper, first a model of pile-soil is created using 2D FEM regarding to the study which is mentioned in [4-6] and with comparing the results of the model and the field test [4], the model is calibrated and then the settlement of the pile is evaluated respect to various ground water level. As it is done in [4] the bored cast-in-situ pile considered in this study is of diameter (D) 1.2m, length (L) 15m and of C30 grade concrete. The site soil is composed of clay, and soft-weathered rock. Table 1 lists the parameters of the soil stratums at the test site. The same parameters have been used for the numerical simulations. A hydraulic jack of 250T capacity was used to apply the vertical load on the pile head through a 20mm thick MS plate. The jack was supported by a 7m×6.2m loading platform made of ISMB 500 and ISMB 300 I-sections. A set of two dial gauges fixed on diametrically opposite points on the pile were used to measure the settlement as the load was applied in increments up to 8250kN. A maximum settlement of 2.56mm was observed. Figure 1 shows the pile load test being carried out for 1.2m diameter pile.

A 2D finite element code is used for this purpose. The first model is a pile with 1.2m diameter and 15m length according to [4] in order to verify the model and calibrate it. The settlements at incremental loads have been simulated and the complete load-settlement curve is calculated and the results have been compared with the field results. As it is mentioned in Table 1, the field model consists of 2 layers of soil, clay (up to 6m), and soft-weathered rock (6m to 20m); the other mechanical and physical properties of the material and soil layers in the model is shown in Table 1. Using 2D-FEM code, the large diameter vertical pile in residual soil has been modeled as an axi-symmetric domain by 15-node triangular element which results in a two-dimensional finite element model with two translational degrees of freedom per each node (see Figure 3). These 15-noded triangles provide a fourth order interpolation for displacements and the numerical integration involves twelve Gaussian points.

Property	Layer 1	Layer 2	Layer 2
Material (Depth)	Clay (0-6 m)	Soft Weathered Rock (6-20 m)	Concrete pile (15 m)
Model	Mohr-Coulomb	Mohr-Coulomb	Linear elastic
Weight, γ [kN/m^3]	21	22	25
Young modulus, E [kN/m^2]	40,000	100,000	30,000,000
Poisson ratio, υ	0.30	0.33	0.20
Cohesion, C_u [kN/m^2]	30	50	-
Friction angle, φ [$^\circ$]	20	25	-

Table 1: Soil data sets parameters.

Large diameter vertical pile in residual soil has been modelled as an axi-symmetric problem. In the model, 15-noded triangular element has been chosen which results in a two-dimensional finite element model with two translational degrees of freedom per node. The 15-noded triangle provides a fourth order interpolation for displacements and the numerical integration involves twelve Gauss points. The pile is made up of reinforced cement concrete and the behavior is assumed to be linear-elastic. The soil behavior as described by Mohr-Coulomb, and Hardening soil models is selected for preliminary analyses. After conducting multiple trials and sensitivity analyses, we conclude that the Mohr-Coulomb model is the most suitable model for all the layers of soil [14,15]. The Mohr-Coulomb model can be considered as a first order approximation of real soil behavior. This elastic perfectly plastic model requires 5 basic input parameters, namely Young's Modulus, Poisson's ratio, cohesion, friction angle and dilantacy angle. This is a basic, well-known soil model. Boundary conditions: The bottom boundary is rigid, i.e., both horizontal (u) and vertical displacement (v) are zero. Standard fixities are used at the left and right boundaries of the model. These side boundaries act likes rollers such that u=0 but $v\neq0$. Interface element: The soil-structure interaction is modelled using an elastic-plastic model to describe the behavior of interfaces. For the interface to remain elastic, the shear stress, $|\tau| < \sigma_n \tan\varphi + c_i$, where φ and ci are the friction angle and cohesion (adhesion) of the interface respectively and σ_n, the effective normal stress. The interface element properties are linked to the strength properties of the soil layers. The main interface parameter is the strength reduction factor Rinter. A strength reduction factor of 1 is used [4]. The pile is made of a reinforced cement concrete and its mechanical behavior is assumed to be linear-elastic and the soil behavior is described by Mohr-Coulomb model. In this model a set of Dirichlet boundary conditions is employed for the bottom side of the model (i.e., both horizontal and vertical displacement are zero at it), also, standard fixities are used at the left and right boundaries of the model and the top side of the soil is modeled using Neumann boundary conditions which are traction free surface (Figure 2).

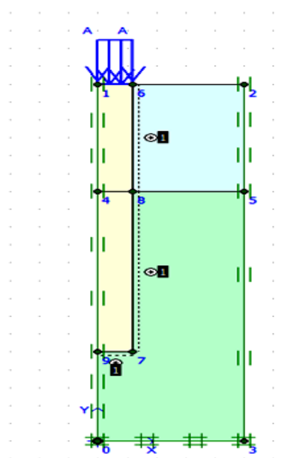

Figure 2. The two-dimensional built model with applied vertical load in FEM code.

The soil-structure interaction is modeled using an elastic-plastic model to describe the behavior of interfaces. The interface element properties are linked to the strength properties of the soil layers and the main interface parameter is the strength reduction factor Rinter (e.g., the strength reduction factor of 1 is used).

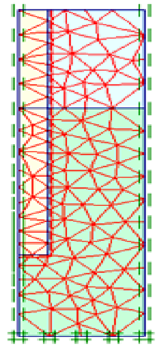

Figure 3. Discretizing the model using a set of 15-node triangle elements and the interface elements of between soil and pile.

As is shown in Figure 3, a global coarseness parameter as well as a local parameter is used while generating a mesh. The average element size and the number of generated triangular elements depend on the global coarseness setting. The global coarseness setting of medium, with 328 triangular elements, was found to be most suitable. Situations where some areas have large stress concentrations or large deformation gradients require the use of the local coarseness parameter, this gives the element size relative to the average element size as determined by the global coarseness setting. Figure 4 is depicted the results from the two-dimensional model which is built in this study and also the field test from [4]. This implies that numerical simulation is applicable where explains a good agreement between the results from the model in the present study and the field test. It is also noticed that field curve has shown a different shape starting from 2mm settlement, which may be attributed to field test problems.

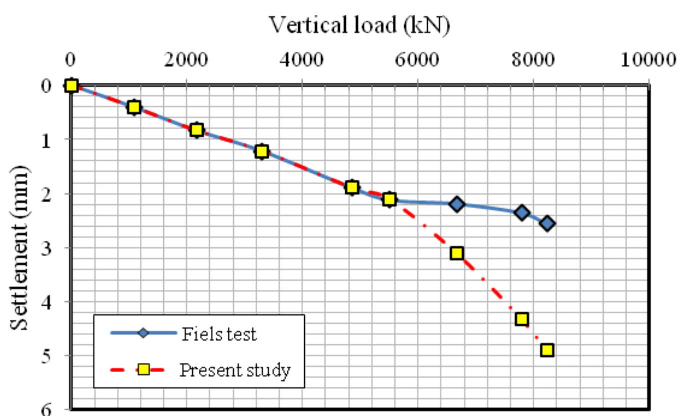

Figure 4. The results of the Load-Settlement Curve for the pile regarding field study [4] and the present study.

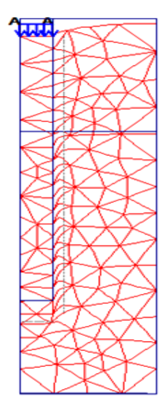

Figure 5. Deformed shape of the soil-pile due to the vertical load which is subjected at the head of the pile.

Figure 5 shows the deformed shape of the pile-soil interaction problem corresponding to 4.91mm settlement which is evaluated in the present study and the 2-D model; this figure shows that the maximum settlement of is occurred around the head of the pile and with increasing the depth, this displacement is reduced.

3 ASSESSMENT OF PILE ASPECT RATIO ON THE SOIL RESPONSE

According to Figure 4, one can see that model which is made based on the field test [4] works well in the present modeling and after this verification we can do the main goal of the present study which is assessment of the ground water level (Hw) on the settlement of the soil and pile under vertical loads; in this regard, five water levels are used as Hw=0, 3, 6, 9, 12 m and also the diameter of pile D=1m is considered in two state as drained and undrained soil and compared with pile embedded in drained soil in absence of water (Hw = 20 m). Each specimen is named as *USHWr* and *DSHWr*, where *U*, *D* and *r* are mentioned respectively the undrained, drained and level of the ground water; for example, USHW20 means an embedded pile in undrained soil with 20m water level. Based on what is explained in section 2, many two-dimensional models are created using FEM-code and in each model the settlement of the soil and pile is considered; in this study the ultimate vertical load that is applied to the head of the piles is 8232 kN.

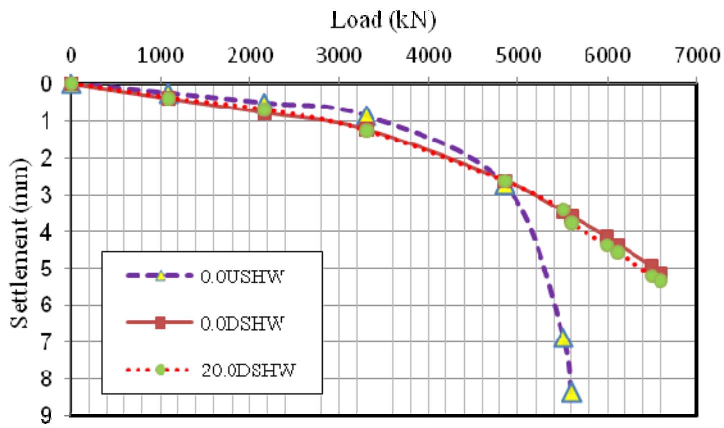

Figure 6. Load-settlement curves for the pile with L=15*m* and D=1*m* and Hw=0*m*.

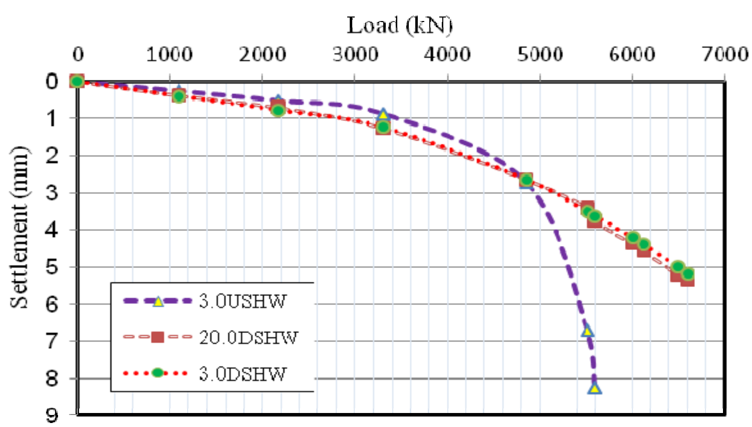

Figure 7. Load-settlement curves for the pile with L=15*m* and D=1*m* and Hw=3*m*.

Figures 6-10 show the effect of variation of the water level on piles with length L=15*m* and diameter D=1*m* under vertical load. Figure 6 depicts the load-settlement variation for piles with L=15*m*; as is clear from these curves, the pile with presence of water and saturated soils for soil undrained condition, compared to the drained soil, the settlement of pile is increased and the static bearing capacity of pile is decreased. Figure 7 also captures similar results for piles with Hw=3*m*, Figure 8 for piles with Hw=6*m*, Figure 9 for piles with Hw=9*m* and Figure 10 for piles with Hw=12*m*. Also, numerical results of settlement of the pile in undrained condition are presented in Table 2.

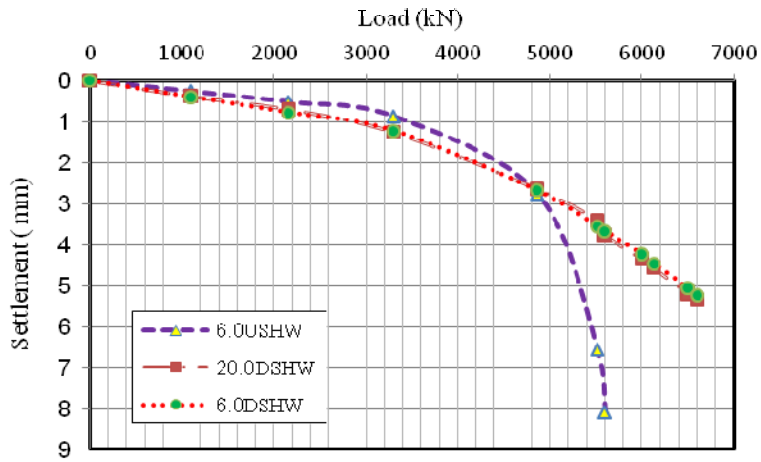

Figure 8. Load-settlement curves for the pile with L=15*m* and D=1*m* and Hw=6*m*.

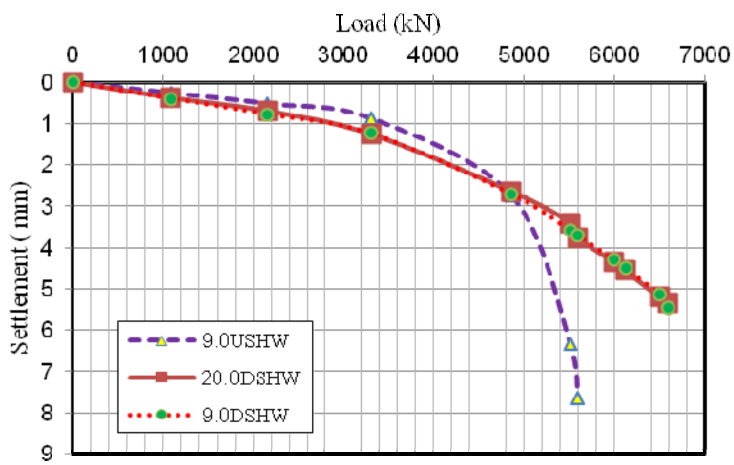

Figure 9. Load-settlement curves for the pile with L=15*m* and D=1*m* and Hw=9*m*.

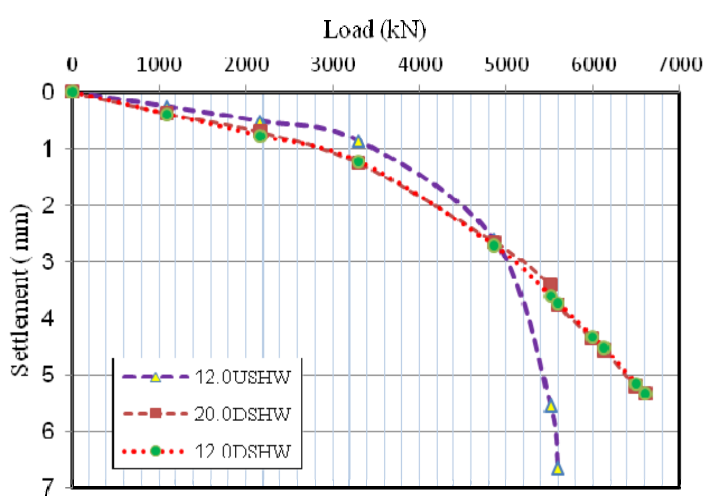

Figure 10. Load-settlement curves for the pile with L=15*m* and D=1*m* and Hw=12*m*.

Ground water level (Hw)	**0(*m*)**	**3(*m*)**	**6(*m*)**	**9(*m*)**	**12(*m*)**
Settlement (mm)	8.37	8.24	8	7.64	6.66

Table 2: Settlement of the pile for variation ground water level for undrained soil (D = 1*m*).

In Figure 11, curves of load–displacement based on changes in the level of ground water in undrained soil compared to drained soil in absence of water are drawn, and obviously difference is observed in increase of settlement, in presence of water, from the absence of water. Finally, by increasing the diameter of the pile, the settlement reduced to reach to allowable settlement in the presence of water and undrained condition, and these results are presented in Figure 12 and Table 3.

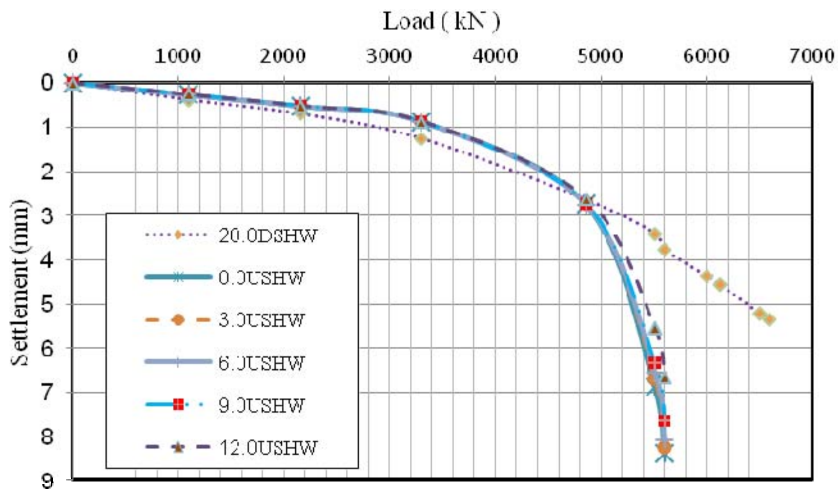

Figure 11. Load - Settlement curves for undrained soil with respect to variation of water level, for the pile (with L=15 *m*, D=1 *m*).

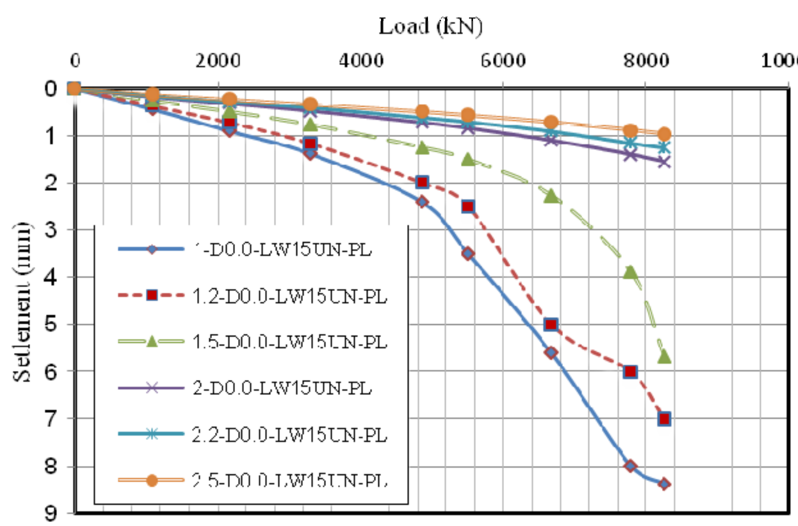

Figure 12. Load - Settlement curves for undrained soil with respect to variation of pile diameter (Hw = 0 *m*, undrained soil).

Pile diameter (*m*)	**1(*m*)**	**1.2(*m*)**	**1.5(*m*)**	**2(*m*)**
Settlement (mm)	8.37	7	5.67	1.55

Table 3: Settlement of the pile for variation of diameter (Hw = 0 *m*, undrained soil).

4 CONCLUSIONS

The vertical loaded pile is studied using a two-dimensional axisymmetric finite element model at the existence of the nonlinear soil-pile-water interaction and effects of soil nonlinearity. The described parametric study includes the assessment of the effects of ground water level (Hw) drainage condition (undrained and drained soil) on the settlement. It can be concluded that there is good comparison of load–displacement relation obtained through field-test and that obtained by FEM. Results show that settlement of pile in saturated undrained soil increases with increased level of water. Parametric study results show that with decreasing in the water level, the settlement of embedded pile decreased in undrained soil condition and with increasing diameter of the pile, the settlement decreased to arrive to allowable settlement in presence of water; also, drainage is more effective in order to reduce the amount of the settlement.

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