Numerical Analysis of Shaft Resistance and Toe Resistance of a Pile in Unsaturated Soil

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Introduction: Piles transfer structural loads to the ground (1) at the surface of their shafts and (2) at their toe (Fig.1). In the calculation of these two components of load transferred from a pile to the soil mass, both the deformation characteristics and the strength properties of the soil need to be taken into consideration. In unsaturated soils, matric suction changes the stress-strain-strength behavior of the soil. Similarly, the adhesion and the friction angle at the contact area between the soil and the pile shaft are affected by the changes in matric suction. In this paper, the effect of soil suction on the shaft resistance and toe resistance of a pile is examined. The pile under consideration is described by Georgiadis et al. (2003). In the present study, soil-pile interaction is analyzed as a contact mechanics problem using COMSOL. The pile is 20 m long and its diameter is 1m. The pile is embedded in the soil with linearly varying matric suction between the ground surface and the GWT which is at D=10m (Fig. 2).

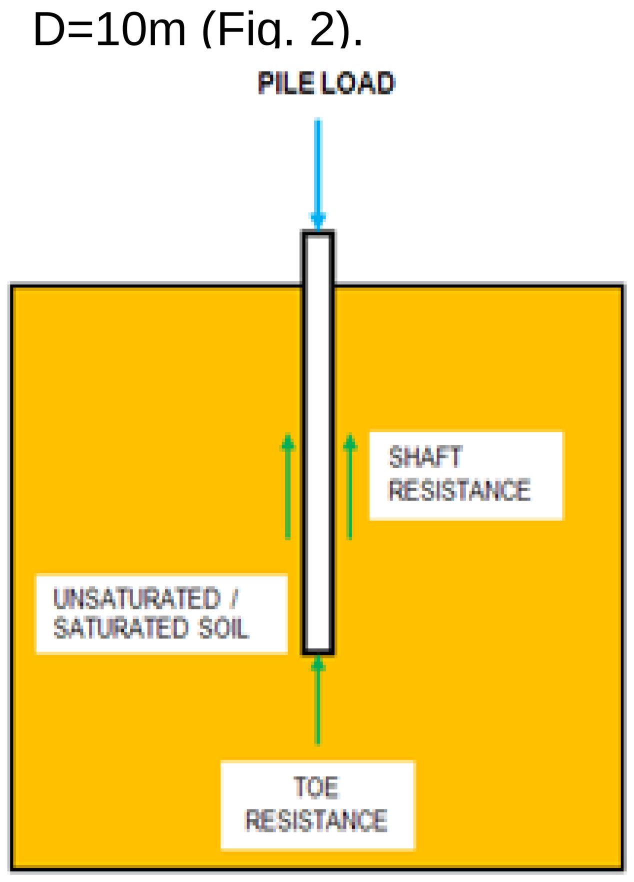

Figure 1. Load transfer from a structure to soil mass.

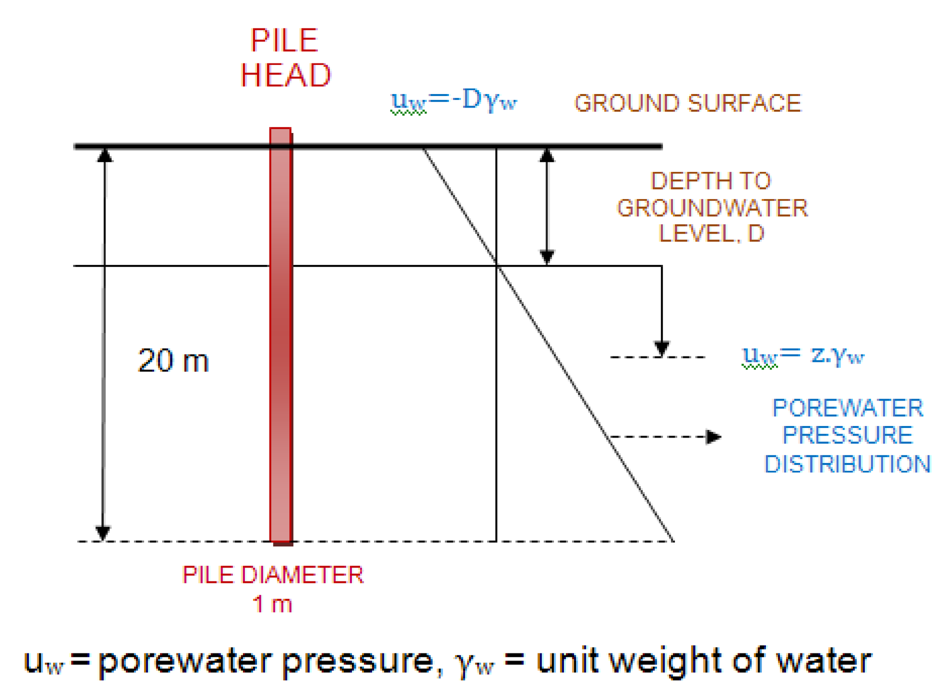

Figure 2. Pile dimensions and pore water pressure distribution.

A solution of this problem requires the simultaneous use of Structural Mechanics, Geomechanics modules and the Contact Mechanics option. The modulus of elasticity of soil in unsaturated state is calculated using an equation by Oh et al. (2009). Shear strength of soil is calculated by using an equation proposed by Vanapalli and Fredlund (2000). The elastic modulus and shear strength values used in this study are shown in Figs. 3 and 4.

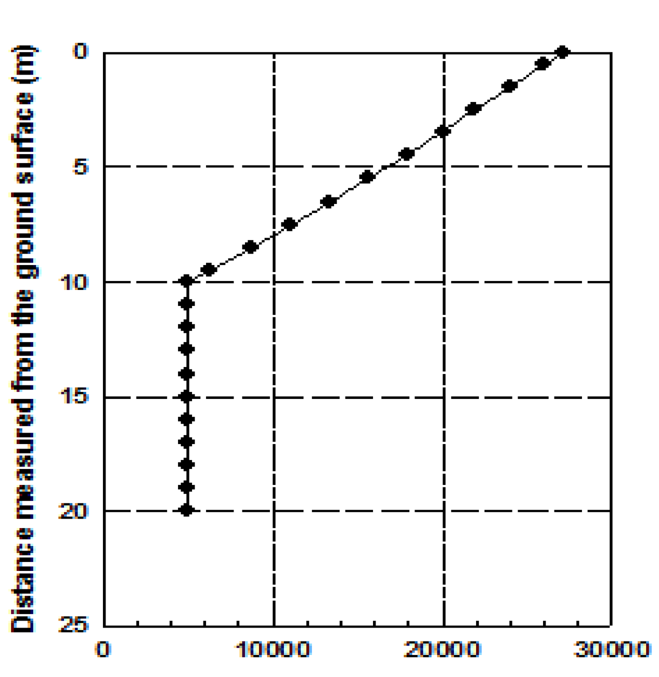

Figure 3. Elastic modulus of soil as a function of depth.

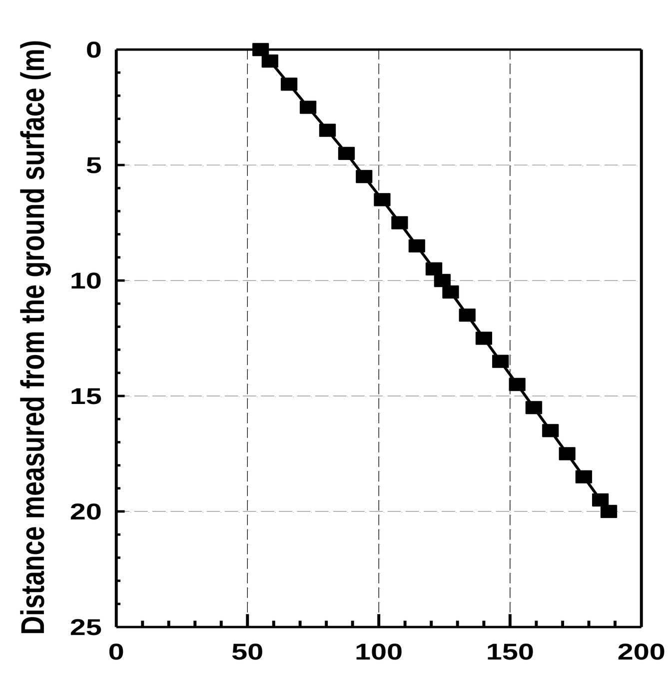

Figure 4. Shear strength of soil as a function of depth.

Model parameters for the saturated soil mass are taken from Taylan et al. (2012). As shown in Fig. 3, the elastic modulus is 5e6Pa in saturated soil mass.

Computational Method: The methodology for calculating the shaft resistance of a pile is described in a paper by Infante et al. (2012) published in COMSOL 2012 Conference. The pile to be analyzed is divided into a convenient number of sections. In the analysis of this pile, each section is 1 m high and the total number of sections is twenty (Fig. 5). These sections are subjected to a different magnitude of lateral earth pressure, which depends on the location of a pile section from the ground surface. The contribution of each pile section to the shaft resistance of the entire pile was determined by analyzing each section separately. In the calculation of the toe resistance, the analysis was performed for the whole pile. Identity pairs are used for the pile toe and the toe resistance (load) is calculated by integration of stresses in the vertical direction.

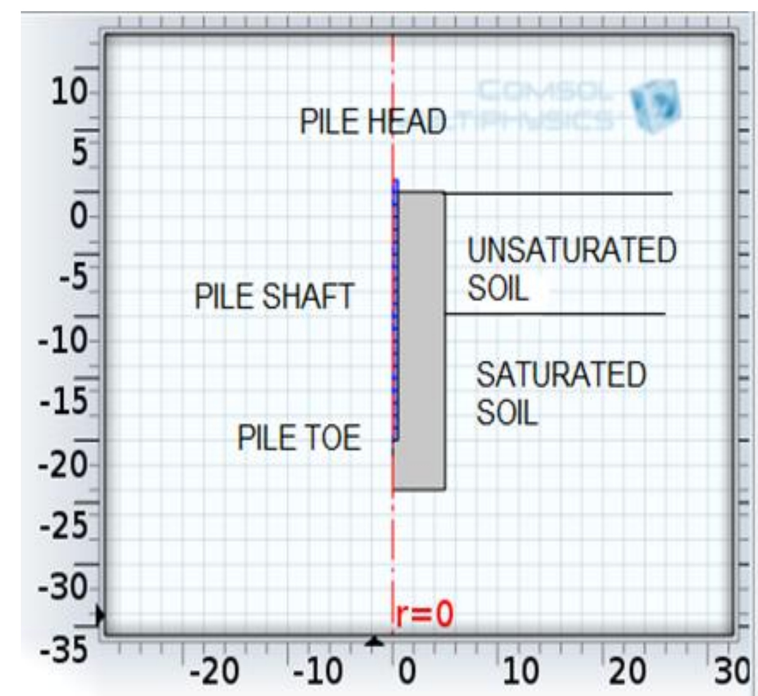

Figure 5. Pile sections used in the analysis.

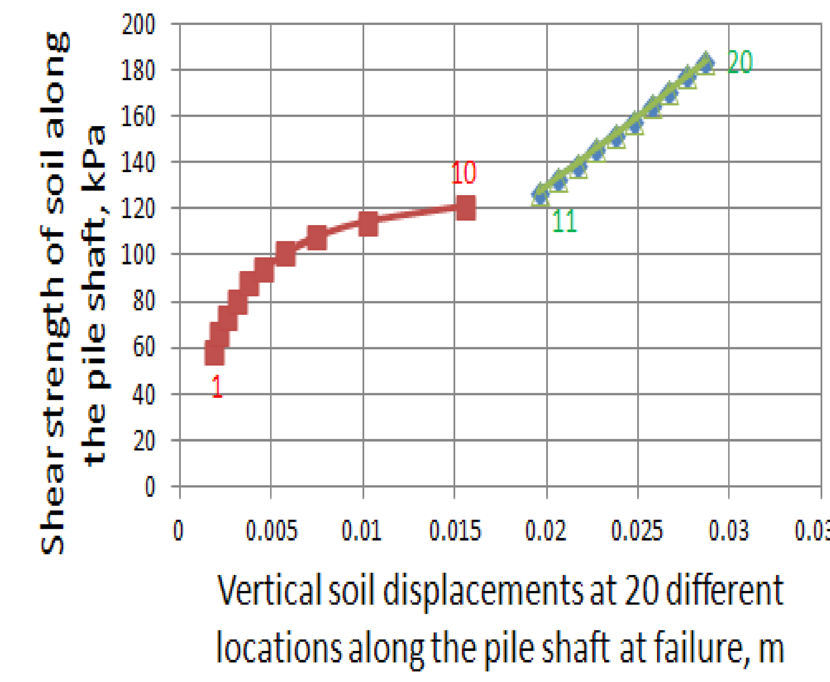

Figure 6. Shear strength of soil and the vertical displacements required for failure at 20 different locations along the pile shaft.

Results: Calculated values of maximum values of shear stress are plotted in Fig. 6. Figure 7 shows the total shaft resistance as a function of vertical displacements of the pile head. At any given pile head movement, the sum of the resistance of each pile section gives one point on the total shaft resistance versus displacement curve. Details of the procedure can be found in Infante et al. (2012). The total shaft resistance calculated by COMSOL in the present study is 7722kN and it compares well with 7740kN determined by textbook calculations.

The toe resistance was rather small. At 0.1m pile head movement, the contribution to the pile capacity was about 500kN. The effect of toe resistance on the total load versus pile head displacement can be seen by comparing Fig. 7 and Fig. 8.

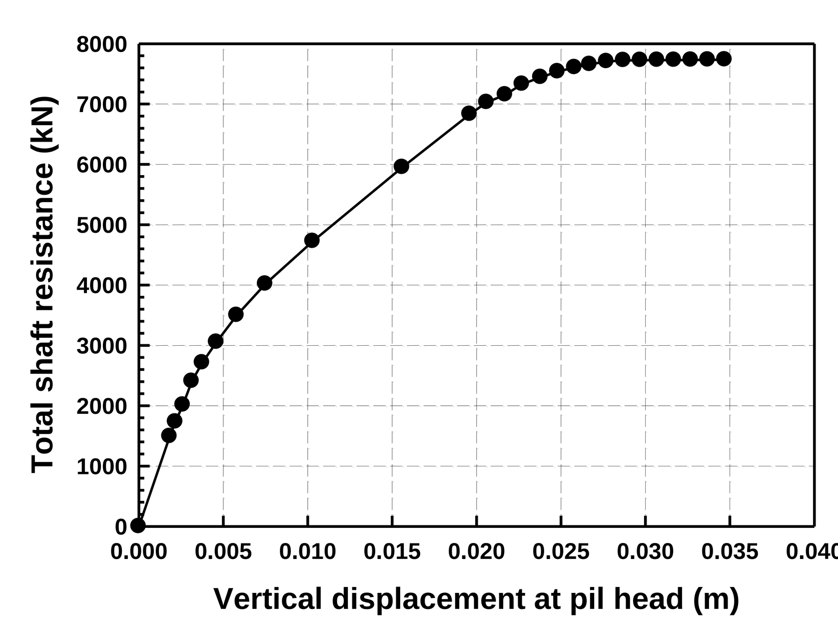

Figure 7. Shaft resistance versus vertical movement of pile head.

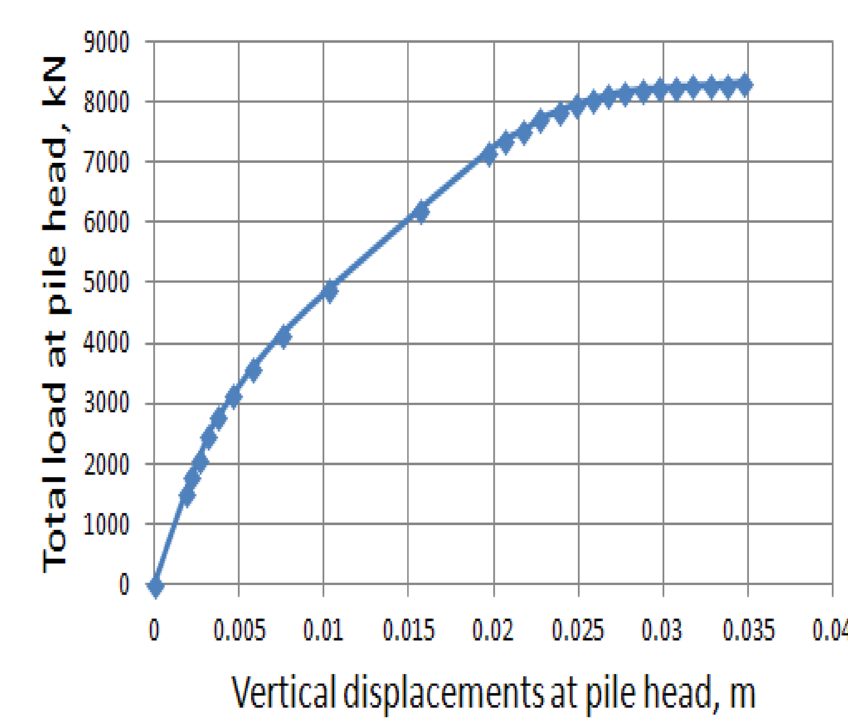

Figure 8. Total load versus displacement at pile head.

Conclusions:

The toe resistance and the shaft resistance of a pile can be calculated, with reasonable success, using the Contact Modeling capabilities of COMSOL Multiphysics code. The amount of vertical movement at the pile head for any specified load can be determined for piles in both unsaturated/saturated soils. In future studies, however, the modeling of the nonlinear, stress level dependent soil deformation properties should be considered.

References:

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