Simulation of collapsible soils subjected to inundation
La simulation des sols affaissables soumis à l'inondation

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ABSTRACT
This paper presents an innovative procedure to model collapsible soil before-during-after inundation using the finite element method. The proposed numerical model can easily be implemented to analyze the case of shallow or deep foundations on/in collapsible soils. The model developed takes into account soil suction reduction resulted from progressive inundation, from two different aspects: soil stress state and its properties, and irrecoverable volume change of the soil. The theories of Unsaturated Soil Mechanics, including Soil Water Characteristic Curve (SWCC), are employed to take into account the effects of inundation on collapsible soil properties. For illustration purpose, numerical modeling of a single pile in collapsible soil before-during-after inundation is presented.

RÉSUMÉ
Cet article présente une méthode originale pour la modélisation des sols affaissables avant, pendant et après l'inondation en utilisant la méthode des éléments finis. Le modèle numérique proposé peut facilement être mis en application pour analyser le cas des fondations superficielles ou profondes fondées sur ou dans des sols affaissables. Le modèle développé prend en considération la réduction de la succion capillaire du sol, résultant de l'inondation progressive, de deux aspects différents : l'état des contraintes du sol et ses propriétés, et le changement irréversible du volume de sol. Les théories de la mécanique des sols partiellement saturés, y compris la courbe de caractéristiques sol-eau, sont utilisées pour prendre en considération les conséquences de l'inondation sur les propriétés des sols affaissables. Dans le but d'illustrer cette simulation, la modélisation numérique d'un pieu simplement chargé dans un sol affaissable et soumis à l'inondation est présentée.

Keywords : collapsible soil, matric suction, volume change, stress-state, inundation, finite element.

1 INTRODUCTION

Collapsible soils form large parts of Canada, the United States, Eastern Europe, China, South East Asia, and Africa (Derbyshire et al. 1995). As human activities continue to increase in these regions, geotechnical engineers must learn how to deal with difficult soil (Brandon et al. 1990; Lim and Miller 2004; Ayadat and Hanna 2007 & 2008). Collapsible soils are known to experience significant volume decrease due to the increase of soil moisture content, with or without an increase in the in situ stress level (Clemence and Finbarr 1981). This significant decrease in volume is due to the drastic decrease in its lateral stress within the soil mass and the deformations in both the vertical and the lateral directions. Soils susceptible to collapse include loessial soils, weak cemented sands and silts, certain residual soils, and fills. Granular material with angular particles compacted on the dry side of the optimum moisture content can form a structure that is susceptible to further densification or collapse (Tadepalli and Fredlund 1991). Lawton et al. (1992) reported that nearly all types of compacted soils are subjected to collapse upon wetting. Empirical formulas were presented to identify collapsible soils (Lutenegger and Saber 1988; Lawton et al. 1992). Ayadat and Hanna (2007) proposed a simple method to identify collapsible soils based on the results of the cone penetration test.

For relatively light structures, the use of shallow foundations combined with soil replacement or soil treatment may constitute economical designs. However, in the case of heavy loads and deep strata of collapsible soils, pile foundations driven to an existing bearing stratum underlying the collapsible soil layer is perhaps the only alternative available. Nevertheless, the presence of collapsible soil layer may affect the capacity and performance of these piles during the lifespan of the structure. Piles driven in collapsible soils will experience sudden reduction in their bearing capacity and further excessive settlement of the foundations during inundation. This is due to sudden decrease in soil stiffness and in lateral support along the pile's shaft (Lawton et al. 1991), which constitutes one of the major challenges in the modeling of this condition.

In the literature, little work can be found for foundations on/in collapsible soils. This is mainly due to the high cost and the length of time it involves and the difficulty associated in achieving sensible results (e.g., Gan and Fredlund 1988; Escario and Juca 1989; Vanapalli et al. 1996).

While numerical modeling may sound appealing to researchers, developing numerical models to simulate the case of unsaturated soil, especially during inundation is difficult at best. To date, a few numerical studies involving the development of computer programs for coupling stress equilibrium and water flow for unsaturated soil can be found in the literature (Miranda 1988; Pereira 1996). This is due to the difficulties associated in developing constitutive relations to describe the behavior of collapsible soil. Furthermore, most of the available computer programs for saturated soil do not take into account the consequences of the transient unsaturated-saturated water flow.

2 SIMULATION OF COLLAPSIBLE SOIL USING PLAXIS

The collapsible soil can be modeled as a linear elastic-perfectly plastic with stress dependent properties, strain softening and irreversible load deformation response at a given degree of saturation. Its behavior can be defined as drained material, which can be modeled by Mohr-Coulomb (MC) constitutive law. MC model operates with five material parameters, including two elastic parameters: namely, Young's modulus (E) and Poisson's ratio (υ); and three plastic parameters: namely,

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angle of shearing resistance (φ), cohesion (c) and angle of dialatancy (ψ). For saturated soils, these five parameters are reasonably constant, but vary significantly for unsaturated soils including collapsible soil, when soil matric suction is reducing as a result of increasing degree of saturation during inundation. In developing the numerical model, it is understood that PLAXIS does not take into consideration matric suction, which is the governing state variable of unsaturated soil, and its effects on soil parameters during inundation, accordingly (Brinkgreve 2002). For example, strength properties of collapsible soil subjected to inundation can only be explained by the extended Mohr-Coulomb theory that takes into consideration both the net mean stress and the matric suction.

The present study utilizes two independent stress state variables: namely, net normal stress (σ -u_a) and matric suction ($u_a - u_w$); for predicting the stress state of collapsible soil at any stage of inundation. Pereira and Fredlund (2000) have shown that the majority of the collapse settlement takes place within the range of 30-80% degree of saturation. Pereira (1996) and others stated that the relationship between collapse settlement and degree of saturation is linear during inundation. In this investigation, it is then expected that six stages, starting at 30% and ending at 100% degree of saturation, will establish the behavior of collapsible soil before-during-after inundation. Accordingly, the effect of inundation will be included in the proposed numerical model by applying the volume change and the modified stress state in the soil mass throughout these six stages. Furthermore, at each stage, inundation induced volume change (collapse settlement) will be incorporated as “prescribed displacement” applied vertically on the soil surface. This prescribed displacement will be estimated knowing the void ratio state surface and the collapse potential following the procedure given by Ayadat and Hanna (2008). The corresponding changes in the stress state are estimated and are incorporated by reassigning the soil properties as described below in this paper.

Soil water characteristic curve (SWCC) plays an important role in the implementation process of the proposed procedure. SWCC defines the amount of water in soil in terms of gravimetric water content, volumetric water content, water degree of saturation, normalized water content or dimensionless water content in the soil, as a function of matric suction. It can also be determined using the grain size distribution following the procedure described by Fredlund (2006).

The cohesion and the angle of internal friction can be determined at any degree of saturation with the use of SWCC using equations (1) and (2) given by Fredlund and Rahardjo (1993) and Futai et al. (2006), respectively. Furthermore, the angle of dilatancy is taken as (φ-30°).

$$c = c' + (u_a - u_w)\tan\varphi^b \tag{1}$$

where c' = cohesion at saturated condition; $\tan\varphi^b$ = slope of the shear strength vs. matric suction relation; c = intercept of the extended Mohr-Coulomb failure envelope at a specific matric suction and zero net normal stress.

$$\varphi(\psi) = \varphi' + \{\varphi_{\max} - \varphi'\}\{1 - 10^{b(u_a - u_w)}\} \tag{2}$$

where $\varphi(\psi)$ = variation of frictional angle due to changes in matric suction; φ' = effective frictional angle at saturated condition; $\varphi_{\max}$ = maximum frictional angle at ($u_a - u_w = \infty$); b = friction angle adjustment factor.

Modulus of elasticity will be predicted at any degree of saturation for a given void ratio following Reznik (2007). In the literature, no methods were found to determine the values of Poisson ratio as a function of matric suction. Nevertheless, Pereira (1996) applied an incremental increase of Poisson ratio based on the void ratio function. Accordingly, at any level of inundation, the unit weight of collapsible soil can be estimated for a given volume and the initial unit weight. During inundation the initially unsaturated collapsible soil will change from normally consolidated state towards the overconsolidated state. The coefficient of earth pressure at rest (K_0), determined for overconsolidated soil using the formula proposed by Hanna and Al-Romhein, (2008), will be used to generate initial stress condition.

3 AN EXAMPLE NUMERICAL MODEL USING PLAXIS

The case of a single pile, 20m long and 0.5m in diameter, that penetrates the upper layer of a 14 m deep, homogeneous collapsible soil (red loess from North-Eastern Thailand, reported by Udomchoke (1991)) and that is supported by a deep bed of medium dense sand (from Kolar and Nemec (1989)), is taken for the illustration of the present numerical model. Groundwater table was located at the bottom of the collapsible soil layer. This example simulates the effects of the gradual saturation process of the upper unsaturated and highly porous collapsible soil layer due to capillary action resulted from the GWT. Red loess shows a severe volume decrease or collapse, of approximately 18% of its initial volume, due to an increase of moisture content from 2.4% (corresponds to its initial state) through 11%.

An axisymmetric finite element model, where the centerline coincides with the pile axis, is developed to simulate the case of a single pile under the vertical loading and the soil conditions stated above. To avoid stress confinement, the vertical boundary is placed at a distance of 25 m, which is taken as the longest of 25 times the pile’s diameter (D) or 0.6 times the pile’s length (L) as proposed by Trochanis et al (1988). The vertical boundaries are restrained in the horizontal direction. The bottom of the model is placed at 34 m (equivalent to 0.7L below the pile tip) from the ground surface (Hanna and Sharif 2006). These dimensions are found sufficient, as no Coulomb plastic points are found near the boundaries. The nodes along the bottom of the mesh are restrained in the horizontal and the vertical directions. The pile is assumed to behave elastically. The pile cluster is modeled as volume elements of non-porous material with Linear-Elastic (isotropic) constitutive relation. Table 1 presents pile input data used in this example.

Table 1. Pile input data.

Length, L (m)	Diameter, D (m)	Modulus of Elasticity, E_p (kPa)	Poisson ratio, υ_p	Unit weight, γ_c (kN/m^3)
20	0.5	3E+07	0.33	24.5

Table 2. Soil data input of red loess and medium dense sand at initial condition.

Soil	Red Loess	M. dense sand
Depth (m)	0 – 14	14 – 34
Modulus of Elasticity E_s (kPa)	20000	40000
Poisson’s Ratio υ_s	0.3	0.3
Unit weight γ (kN/m^3)	14.8	20.0
Cohesion c (kPa)	50	1
Angle of internal friction φ (°)	29	35

Soil is assumed to have a linear elastic-perfectly plastic stress-strain relationship, as defined by Mohr-Coulomb failure criteria. This assumption is confirmed by Hanna and Sharif (2006). Drained condition is assumed, when the soil is in unsaturated state and of sandy type. Table 2 presents data input of Khon Kaen red loess (initial unsaturated state) and medium dense sand (saturated state) as well. The mesh is generated by 15 node triangular elements with medium global coarseness. The soil mesh is refined locally around the pile's shaft, where deformation and stresses were expected to vary significantly. To account for the relative pile-soil movement, interface rectangular elements having five pairs of nodes are placed at the pile-soil interface, connecting the pile elements to the soil elements. The use of these elements captures a realistic interaction between the pile surface and the soil during loading phase. These elements having a virtual thickness, having each node pair take the same coordinates. Interface elements are formulated to behave as linear elastic-perfectly plastic, governed by Mohr-Coulomb criteria. The basic properties of these elements are similar to that of the surrounding soil. The angle of pile-soil friction is taken as 90% of the angle of shearing resistance of the surrounding soil. To avoid stress oscillation at the pile tip, interface elements were extended for 0.5m below the pile tip inside the soil body. However, to prevent an unrealistic weakness in the soil mass, this zone was given the properties of the soil with full strength rather than those of the top part of interface, which was assigned along the pile shaft with reduced strength. The numerical model was validated for the cases of pile foundations in dry and saturated homogeneous soils, where good agreements were achieved. Numerical results are compared against the well-established theories for bearing capacity. Table 3 presents typical calculation phases for simulating the pile installation, the application of pile load and the subsequent inundation of collapsible soil. In this example, volume change and reduced strength parameters are known from experimental results reported by Udomchokhe (1991).

The entire process of inundation is discretized into three critical inundation stages. Stage 1 (the major collapse phase), Stage 2 (the reduced collapse phase) and Stage 3 (the slight collapse phase) correspond to calculation phases III, IV and V, respectively. In PLAXIS Input program, four material datasets (namely, $CS_{initial}$, CS_{III}, CS_{IV} and CS_{V}) are created for collapsible soil for three stages of inundation. $CS_{initial}$ is assigned to define the initial state of collapsible soil. On the other hand, only one data set is used to assign properties of medium dense sand to the cluster underlying the collapsible soil layer, as the properties of sand layer remains unchanged in all calculation phases.

Initial phase is defined by a general phreatic level, developing a hydrostatic pore pressure distribution in medium dense sandy soil and the full depth of collapsible soil layer, which has the properties of $CS_{initial}$, with zero steady-state pore pressure. Initial soil effective stresses were generated using K_0 procedure, while all clusters within the mesh boundaries are given the soil properties.

In Phase I, pile is installed by changing material properties of pile cluster with the properties given in Table 1. In Phase II, external loading on pile is applied vertically as a point load. The software PLAXIS is equipped with features to deal with numerous aspects of complex geotechnical problems such as soil-pile interaction, simulation of foundation installation and time dependent soil behavior. The program uses incremental tangential modulus with constant loading and unloading increments from known initial conditions. After each increment an interactive procedure is used to determine the current stresses and the stress dependent modules in some critical elements.

In Phase III to Phase V, volume changes are applied in staged construction through vertical 'Prescribed Displacement' on the soil surface. Moreover, the changes in soil properties of collapsible soil due to inundation are applied in the calculation with the use of 'Reassigning Material Properties'. For example, in defining Phase III in stage construction mode, 1.37m prescribed displacement is applied and the material dataset $CS_{initial}$, previously assigned to the collapsible soil cluster is changed to the dataset CS_{III}. Figure 1 shows stage construction of Phase II and Phase III. 'Plastic" type of calculation is carried out for all phases.

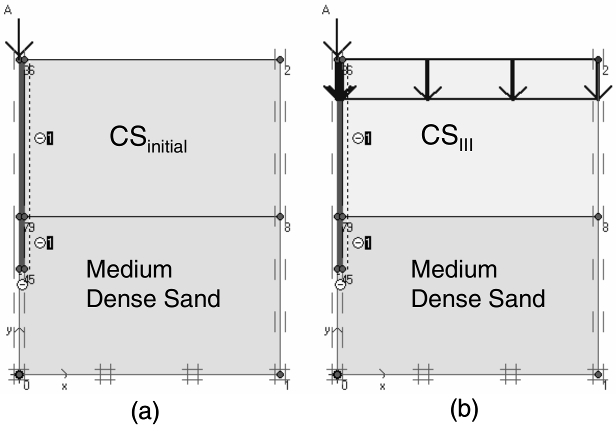

Figure 1. Staged construction: (a) Phase II; (b) Phase III.

4 CONCLUSIONS

The proposed procedure enables geotechnical engineers to examine the physical response of soil elements to pile loadings and soil inundation using the finite element technique. The proposed numerical model was validated with the results of single piles in homogeneous dry and saturated soils. A guideline is presented to assist designers to adjust the soil parameters during inundation. Currently, laboratory testing on prototype set-up is in progress for additional validation for the numerical model.

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Table 1. Detail of phases in the simulation of pile loading and inundation of collapsible soil

Calculation Phase	Stage of Inundation	Moisture Content w (%)	Volume Change ΔV (%)	Unit Weight γ (kN/m^3)	Prescribed Displacement (m)	Cohesion c (kPa)	Angle of internal friction, φ (°)	Remarks
Initial	Stage 0	2.4	x	14.8	X	50	30	Initial condition
I	Stage 0	2.4	x	14.8	X	50	30	Pile Installation
II	Stage 0	2.4	x	14.8	X	50	30	External loading on pile
III	Stage 1	2.4-6	9.8	16.4	1.37	44	26	Collapse and strength reduction
IV	Stage 2	6-9	4.2	17.2	0.59	28	20	
V	Stage 3	9-11	2	17.6	0.28	20	15	

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