Three-dimensional desiccation modeling of very soft soils

Modélisation tridimensionnelle de dessication des sols très mous

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ABSTRACT

Self-weight consolidation and desiccation phenomena of ultra soft soils and slurries have important implications in mining, coastal, and environmental engineering. Disposal of mine tailings behind tailings impoundments, transportation of dredged materials and land reclamation, and disposing of sludge in water/wastewater treatment facilities are some of the engineering applications where self-weight consolidation and desiccation of slurries are of concern. Numerical modeling of desiccation phenomenon is a relatively new subject that enables geotechnical engineers to better manage the large volume of mine tailings, dredged materials, and other slurries that are disposed in confined disposal facilities (CDFs). Sedimentation, consolidation, and desiccation are the consecutive processes that take place in CDFs and lead to considerable reduction in the volume of slurries. In this article, a developed finite difference code for modeling the desiccation phenomenon of very soft soils is described. In addition to simulating the volume change due to surface drying, the cracking process and the water loss from crack side-walls during three-dimensional desiccation has been taken into account. To do this, a new concept has been introduced and implemented into Abu-Hejleh and Znidarcic (1995) desiccation theory. By using this concept the need for direct in-situ measurements to obtain the model parameters can be eliminated. The results of the program have been verified against a number of experimental measurements.

RESUME

les phénomènes de consolidation et de dessication d'Individu-poids des sols et des boues ultra mous ont des implications importantes dans l'exploitation, côtière, et la technologie environnementale. La disposition des produits de queue de mine derrière des impoundments de produits de queue, transport des matériaux et de la réutilisation des terrains draguée, et de se débarrasser du cambouis dans des équipements de traitement des eaux résiduaires de l'eau/sont certaines des applications de technologie où la consolidation d'individu-poids et la dessication des boues sont concernées. La modélisation numérique du phénomène de dessication est un sujet relativement nouveau qui permet aux ingénieurs géotechniques de contrôler mieux le de large volume des produits de queue de mine, les matériaux dragués, et d'autres boues qui sont disposées dans les installations de disposition confinées (CDFs). La sédimentation, la consolidation, et la dessication sont les processus consécutifs qui ont lieu dans CDFs et mènent à la réduction considérable du volume de boues. En cet article, un code développé de différence finie pour modeler le phénomène de dessication des sols très mous est décrit. En plus de simuler le changement de volume dû au séchage superficiel, le processus de fissuration et la perte d'eau des parois latérales de fente pendant la dessication tridimensionnelle a été pris en considération. Pour faire ceci, un nouveau concept a été présenté et mis en application théories dans 1995) dessication d'Abu-Hejleh et de Znidarcic (. En employant ce concept on peut éliminer le besoin des mesures in-situ directes d'obtenir les paramètres modèles. Les résultats du programme ont été vérifiés contre un certain nombre de mesures expérimentales.

Keywords: Desiccation, very soft soils, slurry, numerical simulation

1 INTRODUCTION

The safe, economical and efficient disposal of slurry type fine-grained soils including mine tailings and dredged materials is among important geo-environmental issues that has caused the geotechnical engineering to face an economical and environmental challenge in recent years.

Considering the contamination associated with some of these waste soils, the common practice is disposing of these materials into confined disposal facilities (CDF). The difficulties that exist for site selection, and management of CDFs and reducing their adverse environmental effects have become increasingly important. Obviously, if the waste materials undergo larger strains than it is usually caused by self-weight consolidation, the above goals for reducing the environmental problems and better management of disposal sites become more attainable. Among the several densification techniques which have been developed, desiccation due to surface drying is the most preferable.

The desiccation modeling has been the subject of a number of previous studies (e.g. Krizek et al. 1977; Cargill 1985; Swarbick and Fell 1992; Stark et al. 2005). But a comprehensive work in this field has been performed by Abu-Hejleh and Znidarcic (1995). They developed a new desiccation theory that can model the phases that a soft soil layer undergoes in the field after deposition: 1) consolidation under one-dimensional compression, 2) desiccation under one-dimensional shrinkage, 3) propagation of vertical desiccation cracks with tensile stress release, and 4) desiccation under three-dimensional shrinkage. It should be noted that throughout the process, soil is assumed to be fully saturated.

Due to desiccation, cracks develop at the top soil surface and propagate downward. Before initiation of the cracks, due to vertical flow, only one-dimensional (vertical) deformation occurs. But, when soil starts cracking during desiccation, since pore fluid evaporates from both the top surface and the crack side-walls, soil compresses in three dimensions. The evaporation from shrinkage cracks is significant. Abu-Hejleh and Znidarcic (1995) introduced an area reduction function (α) as a constant value in a unit element, to account for evaporation from the cracks. The results of this approach, however, proved to be approximate. Yao and Znidarcic (1997) incorporated a lump-sum parameter (η) into the proposed desiccation theory by Abu-Hejleh and Znidarcic (1995) to simulate the evaporation from the crack walls. But, for a correct prediction, η should be determined from direct measurements of the evaporation rate from the crack walls, or from the overall matching of the numerical modeling results with the experimental data (Yao et al. 2002). Therefore, it appears that none of the methods explained above, are able to quantify the amount of evaporation that takes place from the crack walls, in an appropriate way.

In this paper, a new concept for modeling desiccation behavior of very soft soils is presented. The method has been implemented in a finite-difference computer program. This computer code, in addition to modeling the desiccation

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mechanism, is able to simulate self-weight consolidation of very soft soils. Verification of the model for simulating different consolidation scenarios has been documented elsewhere (Pak and Samimi 2007a). In the next sections, first, the governing differential equations for desiccation phenomenon of soft soils, and the incorporated new term for taking into account the evaporation from the crack walls, will be presented. In continuation, the required relations for solving the differential equation are explained. Finally, for assessing the performance of the developed model, the numerical model results are compared with the results of a centrifuge test.

2 THEORETICAL CONSIDERATIONS

2.1 *The governing differential equations*

As mentioned in the previous section, Abu-Hejleh and Znidarcic (1995) presented a desiccation theory that provides a rational method for analyzing the desiccation behavior of soft soils. So, in this study, for numerical modeling of desiccation, this theory has been adopted as a platform.

The governing differential equation for modeling the one-dimensional compression of soft soils during consolidation and desiccation processes before cracking is (Abu-Hejleh and Znidarcic 1995):

$$-\left(\frac{\gamma_s}{\gamma_w}-1\right)\frac{\partial}{\partial e}\left[\frac{k(e)}{1+e}\right]\frac{\partial e}{\partial z}-\frac{\partial}{\partial z}\left[\frac{k(e)}{\gamma_w(1+e)}\frac{d\sigma_v'}{de}\frac{\partial e}{\partial z}\right] = \frac{\partial e}{\partial t} \tag{1}$$

The proposed partial differential equation for three-dimensional desiccation (after cracking) is (Abu-Hejleh and Znidarcic 1995):

$$\frac{\partial}{\partial a}\left[k(e)-\frac{k(e)}{\gamma_w}\frac{(e\gamma_w+\gamma_s)}{1+e}\left(1-\frac{\partial\sigma_v'}{\partial e_{cr}}\frac{de_{cr}}{d\sigma_v}\right)\right]- \frac{\partial}{\partial a}\left[\frac{k(e)}{\gamma_w}\frac{\alpha(1+e_0)}{1+e}\frac{d\sigma_v'}{de}\frac{\partial e}{\partial a}\right]=\frac{1}{\alpha(1+e_0)}\frac{\partial e}{\partial t} \tag{2}$$

In the above equations a = vertical Lagrangian coordinate, that is positive upward, $t =$ time, σ_v' = vertical effective stress, $e =$ void ratio, $e_0 =$ initial void ratio, $k =$ hydraulic conductivity, γ_w = unit weight of water, $\alpha =$ an area reduction function during three-dimensional desiccation, e_{cr} = cracking void ratio

2.2 *A new term for simulation of evaporation from the crack sides*

Consider soil element *ABCD* which is located at a desired depth of a soil column whose cross-section area is equal to unity, and has a void ratio of e_0, and the volume of $1+e_0$, at the time $t=0$ [Fig. 1(a)].

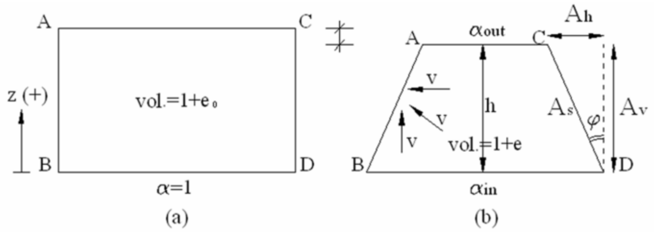

Figure 1 . Soil element deformation during 3D. desiccation, a) before cracking, b) after cracking

The element at some subsequent time t, deforms as shown in Fig. 1(b) in a way that its top and bottom areas become α_{out} and α_{in}, respectively, and has a current void ratio of e, and a volume of $1+e$. So the element height at time t will be equal to $h=(1+e)/\alpha$. Assuming that the element has a unit dimension in the perpendicular direction to the page, the area of crack surface in the inclined plane (A_s), can be obtained:

$$Cotg\varphi=\frac{A_v}{A_h}=\frac{h\times 1}{\frac{\alpha_{in}-\alpha_{out}}{2}\times 1}=\frac{\frac{1+e}{\alpha}}{\frac{\Delta\alpha}{2}} \tag{6}$$

$$A_s=\frac{A_h}{Sin\varphi}=\sqrt{1+Cotg^2\varphi}\times A_h= \sqrt{1+\left(\frac{2(1+e)}{\alpha\times\Delta\alpha}\right)^2}\times\frac{\Delta\alpha}{2} \tag{7}$$

Since $\frac{\Delta\alpha}{2}$<<1, then $Cotg\varphi$ >>1, Eq. (7) can be written as:

$$A_s\approx Cotg\varphi\times A_h=\frac{\frac{1+e}{\alpha}}{\frac{\Delta\alpha}{2}}\times\frac{\Delta\alpha}{2}=\frac{1+e}{\alpha}=A_v \tag{8}$$

where $A_h, A_v =$ projection of crack surface in the horizontal and vertical planes, respectively, and $\varphi=$ the angle between the crack and vertical directions. By determining A_s, the flow rate of evaporation from the crack walls will be:

$$Q_{cr}=2A_s\times v \tag{9}$$

where $v =$ the evaporation rate acting on the crack walls. The field test results have shown that the evaporation rate from the crack openings varies along the crack depth (Fujiyasu et al. 2000), and also with time. So, it is necessary that v is expressed as a function of time and crack depth. It is obvious that the steeper the slope of the crack walls, or the smaller the plan area of the cracks, the less will be the amount of evaporation from the crack side-walls. In other words, there is a direct relationship between v and $\Delta\alpha$. Using this dependency and considering that $\Delta\alpha$ also varies over time and space (along the crack depth), one can express the variations of v as:

$$v=E\times\frac{\Delta\alpha}{2} \tag{10}$$

where $E =$ the evaporation rate at the site. Using this relationship the flow rate of water out of the crack walls can be written as:

$$Q_{cr}=2A_s\times v=2\left(\frac{1+e}{\alpha}\right)\times\left(E\times\frac{\Delta\alpha}{2}\right)= \frac{1+e}{\alpha}\times\Delta\alpha\times E \tag{11}$$

According to the above equation and as stated by Yao and Znidarcic (1997), the fluid loss from the crack walls in the element is proportional to the area of the side-wall ($A_v=(1+e)/\alpha$), and the evaporation rate (E), and is inversely proportional to the slope of crack side wall

($\approx 1/\Delta\alpha$). With incorporating Eq. (11) into the desiccation theory by Abu-Hejleh and Znidarcic (1995), α across the element will no longer be a constant value and the differential Eq. (2) is modified to a new form in the material coordinate system:

$$(1-G_s)\frac{\partial}{\partial e}\left[\alpha\frac{k(e)}{1+e}\right]\frac{\partial e}{\partial z}+ \frac{\partial}{\partial e}\left[\alpha k(e)\frac{(e+G_s)}{1+e}\frac{d\sigma_v'}{de_{cr}}\frac{\partial e_{cr}}{\partial \sigma_v}\right]\frac{\partial e}{\partial z}- \frac{\partial}{\partial z}\left[\alpha\frac{k(e)}{\gamma_w}\frac{\alpha}{1+e}\frac{d\sigma_v'}{de}\frac{\partial e}{\partial z}\right]+\frac{1+e}{\alpha}E\frac{\partial \alpha}{\partial z}=\frac{\partial e}{\partial t} \tag{12}$$

According to Fig. (1), the spatial coordinate (z) is positive upward, so the discrete form of $\partial\alpha/\partial z$ can be written as: $\Delta\alpha/\Delta z=(\alpha_{out}-\alpha_{in})/\Delta z$. However, since in Eq. (6) $\Delta\alpha$ has been defined as $\alpha_{in}-\alpha_{out}$, Eq. (11) has been incorporated into the formulation with a negative sign. Therefore, in this study, Eq. (12) has been used as the governing differential equation for three-dimensional desiccation.

2.3 *Material functions*

As can be seen, for solving Eqs. (1), (3), and (12), besides considering appropriate initial and boundary conditions, a number of material functions must also be determined. These include:

(a) Cracking function: Cracking function is defined as the relationship between vertical total stress and cracking void ratio. The cracking function can be described by the following empirical relation (Yao and Znidarcic 1997):

$$e_{cr}=\frac{1}{d^*}+\frac{1}{(b^*\times\sigma_v^{\,cr}+a^*)^{c^*}} \tag{13}$$

where $a^*, b^*, c^*, d^*=$ parameters that can be determined from centrifuge experiments (Oliveira Filho 1998), and $\sigma_v^{\,cr}=$ the vertical total stress corresponding to cracking void ratio.

(b) Constitutive relationships: Variation of void ratio with effective stress, and variation of the coefficient of permeability with respect to the void ratio are two basic relations for consolidation /desiccation modeling. Among several forms that have been presented so far, the power function has found to be most appropriate. So in this study, the following constitutive relationships have been used (Yao et al. 2002; Oliveira Filho 1998):

For one-dimensional consolidation and desiccation:

$$e=A_1(\sigma_v'+Z_1)^{B_1} \tag{14}$$

For three-dimensional desiccation:

$$e=A_2(\sigma_v'+Z_2)^{B_2} \tag{15}$$

For consolidation and desiccation:

$$k=C(e)^D \tag{16}$$

where $A_1, B_1, Z_1, A_2, B_2, C, D=$ material parameters that should be determined experimentally, and Z_2 parameter is defined by the cracking void ratio. Oliveira Filho (1998) has explained the testing procedures for determining these parameters.

(c) α - function: α - function is defined as the area of soil elements which before the beginning of three-dimensional desiccation, is equal to unity. In isotropic and homogeneous soils α - function can be assumed as (Yao and Znidarcic 1997; Yao et al. 2002):

$$\alpha=\frac{1+e}{1+\frac{2}{3}e_{cr}+\frac{1}{3}e} \tag{17}$$

3 NUMERICAL MODELING PROCEDURE

For solving Eqs. (1), (3) and (12), the finite difference method has been used. For spatial discretization, the centered-difference and for time discretization, the explicit scheme, were employed. Then, a computer code has been developed in MATLAB environment to solve the obtained algorithms. Details of this code have been described elsewhere (Samimi 2007).

4 VERIFICATION OF THE DEVELOPED NUMERICAL MODEL

In order to evaluate the performance of the developed computer program in the analysis of the desiccation behavior of soft soils, the predicted results by the model have been compared with the results of a centrifuge test performed at 50g level by Oliveira Filho (1998). The soil used in the consolidation and desiccation tests, is Georgia Kaolin that has the following characteristics:

(a) $G_s=2.66$, $e_{sl}=0.8$ (void ratio at the shrinkage limit)

(b) The compressibility relationships parameters:

$A_1=A_2=2.812$, $B_1=B_2=-0.202$, $Z_1=0.338\ kPa$

(c) The permeability relationship parameters:

$C=4.84\times10^{-10}\ m/s$, $D=3.827$

(d) The cracking function parameters for boundary cracks:

$a^*=0.024$, $b^*=0.032$, $c^*=0.189$, $d^*=3.533$

These characteristics have been determined experimentally prior to the centrifuge test (Oliveira Filho, 1998). Experimental data from this centrifuge test has been used to model consolidation and desiccation of a prototype soil layer, 9.6 m thick, with impervious bottom and uncovered top surface (zero effective stress). Initial conditions for the soil layer include a uniform void ratio profile, with $e_0=3.5$. The first stage in this test was to allow the soil layer to undergo consolidation under its self-weight for a period of 5153 days. Then all the remaining water on top of the soil surface from the self-weight consolidation process was removed, and desiccation phase began. In this phase, the bottom of soil layer was again impervious and the top boundary was pervious, allowing water to evaporate from the soil surface. The evaporation rate from the top surface (E) was $4.42\times10^{-4}\ m/day$ in this test. The desiccation phase lasted 2047 days (Oliveira Filho, 1998).

Predicted values for variation of settlement by the developed numerical model along with the experimental data are illustrated at Fig. 2(a). As can be seen, there is a good agreement between the predicted values and experimental data on the settlement curve. The observed difference in the early stages of the test, as mentioned by Oliveira Filho (1998), is due to the change in soft soils characteristics formed at high void ratios when spun in the centrifuge. It is noticeable that the developed model is capable of simulating the desiccation phenomenon without needing any curve fitting parameter.

Fig. 2(b) shows the void ratio distribution at the end of consolidation and onset of desiccation (at day 5153), and at the end of the test (at day 7200). As can be observed, the predicted values by the model for void ratio distribution are in good agreement with the experimental data during desiccation.

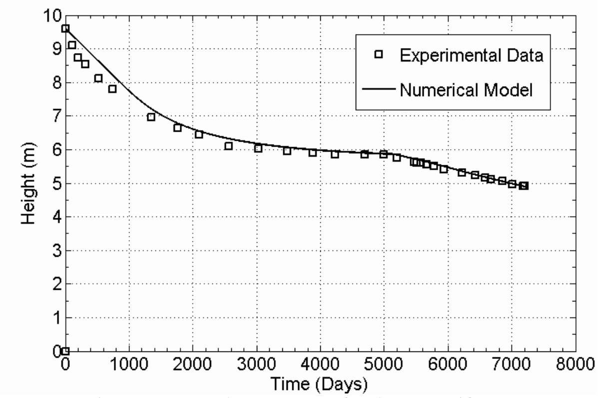

Figure 2(a). Settlement curve for 50-g centrifuge test

Figure 2(c) illustrates the variation of crack volume over time. Although measurements of the crack depth and crack width are relatively difficult in the laboratory, the agreement between numerical results the experimental data is remarkable. This indicates that the model can properly predict the crack initiation and propagation [Fig. 2(c)].

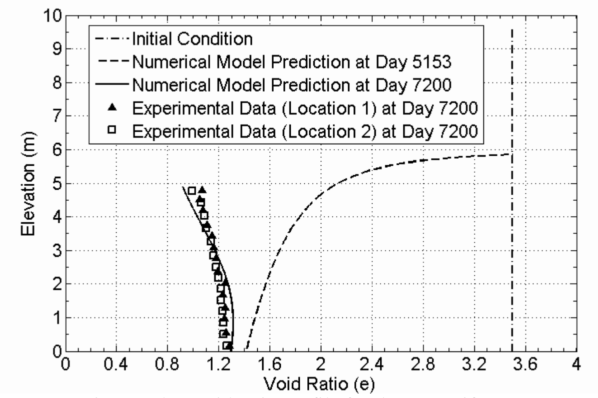

Figure 2(b). Void ratio profile for 50-g centrifuge test

5 CONCLUSIONS

Management of CDFs, where the dredged materials and /or mine waste slurries are stored, requires a good deal of knowledge regarding the sedimentation, consolidation, and desiccation mechanisms of ultra soft soils. Among these mechanisms, the desiccation phenomenon is more complex because the surface drying process eventually leads to cracking. Upon cracking, three-dimensional evaporation starts which should be taken into account in the analysis and the crack depth must be evaluated.

In this paper, a finite difference code has been introduced that can simulate three-dimensional desiccation process of very soft soils, a phenomenon that most of the existing numerical models are unable to consider. A new concept that distinguishes the current numerical study from previous works is that there is no need for direct in-situ measurement of model parameter for desiccation. Verification of the developed code against centrifuge test shows very good agreement with experimental measurements.

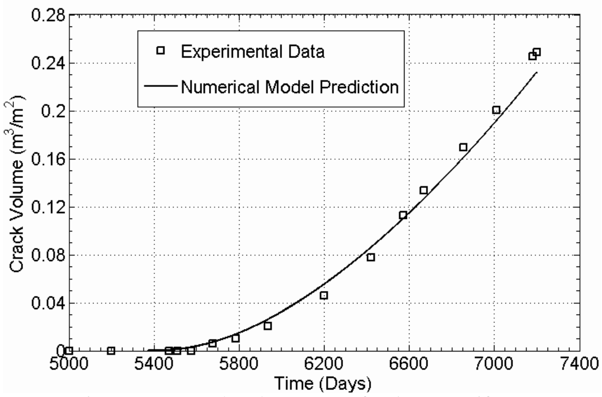

Figure 2(c). Crack volume curve for 50-g centrifuge test

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