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Geosynthetic Civil Infrastructure, Disaster Monitoring, and Environmental Geotechnics

Edited by
Sao-Jeng Chao, Ph.D.
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Kwok-Leung Pun, Ph.D.

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Preface

This Geotechnical Special Publication (GSP) contains 20 papers presented at the 4th GeoChina International Conference held in Shandong, China from July 25 to 27, 2016. The conference is endorsed by a number of leading international professional organizations. The technical programs for the 4th GeoChina International Conference came into contact with a balance between the fundamental theories and field applications. The papers in this GSP address a mixture of current issues in the Advances in Unsaturated Soil, Seepage, and Environmental Geotechnics, Natural Hazard and Disaster Monitoring, and Geosynthetic Reinforced Soil Retaining Structure. Furthermore, this GSP includes investigations and solutions from numerous countries, and it expands ranges of tools that are available to engineers and scientists.

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Contents

Consolidation-Induced Contaminant Transport in Multi-Layer Soils

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Abstract: This paper presents a numerical investigation of the effects of large strain consolidation on contaminant transport in multi-layer soils. Numerical simulations were conducted using the CST3 model, which accounts for one-dimensional coupled large strain consolidation and contaminant transport in saturated multi-layer porous media. The consolidation algorithm accounts for vertical strain, soil self-weight, general constitutive relationships, relative velocity of fluid and solid phases, changing compressibility and hydraulic conductivity during consolidation, unload/reload, time-dependent loading, time-dependent boundary conditions, external hydraulic gradient, variable preconsolidation stress profiles, and multiple soil layers with different material properties. The contaminant transport algorithm accounts for advection, diffusion, mechanical dispersion, linear and nonlinear sorption, equilibrium and nonequilibrium sorption, porosity-dependent effective diffusion coefficient, and first-order decay reactions. Simulation results indicate that layered soil heterogeneity can have significant effects on both consolidation behavior and contaminant transport behavior. Characterization of a multi-layer soil stratum as a homogeneous single layer with average properties may result in significant errors in the analysis of consolidation-induced contaminant transport in multi-layer soils.

INTRODUCTION

The phenomenon of consolidation-induced contaminant transport is observed in a variety of geoenvironmental engineering applications, including contaminant transport through landfill bottom liner systems during waste placement operations, confined disposal of dredged contaminated sediments, and subaqueous capping of contaminated sediments (Fox and Shackelford 2010). For these applications, contaminant transport processes involve advection, dispersion, and sorption, which is similar to the transport in rigid porous media as described by classical transport theory. In addition, consolidation-induced contaminant transport processes also involve transient advective flows and changes in transport properties such as porosity and effective diffusion coefficient, which further complicate the modeling of such transport processes.

Over the last two decades, several research groups have utilized different methods to consider consolidation-induced contaminant transport in porous media, such as the work by Potter et al. (1994), Smith (2000), Peters and Smith (2002), Fox (2007a, 2007b), Fox and Lee (2008), Pu and Fox (2015a), Fox and Pu (2015), and Pu et al. (2015). All of these studies assume that the porous medium is homogeneous and thus layered soil heterogeneity, which is more common in reality, is neglected. Although many solutions are available for the contaminant transport in rigid multi-layer porous media (e.g., Leij and van Genuchten 1995; Li and Cleall 2011), very limited progress has been made in the area of coupled consolidation and contaminant transport in multi-layer soils. Recently, Pu and Fox (2015b) developed a piecewise-linear numerical model, called CST3, to model such problem.

This paper provides an overview of the capabilities of the CST3 model. Then, numerical simulations were performed using CST3 to illustrate the effects of layered soil heterogeneity on the consolidation results and associated contaminant transport results. The errors for modeling multi-layer soils as a homogeneous single layer were discussed for the analysis of consolidation-induced contaminant transport in multi-layer soils.

MODEL DESCRIPTION

CST3 was developed on the basis of the CS2, CS3 and CST2 models and follows similar procedures with regard to geometry, effective stress, fluid flow, settlement, and contaminant transport. The CST3 model and its predecessors have undergone extensive validation, including comparisons with experimental data (e.g., Fox and Berles 1997; Fox 2007b; Fox and Lee 2008; Lee and Fox 2009; Pu and Fox 2015b). Only a brief summary is provided below.

A saturated compressible soil stratum has initial height H_{To}, contains R_i horizontal layers, and is treated as an idealized two-phase material in which the solid particles and pore fluid are incompressible. The initial geometry, prior to application of surcharge load at time t = 0, is shown in Fig. 1. The stratum is sufficiently wide such that all quantities vary only in the vertical direction and consolidation can be treated as one-dimensional. Vertical coordinate z and layer coordinate i are defined as positive upward from a fixed datum at the bottom of the stratum. Each layer i has initial height $H_{o,i}$ and the solid phase of layer i is represented as a column of $R_{j,i}$ vertical solid elements, and thus the total number of solid elements for the stratum is $R_{Ts}\left(=\sum_{i=1}^{R_i} R_{j,i}\right)$. Layer elevation coordinate z_i and layer solid element coordinate j are defined as positive upward from the base of each layer. Each solid element j of layer i has unit cross-sectional area (plan view), initial height $L_{so,i}$, a central node at initial elevation $z_{so,i,j}$, and initial void ratio $e_{o,i,j}$. Nodes translate vertically and remain at the center of their respective elements throughout the consolidation process. The distribution of void ratio is assumed to be uniform within each solid element and varies vertically among solid elements depending on the initial vertical effective stress at the top of the stratum q_o, the compressibility and self-weight of the soil, and any vertical seepage forces due to an external hydraulic gradient acting across the stratum (Fox 2007a).

The pore fluid of each layer i is also represented as a column of elements, with $R_{mo,i}$ fluid elements initially in the column, and thus the initial total number of fluid elements for the stratum is $R_{Tf}\left(=\sum_{i=1}^{R_l} R_{mo,i}\right)$. Fluid elements are defined by vertical element coordinate m upward from the base of each layer. Each m^{th} fluid element of layer i has initial height $L_{fo,i}$, unit cross-sectional area (plan view), and a central node located at initial elevation $z_{fo,i,m}$. Each m^{th} fluid element of layer i has initial solute (i.e., dissolved) concentration $c_{o,i,m}$ [mass solute/volume fluid] and initial solute mass $C_{fo,i,m} = c_{o,i,m}V_{fo,i,m}$, where $V_{fo,i,m} = L_{fo,i}e_{o,i,j}/(1+e_{o,i,j})$ is the initial volume of fluid in the element and $e_{o,i,j}$ is the initial void ratio of the solid element at the same elevation. The initial sorbed concentration for each solid element $s_{o,i,j}$ [mass contaminant/mass solid] is assumed to be in equilibrium with the local solute concentration.

Constitutive relationships are defined using conventional log-linear parameters for each layer. Each solid element is characterized as normally consolidated (NC) or overconsolidated (OC). If OC, the compressibility relationship is defined by $(\hat{e}_i, \hat{\sigma}'_i)$, recompression index $C_{r,i}$, preconsolidation stress $\sigma'_{p,i,j}$, and compression index $C_{c,i}$, where $(\hat{e}_i, \hat{\sigma}'_i)$ is a known point on the compressibility curve. Vertical hydraulic conductivity k for each solid element is defined by a log-linear relationship $k_{i,j} = k_{o,i,j}\exp[(e_{i,j} - e_{o,i,j})C'_{k,i}\ln 10]$, where $k_{o,i,j}$ is the vertical hydraulic conductivity at $e_{o,i,j}$, and $C'_{k,i}$ is the reciprocal of hydraulic conductivity change index = $\Delta \log k / \Delta e$. Aside from unload/reload effects, a one-to-one correspondence is assumed for each constitutive relationship. Thus, CST3 does not account for the effects of strain rate, secondary compression, or aging on the compressibility or hydraulic conductivity of the soil. Furthermore, the solute is assumed to be sufficiently dilute so as to not alter the constitutive relationships of the soil.

Top and bottom boundaries of the stratum can be specified as drained or undrained and, if drained, are assigned individual total hydraulic head values, h_t and h_b, taken with respect to the datum (Fig. 1). Transport conditions for the top and bottom boundaries can be specified as prescribed concentration (Type I), prescribed concentration gradient (Type II), or prescribed solute mass flux (Type III). CST3 can also consider a reservoir boundary condition, which represents the time-varying concentration of an accumulating well-mixed aqueous reservoir formed above the soil stratum from fluid outflow at the top boundary (Fox and Lee 2008).

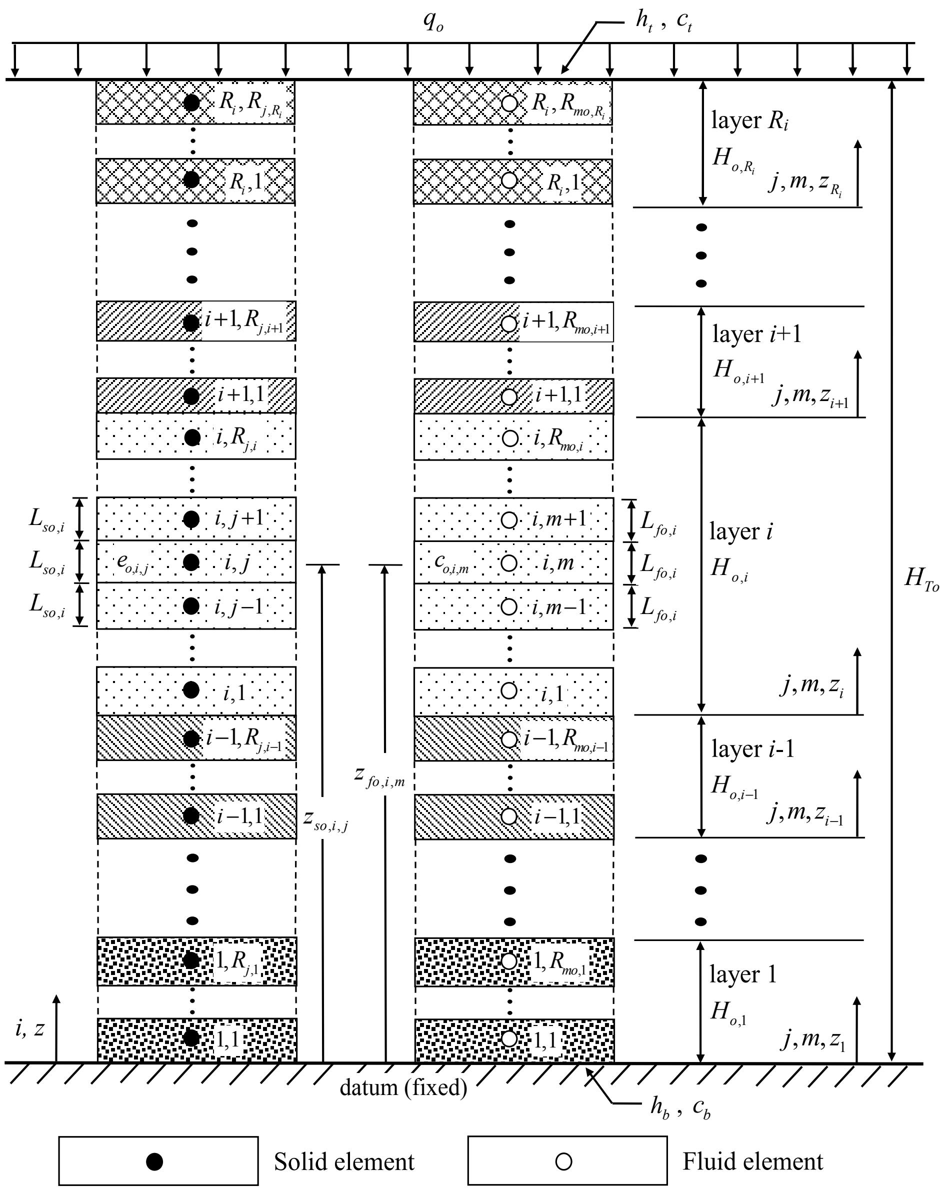

Fig. 1. Initial geometry for CST3 (Pu and Fox 2015b).

Surcharge load is applied to the soil stratum beginning at t = 0. The vertical effective stress at the top boundary at time t is equal to $q_o + \Delta q^t$, where effective stress increment Δq^t is constant with depth but can change with time. In response to surcharge loading, excess pore pressures generated within the layer cause fluid flow to all drainage boundaries. Soil deformation is one-dimensional and occurs in response to the net fluid outflow from each element. In a deforming soil stratum, contaminant transport occurs by transient advection and dispersion in the fluid phase and sorption onto moving solid elements. The sorption can be considered as linear or nonlinear (Freundlich isotherm), equilibrium or nonequilibrium (i.e., kinetic). An effective diffusion coefficient that changes with soil porosity during consolidation can