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Numerical Study of Contaminant Transport Coupled with Large Strain Consolidation

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Abstract

Contaminant transport has been widely studied in rigid porous media, but there are some cases where a large volumetric stain occurs such as dewatering of dredged contaminated sediment, landfill liner, and in-situ capping. This paper presents a numerical investigation of contaminant transport coupled with large strain consolidation. Consolidation test was performed with contaminated sediments collected in Gary, Indiana, U.S. to obtain constitutive relationships, which are required for numerical simulations. Numerical results using CST2 show an excellent agreement with measured settlement and excess pore pressure. CST2 is then used to simulate contaminant transport during and after in-situ capping. Numerical simulations provide that transient advective flows caused by consolidation significantly increase the contaminant transport rate. In addition, the numerical simulations revealed that active capping with Reactive Core Mat (RCM) significantly decelerates consolidation-induced contaminant transport.

Keywords : Numerical simulations, Consolidation, Contaminant transport, Transient advective flows, In-situ capping

I. Introduction

Contaminant transport has been studied for several decades, and most of available analytical and numerical solutions are based on assuming that contaminated soils are rigid. Therefore, contaminant transport has been predicted with constant porosity and seepage velocity. However, there are some cases where a volumetric change occurs such as dewatering of dredged contaminated sediment, landfill liner, and in-situ capping. For example, in-situ capping is one of remediation methods to isolate contaminated sediments but self weight of capping materials consolidates the sediments. Sediments at the bottom of the lake, river, and coast near the industrial district are highly contaminated due to wide spread applications of contaminants such as Polychlorinated Byphenyls(PCBs) and heavy metals. Contaminated sediments with high moisture content experience large strain consolidation even though small surcharge pressure of in-situ capping is applied(Fox, 2007b). Transient advective flows caused by consolidation may accelerate the migration of contaminants(Alshawabkeh and Rahbar, 2006 Fox, 2007b).

Potter et al.(1997) and Moo-Young et al.(2003) investigated the consolidation-induced solute transport using geotechnical centrifuge, and found

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that consolidation affects solute transport. Alshawabkeh et al.(2004) performed two consolidation tests on two layered kaolinite specimens; an upper layer contaminated with sodium bromide and a lower layer contaminated with sodium chloride. Each specimen was consolidated under a constant pressure of 25 kPa and single top drained boundary condition. Measured settlements and bromide concentrations show similar trends and indicate that consolidation accelerated the outflow rate of bromide from the specimens. Previous researches provide a valuable insight into the effect of consolidation on solute transport, but numerical investigations of previous researches are based on small strain consolidation theory. Significant errors of small strain analyses may occur when the stress-strain relationship is highly nonlinear and the hydraulic conductivity may vary(Olson and Ladd, 1979 McVay et al.,1986).

A new approach, developed by Fox and Lee (2008), for the simulation of coupled nonlinear large strain consolidation and solute transport is based on the piecewise-linear method and is coded in the numerical model CST2(Consolidation and Solute Transport 2). The consolidation algorithm in CST2 is one-dimensional and accounts for the effects of vertical strain with associated geometric and material nonlinearities. CST2 can accommodate variation of effective diffusion coefficient during consolidation, nonlinear nonequilibrium sorption, and reservoir boundary condition. Verification checks were performed with established analytical and numerical solutions for solute transport through rigid porous media(Fox and Lee, 2008). For consolidation-induced solute transport, in addition, simulated results using CST2 were compared with experimental results of Kaolinite slurry and the simulation shows an excellent agreement with experimental measurements(Lee, 2007).

This paper presents the results of numerical investigations of contaminant transport induced by large strain consolidation. The experimental test was conducted using contaminated sediments in order to find constitutive relationships(void ratio vs. effective stress and void ratio vs. hydraulic conductivity) for numerical simulations. The experimental procedures to obtain constitutive relationships are first described, and then experimental and numerical results are presented to show the accuracy of CST2 predictions for consolidation. This paper concludes with simulations illustrating the importance of consolidation on contaminant transport and the effect of a thin reactive layer in the capping system.

II. Experimental Test

Experimental tests were performed with contaminated sediments obtained from Grand Calumet River in Gary, Indiana, U.S. Heavy industrialization in this area produced highly contaminated sediments including PCBs, PAHs, and heavy metals(Scullion, 2006). The sediment has a specific gravity of solids(G_s) of 2.05, but Atterberg limit test could not be performed due to high PCBs content. Incremental loading consolidation test was performed to determine compressibility and hydraulic conductivity constitutive relationships. The experimental apparatus is shown in Fig. 1. Contaminated sediments were placed in a rigid wall cell(dia. = 102 mm) by a combination of spooning and pouring. Care was taken to remove entrapped air from the test cell apparatus and to entrain as little air as possible into the slurry during this process. The initial height and initial void ratio(e_o) are 45.1 mm and 1.35,

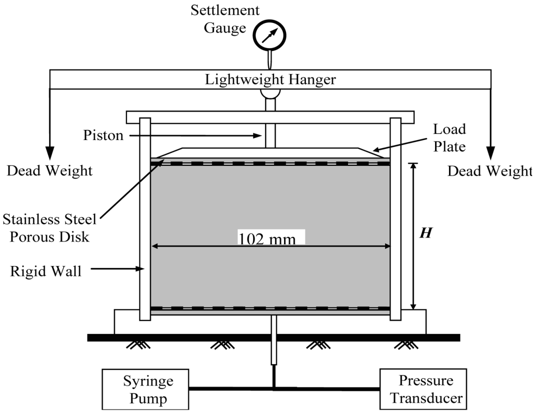


Fig. 1 Consolidation test apparatus

respectively. The specimen was consolidated with loading and unloading schedules (1.8, 6.5, 15.9, 34.7, 72.4, 15.9 kPa), single drainage at the top boundary, and pore pressure measurements taken at the base. Hydraulic conductivity measurements were obtained in between load increments using a syringe flow pump connected to the base of the cell as shown in Fig. 1. These tests began once consolidation was completed, as determined from settlement and pore pressure data. Upward flow was used to decrease effective stress within the specimens and thus avoid additional consolidation. Settlement measurements confirmed that void ratio remained constant during permeation. Each hydraulic conductivity and load increment remained on the specimen lasted 24 h. Permeant used for hydraulic conductivity was Grand Calumet River water.

III. Results and Simulations

1. Consolidation

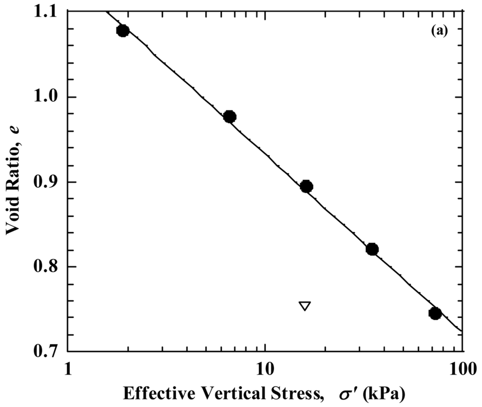
Compressibility and hydraulic conductivity relationships from the consolidation test are shown in Fig. 2 and expressed as,

$$e = -0.21\log(\sigma') + 1.142 \text{ (kPa)} \tag{1}$$

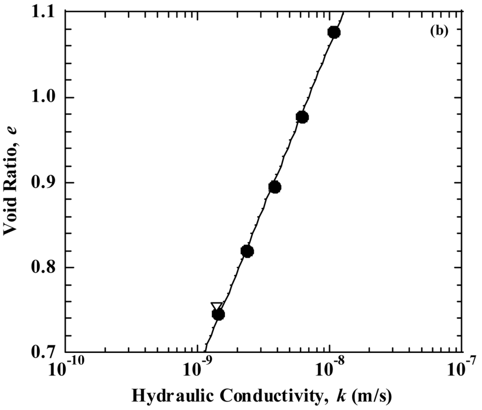
$$e = 0.38\log(k) + 4.095 \text{ (m/s)} \tag{2}$$

where e is void ration, σ' is vertical effective stress, and k is hydraulic conductivity. Essentially constant values of compression index C_c = 0.21 is indicated. A linear relationship between hydraulic conductivity and void ratio on the semi-log plot is characterized by hydraulic conductivity index $C_k = de/d\log k = 0.38$. Similar to the findings of Al-Tabbaa and Wood(1987), Nagaraj et al.(1994), and Fox(2007b), Fig. 2 indicates that hydraulic conductivity follows the same relationship for normally consolidated and overconsolidated conditions.

Fig. 3(a) presents vertical total stress(σ_v) and settlement(S) as a function of time for all load increments. Settlement increased with increasing σ_v to a final value of 11.6 mm, which corresponds to an average vertical strain of 25.7%. Excess pore pressures(u_e) at the base of the specimen(Fig. 3(b)) show progressively increasing maximum values with increasing load increments and indicate that consolidation was completed in each case prior to the next load application. Numerical simulations using CST2 for settlement and excess pore pressure are also presented in Fig. 3. Detail development of CST2 is not presented in this paper, because it is over the limit and scope of this paper. Constitutive relationships for CST2 prediction were obtained from Eq. (1) and (2), and prepared as 90 discrete data points. The simulations were conducted for single drained condition using 100 solid elements and assuming a uniform initial void ratio(e_o = 1.35) for the specimen.



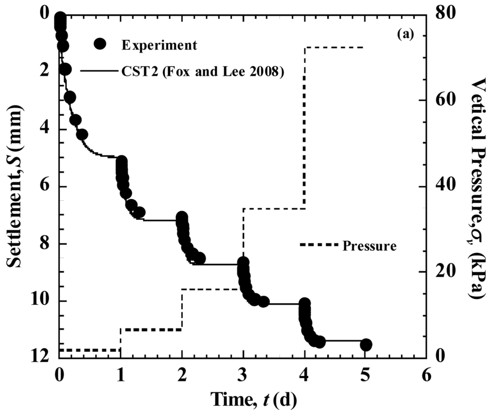
(a) compressibility



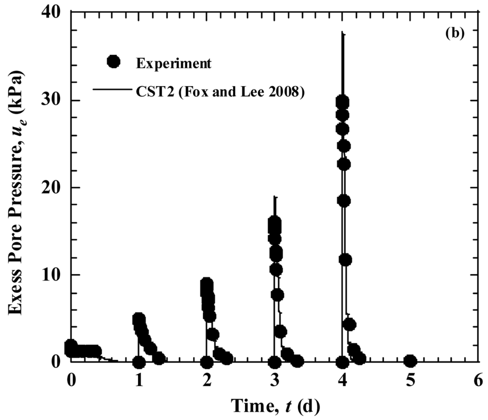
(b) hydraulic conductivity

Fig. 2 Constitutive relationships for Grand Calumet river sediment

The final settlement for each load increment was closely matched to the measured value as shown in Fig. 3(a), because measured compressibility curve for the consolidation test(Fig. 2(a)) was used. Close agreement of maximum measured and predicted pore pressures in Fig. 3(b) also suggests that air bubbles were not trapped in the tubing and valves of the pore pressure measurement system. Accurate predictions for time dependent settlement and excess pore pressure in Fig. 3(a) and (b) suggest that the hydraulic conductivity constitutive relationship(Fig. 2(b)) is an accurate approximation. The numerical simulations are generally in good agreement with the experimental measurements, which means that CST2 model eliminates unnecessary variability in transient advective flows for the simulations of consolidation-induced contaminant transport.



(a) settlement



(b) pore pressure

Fig. 3 Experimental and numerical results of Grand Calumet river sediments

2. Case Studies

Numerical investigations of consolidation-induced contaminant transport were performed. CST2 was used to simulate contaminant transport for a hypothetical in-situ capping of contaminated sediments. It is assumed that initial height of the contaminated sediments is 1 m and initial void ratio(e_0) of 1.35 is distributed uniformly. A cap layer increases vertical effective stress and causes consolidation of underlying the contaminated sediments. The applied effective stress Δq due to in-situ sand capping is assumed to be 13.1 kPa. In addition, self weight consolidation of the contaminated sediments is also accommodated in CST2(Fox et al., 2005; Lee and Fox, 2005). The contaminated sediments are assumed to be placed on impervious soil layer. Three simulations were performed

Case I : Sand Capping but ignoring consolidation effect(diffusion only)
Case II : Sand Capping including consolidation effect
Case III : Sand Capping with 1 cm Reactive Core Mat(RCM)

First simulation(Case I) without consolidation is a classical contaminant transport analysis during and after in-situ capping. Therefore, only diffusive transport driven by concentration gradient results in contaminant transport. Case II presents the significance of consolidation on contaminant transport compared with Case I. Final simulation(Case III) elucidates the effect of in-situ active capping system such as lower Reactive Core Mat(RCM) layer and upper sand layer. RCM includes sorbent materials such as activated carbon or organically modified clay incorporated within geotextiles. Traditional sand capping prevents mainly colloidal transport, but it removes little contaminants associated with pore water in contaminated sediments. The active capping with RCM compensates the deficiency of classical sand capping.

Numerical simulations were performed with Grand Calumet River sediments. Compressibility and hydraulic conductivity relationships in Eq. (1) and (2) were used for the simulations. It is assumed that the contaminated sediments contain PCBs with a uniform initial pore fluid concentration c_o = 100 mg/L, and solids have a uniform initial sorbed concentration($s = K_d c_o$). Following transport parameters are assumed; $D^* = 5 \times 10^{-10}$ m^2/s, $\alpha_L = 0$ m, and K_d = 15 mL/g for PCBs, where D^* is effective diffusion coefficient, α_L is longitudinal dispersivity, and K_d is distribution coefficient. CST2 simulations without RCM were performed with 100 solid elements and 300 fluid elements. CST2 simulations with RCM were performed with 101 solid elements and 303 fluid elements in order to accommodate 1 cm RCM. Compressibility and hydraulic conductivity of RCM are assumed to be the same as the Grand Calumet sediments.

Simulation results are presented in Figs. 4-5. Case I is "diffusion only" simulation, so the final height is the same as the initial height of 1 m. Settlements for Case II and III are 0.186 and 0.187 m, respectively. The discrepancy of settlements between Case II and III was caused by the existence of RCM in Case III, but it is negligible as shown in Fig. 4. Thus, the consolidation behavior of Case II and III appears to be comparable. Consolidation of 90% was achieved after 70 days at which transient advective flows are almost dissipated. Top concentration boundary is assumed to be kept as zero(constant concentration boundary) based on two reasons; First, top of sediments is always contacted with clean river water. Second, top boundary condition of zero concentration maximizes the diffusive transport. If diffusive transport dominates contaminant transport, transient advective transport caused by consolidation does not make any significant changes. Both advective and diffusive transports of PCBs are upward due to boundary conditions,

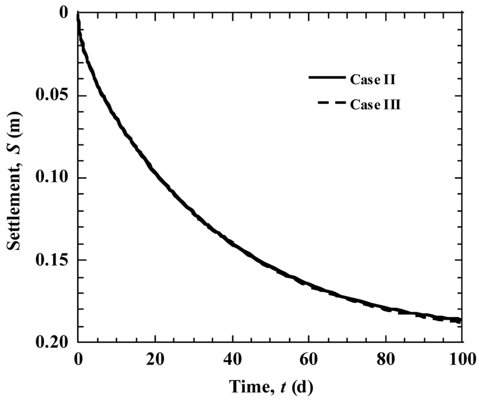
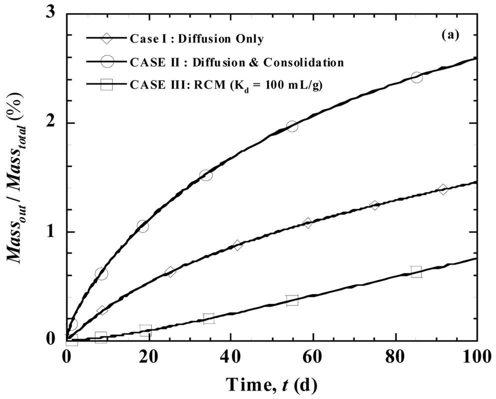


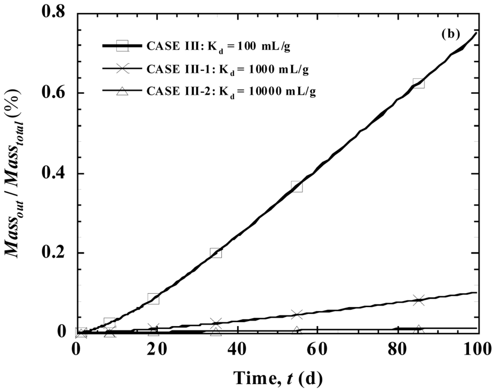
Fig. 4 Settlement curves for Case II and III obtained from CST2

but effluent concentrations out of contaminated sediments remain as zero due to the top concentration boundary condition. Breakthrough curves based on concentration mode, therefore, are useless. The mass of PCBs inside the sediments always moves out of the top boundary, so mass outflow provides an insight to see the effect of consolidation. CST 2 is capable to trace not only the mass in solids and pore fluid, but also the mass into and out of boundaries(Fox, 2007a; Fox and Lee, 2008).

Fig 5(a) shows cumulated mass outflows for Case I, II, and III during 100 days. Cumulated mass outflow is normalized with initial total mass which is calculated by adding mass in pore fluid and sorbed mass in solids of the sediments. Final cumulated mass out for Case II is 1.8 times greater than that for Case I. Based on mass outflow results, therefore, transient advective flows caused by consolidation significantly accelerate contaminant transport. Cumulated mass outflow curve of Case III presents the effectiveness of RCM to remove PCBs. RCM in Fig. 5(a) was assumed to possess a sorbent material with K_d of 100 mL/g. Equilibrium sorption reaction was assumed to be achieved instantaneously(i.e., no kinetic sorption). As shown in Fig. 5(a), RCM for Case III



(a) mass outflow for Case I, II, and III



(b) mass outflow with three different RCMs

Fig. 5 Simulation results for contaminated sediments

decreases the rate of contaminant transport. Final cumulated mass out for Case III is twice and 3.4 times less than that of Case I and Case II at 100 days, respectively. Distribution coefficient K_d of reactive sorbent materials is practically much greater than 100 mL/g(Scullion, 2006). Further simulations were performed with higher K_d values (1000 and 10000 mL/g) as shown in Fig. 5(b). As K_d increases, the rate of mass outflow decelerates and final cumulated mass out decreases. If K_d value is over 10^5 mL/g, cumulated mass out is negligible(cumulated mass out $<$ 0.004% of initial total mass inside the sediments). If kinetic sorption exists between a sorbent material in RCM and contaminants, transient advective flows at the early stage of consolidation may significantly increase the rate of mass outflow and cumulated mass out(Lee, 2007).

IV. Conclusions

The following conclusions are reached as a result of numerical investigations of contaminant transport induced by consolidation.

1. Consolidation test was conducted on contaminated sediments. Numerical simulations using CST2 model were in close agreement with experimental measurements for both settlement and excess pore pressure. This suggests that the CST2 computational model is capable of simulating local flow, and simulating transient advective transport caused by consolidation.
2. Numerical investigations were performed to see the significance of consolidation on contaminant transport. Even though concentration boundary condition was imposed to maximize the diffusive transport, transient advective flows significantly increase the rate of contaminant mass outflow and cumulated mass out. However, two layered capping system with RCM effectively reduces the rate of contaminant mass outflow which is accelerated by consolidation. This limited study has also indicated that neglecting to consider transient consolidation effects may lead to significant errors in transport predictions for soft contaminated sediments.

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Notation

The following symbols are used in this paper:

C_c	compression index
C_k	hydraulic conductivity index
c_0	initial pore fluid concentration
D^*	effective diffusion coefficient
e	void ration
e_0	initial void ratios
G_s	gravity of solids
K_d	distribution coefficient
k	hydraulic conductivity
S	settlement
s	sorbed concentration
u_e	excess pore pressures
α_L	longitudinal dispersivity
Δq	applied vertical effective stress
σ_v	applied vertical total stress
σ'	vertical effective stress