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Flow visualization using transparent synthetic soils

Visualisation de l'écoulement en utilisant des sols synthétiques transparents.

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ABSTRACT

Transparent materials including glass beads or quartz powder have been used to help in understanding flow processes through the soil. However, glass and quartz surrogates are limited by both their poor transparency and their inability to represent the geotechnical properties of soils. This paper demonstrates the feasibility of producing transparent soils made of amorphous silica gels or powders and liquids with matching refractive indices that can be used for modeling flow in soils, while representing the macroscopic geotechnical properties of a wide range of soils including sands and clays. Movement of a contaminant through soil was modeled. A clear pore fluid made of clear calcium bromide brine was used. A red dye was mixed in a mineral oil solution to represent contamination. The concentration of the oil-soluble dye solutions with known concentrations was simulated. These tests demonstrate that transparent synthetic soil can be used to visualize and non-intrusively measure pollutant transport in natural soils

RÉSUMÉ

Des matériaux transparents comprenant des perles de verre ou de la poudre de quartz ont été utilises pour mieux comprendre les procédés d'écoulement des sols. Cependant, le verre et des substituts à quartz sont limités par la médiocre qualité de leur transparence et leur incapacité de représenter les propriétés géotechniques des sols. Cet article démontre qu,il est possible de produire des sols transparents en utilisant des gels ou poudres de silice amorpheitatis et des liquides avec indices de refraction (index refringent) compatibles permettant de modeler l'écoulement des sols, tout en indiquant les propiétés géotechniques macroscopiques d,une large variété de sols, y compris les sables et argiles. Le movement d'un contaminant par le sol a été modelé. Un liquide de pore clair fait de saumure de bromure de calcium clair a été utilisé. Une teinture rouge a été mélangée à une solution d,huile minérale pour représenter la contamination. La concentration de la solution de teinture à l,huile soluble a été mesurée avec les concentrations préliminairement connues. Ces tests ont demontrés qu,un sol synthétique transparent peut etre utilisé pour visualiser et mesurer d,une maniére non-intrusive le transport de pollutant dans les sols naturels.

1 INTRODUCTION

One of the most difficult tasks in cleaning up a hazardous waste site where ground water may be contaminated, is to identify the location of the contaminants, which are released as either an aqueous solution or a non-aqueous phase liquid (NAPL). Currently, borings are relied on for both quantifying and locating the contaminants and are often unreliable and costly. The development of better technologies to address this problem requires laboratory testing using physical models. Transparent materials such as glass bead have increasingly been used in micromodels along with imaging technique (Corapcioglu and Fedirchuk 1999, Jia et al 1999, and Huang et al 2002). At the present time, large-scale models made of glass bead or quartz powder are limited by their poor transparency because air entrapped in the tiny cracks of glass particles reduces the transparency of these materials.

2 TRANSPARENT SYNTHETIC SOILS

Transparent synthetic soils have been showed to exhibit macro-scale geotechnical properties similar to those of natural soils *(Iskander, 1997, Iskander et al. 2002a,b* Sadek et al. 2002 *and Liu et al 2003).* These materials are truly transparent — not merely translucent. The transparent synthetic "Soils" used in this research are made by matching the refractive indices of amorphous silica and the pore fluids. Two families of transparent materials were developed for modeling sand and clay. The first family which models sand is made of transparent amorphous silica gels. The second family which models clay is made by consolidating suspensions of amorphous silica powders and liquids with matched refractive indices. The main advantage of these families is that they are the only system capable of resembling soils having a wide range of grain sizes including sand and clay using the same pore fluid (Fig. 1).

In this research, 2-D flow tests were performed to study the potential application of transparent synthetic soils for studying pollutant transport in soil. Visualizing the advection-dispersion process of pollutant transport was attempted by using image processing techniques to give a better understanding of the process.

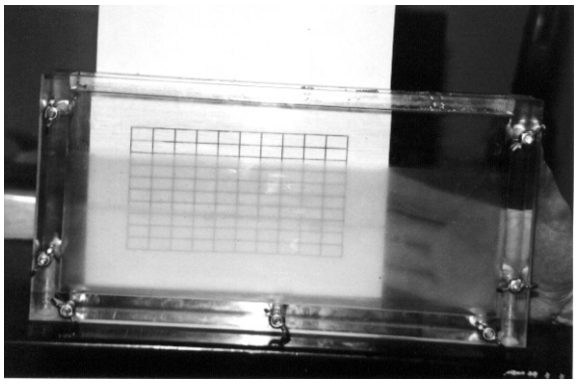

Fig. 1 — Target grid viewed through 50 mm thick layered transparent soil model. The bottom three rows are viewed through amorphous silica powder (represents clay) and the middle 4.5 rows are viewed through silica gel (represents sand). The top 2.5 rows are viewed through pore fluid.

2.1 *Sample Preparation*

Amorphous silica gel to model sand was used and obtained from Multisorb Technologies, Inc. with an average aggregate size of 1 mm. The geotechnical ptroperties of this material are detailed in Iskander et al (2002a). Two pore fluids were used in the flow tests. The first was mineral oil blend, which is a 1:1 blend of Drakeol 35 mineral oil and Norpar® 12 paraffinic solvent, by weight. The refractive index, viscosity, and density of the oil blend at room temperature (24°C) were 1.447, 5.0 cP, and 800 kg/m^3, respectively. The second pore fluid was a calcium bromide brine, which is a mixture of calcium bromide and water to have a refractive index of 1.448 at 25˚C to match the refractive index of mineral oil blend. The viscosity and density of this mixture at room temperature were 3.6 cP and 1572 kg/m^3, respectively.

Sample preparation proceeded as follows. First, amorphous silica gel was immersed in the oil blend. Second, vacuum was applied to de-air the mix until the mixture became transparent. Approximately 24 hours was required to fully saturate the silica gel. Third, silica gel was packed into a Plexiglas box to form a transparent amorphous silica gel sample. The box was partially filled with oil blend before packing. Silica gel was slowly poured into the box using a spoon. At the same time, the silica gel sample was stirred to release air bubbles entrapped during pouring. Once silica gel filled the box, a cover plate was screwed tightly onto the box with a gasket between the plate and the box.

3 TEST PROCEDURE

A Plexiglas box with an internal dimensions of 25×152×406 mm was used to perform the flow test. Pore fluid containing an oil-soluble dye was injected through one end of Plexiglas mold. Two reservoirs containing clear and dyed oil blend were connected to the pressure panel board to keep the pressure head constant. A manual switching valve was used to control the tracer injection. Flow was collected at the other end using a graduated cylinder. An optical system was used to measure the dye movement through transparent synthetic soil model (Fig. 2). The camera was set 1.20 m from the model with its optical axis perpendicular to the Plexiglas mold. A fluorescent lamp was used to illuminate the experiment.

Oil Red O from Fisher Scientific Company, Atlanta, GA. was used to dye the pore fluid in these tests. The concentration of the oil-soluble dye was measured using a fluorometer. The fluorometer used in this research was Spectronic® 20 GenesysTM (SG) from Spectronic Instruments. A calibration curve was made using ASTM Standard D5613. The frequency of light was selected based on the dye used and kept the same throughout the test. The calibration curve for Oil Red O is shown in Fig. 3. Fluorometer readings were linear up to a concentration of 0.15kg/m^3.

There is a chromatographic separation in silica gel when using an oil-soluble dye for flow test, where the dye was adsorbed by silica gel and became separated from the moving oil blend. Instead of using dyed oil blend, flooding transparent synthetic soil specimen with calcium bromide brine having a matching refractive index was recommended by Mannheimer and Oswald (1993), and later used by Welker et al (1999) to prevent chromatographic separation in transparent silica powder. So, after the sample preparation described earlier, two additional steps were followed. The sample was flooded with calcium bromide brine until the oil blend in the inter-aggregate pore volume was displaced by calcium bromide brine. The sample was flooded with the oil blend again until the brine in the inter-aggregate pore volume was replaced by mineral oil blend.

4 IMAGE ANALYSIS

When using a linear detector, the intensity of the image is proportional to the concentration of tracer. A similar method has been used by many researchers, including Aeby (1998), Corapcioglu and Fedirchuk (1999), and Huang et al (2002). In a solution containing a dye with a concentration, C, the fluorescence intensity F is given by Slavik (1994) as

$$F = \phi_f I_0 (1 - e^{-2.303\varepsilon Cl}) \tag{1}$$

where I_0 is the intensity of the incident light, l is the path length of the light, ε is the molar extinction coefficient of the dye, and ϕ_f, named the fluorescence efficiency, is the fraction of the absorbed light which is re-emitted as fluorescence. At low concentrations, where 2.303εCl<0.05, Eq. 1 can be approximated as follows:

$$F = 2.303\phi_f I_0 \varepsilon Cl \tag{2}$$

In this test, a linear detector (a CCD camera) was used. Therefore, the intensity of fluorescence in the image, I, is proportional to the fluorescence intensity F.

Background correction is required to reduce non-uniform lighting or camera response in different areas of the image. The correction was obtained by using an image processing toolbox of Matlab®.

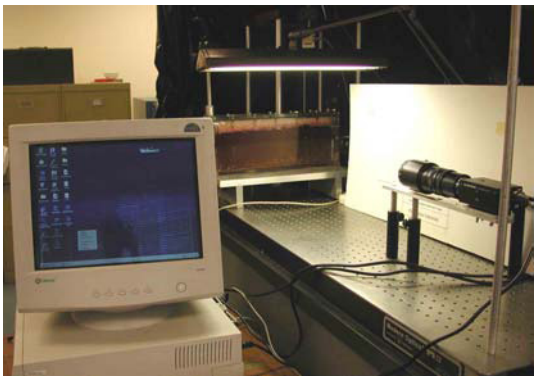

Fig. 2 – Optical Setting for Flow Measurement

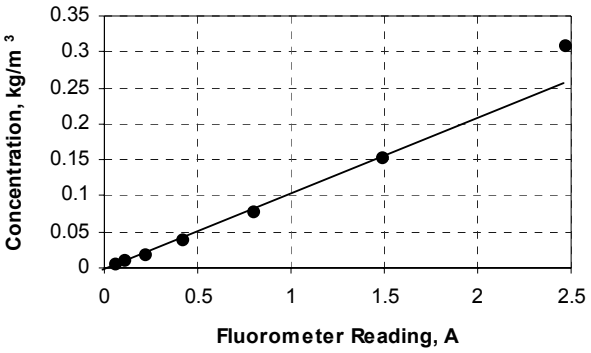

Fig. 3 – Calibration Curve for Oil Red O at 581 nm

Movement of the tracer through silica gel is shown in Fig. 4. In order to have a clearer view of flow movement, a three-dimensional view was performed, where the intensity value at each point was projected along the z-axis. The figure shows that both advection and dispersion processes occurred in the flow transport through transparent silica gel. In order to illustrate the dispersion with time, the contour of relative intensity is also

shown. The regions were labeled to illustrate qualitatively the dispersion process with time.The volumes obtained directly from Fig. 4 are given in Table 1. The areas under the distribution curves were increasing with time.

Table 1 – The Volume under The Intensity Surface

Time, min (Min)	Volume (ml)	Change %
163	3644647	---
180	3648481	1%
216	4086105	12%
233	4376765	---
261	4457327	1.9%
280	4678450	6.7%

5 BREAKTHROUGH CURVE

The breakthrough curve of the dye through silica gel is shown in Fig. 5, where the flow volume was measured in the effluent using a graduated cylinder. Times for the measurements were also recorded at the same time. The injected fluid volume was recorded from the beginning of tracer injection.

The breakthrough curve resembled the typical bell shape and slightly steeper on the rising limb than on the falling limb. The tail was much longer and flatter than the leading stage. Dye was not detected in the first 250 ml. The concentration increased sharply after this until the peak of concentration was measured at the flow volume of approximate 340 ml. Concentration of dye reduced much slower after the peak concentration and still could be detected after the flow volume of 650 ml, where the test was stopped.

6 CHARACTERIZING THE PROPERTIES OF SILICA GEL

Silica gel has a two-pore structure, internal porosity and inter-aggregate porosity. The total porosities under loosest and densest test conditions were estimated by measuring the volume of dry silica gel. Based on the assumed specific gravity of 2.1 for silica gel, the volume was indirectly estimated by measuring the unit weight of sample. The total void ratios of the loosest and densest conditions were 1.79 and 1.46 corresponding to total porosities of 0.64 and 0.59. In order to estimate the inter-aggregate porosity of the silica gel, natural sand with a similar grain size distribution was used to estimate the inter-aggregate porosity of silica gel. The inter-aggregate void ratio was 0.60 corresponding to a porosity of 0.37 for the densest condition.

Pore volume can also be estimated by performing a tracer test and studying the resulting concentration history measured at the out flow. For a single-phase, nonreactive flow in a packed bed, the pore volume corresponds to the dimensionless mean residence time (Himmelblau and Bischoff 1968 and Jin 1995), $\overline{t_D}$, which is calculated from the tracer breakthrough curves resulting from an idealized instantaneous tracer pulse.

$$\overline{t_D} = \frac{\int_0^\infty t_D C_D \, dt_D}{\int_0^\infty C_D \, dt_D} \tag{4}$$

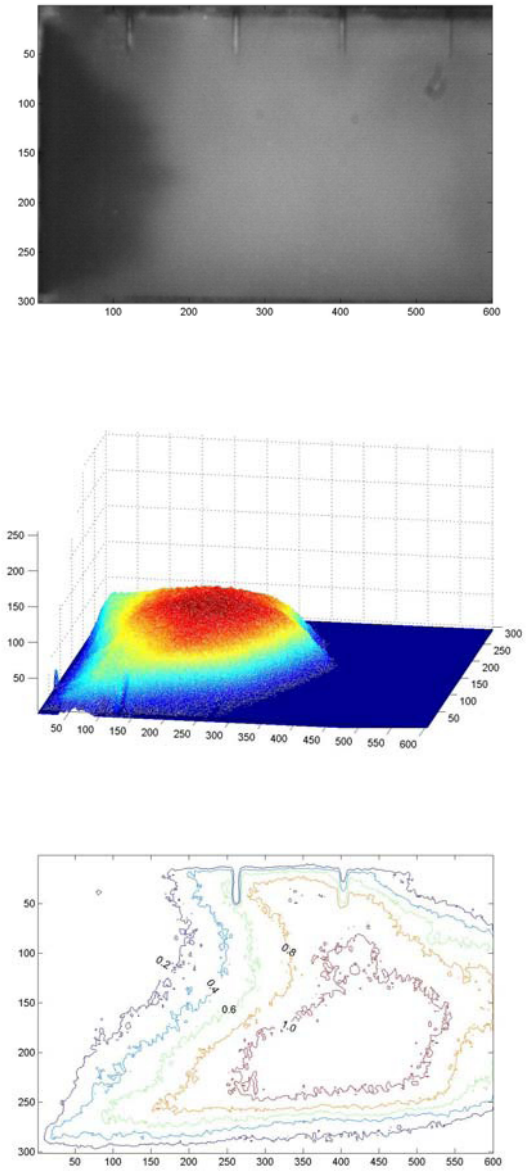

Fig. 4 - Flow through transparent soil model. Corrected image after 102 min of flow (top) 3-D View of Solute Transport after 233 min (middle) Contours of Dye Concentrations after 326 min (bottom)

where $C_D = \frac{C - C_{initial}}{C_{injected} - C_{initial}}$ is dimensionless tracer concentration, which is a function of t_D, and $t_D = \frac{\int_0^t q dt}{V_p}$ is dimensionless time. Vp is the pore volume of vessel and q is the volumetric flow rate. The dimensionless pore volume is the difference between the mean residence time of output and input tracer curves for a finite-volume. Corrected pore volume is given by

$$\overline{t_D} = \frac{\int_0^\infty t_D C_D \, dt_D}{\int_0^\infty C_D \, dt_D} - \frac{t_s}{2} \tag{5}$$

where t_S is duration of slug injection.

The pore volume estimated from breakthrough curve was 353 ml, which was 40 % smaller than that estimated by using

dry sand. The mass of slug predicted from breakthrough curve was 0.0248g, which was 25 % larger than the injected slug, 0.0199g. The difference was mainly caused by the errors in the estimation of the inter-aggregate pore volume. Manual sampling and a low sampling frequency were believed to introduce some errors in the test. A better result is expected by using an auto-sampler sampling at a higher sampling frequency.

Flexible wall permeability tests were performed according to ASTM test method D5084 to measure hydraulic conductivity. The samples were permeated with the oil blend during the triaxial tests. Hydraulic conductivity around 1.5×10-4 cm/sec was measured for the silica gel, which corresponds to intrinsic permeability of 1 Darcy.

The longitudinal dispersivity, Dl , is a characteristic of soil used to describe the dispersion in the direction of flow. The longitudinal dispersivity was calculated using the method mentioned by Domenico and Schwartz (1990) based on the measured breakthrough curve.

$$D_l = \frac{v^2 \sigma_t^2}{2t} \tag{6}$$

where σ_t is the standard deviation derived graphically from breakthrough curve form, which can be estimated as the following.

$$\sigma_t = \frac{t_{84} - t_{16}}{2} \tag{7}$$

where t_{84} and t_{16} are the breakthrough times corresponding to relative concentration of 0.84 and 0.16, respectively, and t is the time corresponding to relative concentration of 0.5. The breakthrough curve is shown in Fig. 5. An average flow rate of 0.008 mm/sec was used. Based on the method mentioned above, a longitudinal dispersivity around 0.60 mm was calculated, which is within the measured laboratory range of 0.1 to 1mm for natural soil (Charbeneau 2000).

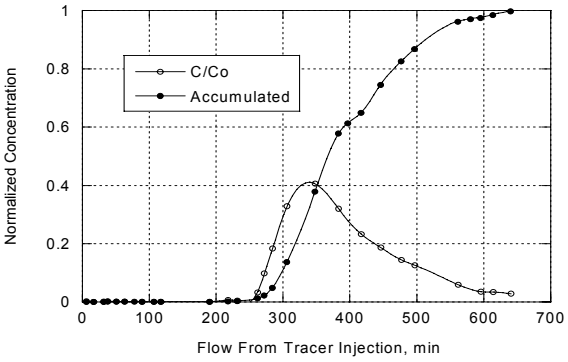

Fig. 5 – Relative and Accumulated Concentration Curves

7 CONCLUSIONS

2-D flow of an oil-soluble dye through transparent silica gel and fused silica were performed. The breakthrough curves of dye through both materials were typical of the bell-shape reported for natural soil. Image analysis shows both the advection and dispersion processes clearly visible in the test. It demonstrated that transparent synthetic soil can be used to visualize and non-invasively measure pollutant transport in natural soil. Calcium bromide brine was effective in preventing chromatographic separation in silica gel, though it reduces the transparency of sample. More research and improvement in the test set-up and analysis are needed as follows. First, a more accurate relationship between tracer concentration and light intensity is required. Second, a more accurate method is required in estimating the pore volumes in silica gel. Finally, comparisons with numerical solutions for well-defined test conditions are needed for the application of transparent soil in pollutant control.

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REFERENCES

Aeby, P.G. (1998). *Quantitative Fluorescence Imaging of Tracer Distributions in Soil Profiles*, Ph.D. Dissertation, Swiss Federal Institute Of Technology, Zurich, Swiss.

ASTM Standard D5084 (1993). "Standard test method for measurement of hydraulic conductivity of saturated porous materials using a flexible wall permeameter." *1993 Annual Book of ASTM Standards*, ASTM Vol. 04.08, Philadelphia, PA, 1199–1206.

ASTM Standard D5613 (1994). "Standard Test Method For Open-Channel Measurement Of Time Of Travel Using Dye Tracers. " *1994 Annual Book of ASTM Standards*, ASTM Vol. 04.11, Philadelphia, PA, 725–742.

Charbeneau, R.J. (2000). Groundwater Hydraulics and Pollutant Transport, Prentice Hall, NJ.

Corapcioglu, M. and Fedirchuk, P.(1999). "Glass bead micromodel study of solute transport." *J. of Contaminant Hydrology*, 36(2), 209-230.

Domenico, P. and Schwartz, F. (1990). *Physical and Chemical Hydrogeology*. Wiley, NY.

Himmelblau,D.M. and Bischoff, K.B.(1968). *Process Analysis and Simulation. Deterministic Systems*, John Wiley & Sons, Inc., New York.

Huang, W.E., Smith, C., Lerner, D., Thornton, S., Oram, A. (2002). "Physical modeling of solute transport in porous media: evaluation of an imaging techniques using UV excited fluorescent dye." *Water Research*, 36(7), 1843-1853.

Iskander, M. (1997) "A Transparent Material to Model the Geotechnical Properties of Soils," *Proceedings, ICSMFE,* Hamburg Germany

Iskander, M., S. Sadek, and Liu, J. (2002a). "Optical measurement of deformation using transparent silica gel to model sand." Int.J. of Physical Modeling in Geotechnics, 2(4), 13-26.

Iskander, M., Liu, J., and Sadek, S. (2002b). "Transparent amorphous silica to model clay." ASCE *J. of Geot. & Geoenv. Eng*., 128(3), 262-273.

Jia, C., Shing, K. and Yortsos, Y.C. (1999). "Visualization and simulation of non-aqueous phase liquids solubilization in pore networks." J. of Contaminant Hydrology, Vol. 35, 363-387.

Jin, M. (1995). *A Study of Nonaqueous Phase Liquid Characterization and Surfactant Remediation*. Ph.D. Dissertation, University of Texas at Austin, Austin, USA.

Liu, J., Iskander, M. & Sadek, S. (2003). "Consolidation and Permeability of Transparent Amorphous Silica." ASTM Geotechnical Testing Journal, 26(4) 390-401

Mannheimer, R. and Oswald, C. (1993). "Development of transparent porous media with permeabilities and porosities comparable to soils, aquifers, and petroleum reservoirs." *Ground Water* 31(5), 781-788.

Multisorb Technologies Inc. (2001). 325 Harlem Road Buffalo, NY 14224-1893 USA www.multisorb.com

Sadek, S., Iskander, M., & Liu, J. (2002). "Geotechnical properties of transparent material to model soils." *Canadian Geotechnical J.*, 39(1), 111-124.

Slavik, J. (1994). *Fluorescent Probes in Cellular and Molecular Biology*, Boca Raton, CRC Press.

Welker, A., Bowders, J., and R. Gilbert (1999). "Applied research using transparent material with hydraulic properties similar to soil." *Geotechnical Testing J*., GTJODJ, 22(3), 266–270.