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An experimental study of LNAPL lens formation using a centrifuge

Une étude expérimentale de formation d'objectif de LNAPL enutilisant une centrifugeuse

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ABSTRACT

Understanding movement of light non-aqueous phase liquids (LNAPLs) in a subsurface environment is important for effective remediation and recovery. Processes involving LNAPL formation of a lens shaped plume on the groundwater table is of particular interest since the LNAPL lens can act as a long-term source of groundwater contamination. In this study, two-dimensional centrifuge model tests were carried out to simulate the movement of an LNAPL plume in the vadose zone and to investigate how LNAPL accumulates and forms a lens-shaped plume above the unconfined aquifer. The model represents a point spill of an LNAPL from approximately 1 meter above the water table in prototype scale. We present a description of the centrifuge test system we developed and the results obtained from image analysis. The comparison of the centrifuge tests and the numerical simulations showed good overall agreement especially in the plume shape and propagation pattern. The shape of the LNAPL plume was observed to elongate when a sloping groundwater table was simulated in the model tests.

RÉSUMÉ

La compréhension du mouvement des liquides légers en phase non-aqueuse (LNAPLs) dans l'environnement sousterrain est important pour leur remédiation efficace. Le processus de LNAPL formant une plume en forme de lentille sur la table d'eaux souterraines est d'un intérêt particulier puisque une lentille de LNAPL peut agir comme une source à long terme pour la contamination des eaux souterraines. Dans cette étude, une série d'essais sur maquette bidimensionnels de centrifugeuse a été effectuée pour simuler le mouvement d'une plume de LNAPL dans la zone vadose et pour étudier comment LNAPL s'accumule en formant une plume en forme de lentille au-dessus d'un aquifère non restreint. Le modèle représente un point de contamination du LNAPL approximativement a 1m au-dessus de la table de l'eau à l'echelle du prototype. Summerized en cet article est la description de système d'essai de centrifugeuse ainsi que les résultats obtenus dans cette experience.

1 INTRODUCTION

Migration of non-aqueous phase liquids (NAPLs) in the subsurface is complex and the transport processes are not well understood yet. Spilled LNAPLs, such as gasoline, generally migrate downward through the vadose zone due to gravitational forces, eventually forming a lens-shaped mound above the groundwater zone. This LNAPL lens acts as a long-term source of contamination. LNAPL components such as MTBE (Methyl Tertiary Butyl Ether) can be transported by diffusion or convection into groundwater (Squillace et al., 1995). Migration of MTBE into groundwater depends on the size of the lens-groundwater diffusion interface and therefore strongly depends on the lateral extent of the LNAPL lens plume.

The propagation of LNAPL in the subsurface involves multiphase flow through porous media (air, water, and LNAPL). Several numerical models for multiphase transport have been presented. While these models are theoretically rigorous and their capabilities address a variety of subsurface environments, such models often have limited applicability, especially for the analysis of transport in three-dimensional domains, due to their high computational cost. Furthermore, laboratory experiments are indispensable for model verification as well as comparisons with analytical or numerical solutions of alternative mathematical models.

Laboratory experiments have been conducted to simulate LNAPL migration in the subsurface. Laboratory experiments can be used to evaluate spill and remediation scenarios under controlled conditions; however, conventional experimental approaches are typically time-limited because there exists both geometrical and temporal restrictions for conducting simulation of LNAPL migration at the field-scale (Chevalier and Petersen, 1999). The geotechnical centrifuge has been recognized as a tool to overcome some of these restrictions for multiphase flow problems. The major attraction of using a geotechnical centrifuge to study NAPL transport is the ability to reduce testing time and to mimic unsaturated conditions above the water table in a scale model. By reducing the time scale, one is able to simulate long-term transport processes, while minimizing exogenous effects, such as evaporation or change of fluid properties by microbe growth. Reduction of the geometric scale enables the simulation of processes at the field-scale. However, the number of centrifuge studies for multi-phase problems is still few and the applications reported to date are often highly hydrogeologically simplified. For instance, the effect of a sloped water table, which is most likely seen in a remediation scenario, has not been studied extensively.

The main objectives of this study are to identify the dependency of the LNAPL lens on groundwater table inclination and to investigate feasibility of the centrifuge as a tool to simulate multiphase transport. For these purposes, we performed a series of two-dimensional centrifuge tests and compared test results with a numerical code. This paper describes the experimental system we developed and presents test results obtained from image analysis.

2 EXPERIMENTAL SETUP

Two-dimensional centrifuge model tests were performed using the 1 m radius centrifuge at the University of California, Davis. A finite source of test LNAPL was introduced at the middle of the vadose zone in the uniformly packed sand and left to distribute. All three centrifuge tests presented in this paper were conducted at 10g. In prototype scale, the dimension of the domain is 4.32 m long and approximately 2.54 m in depth, with a groundwater table approximately 1 m below the point source. Groundwater was considered to be at steady condition.

2.1 *Test material and system*

Nevada sand was used as the test soil. Mean particle diameter, uniformity coefficient, and saturated hydraulic conductivity of Nevada sand are 0.15 mm, 1.6, and 1.35×10^{-1} mm/sec, respectively. Soltrol 220 was selected as the test LNAPL because it presents a low hazard, and it has properties suitable to this study. Soltrol 220 is virtually non-soluble and non-volatile synthetic oil having a density of 0.8 g/cm^3 and a viscosity of 4.5 cSt. Interfacial tension of air-Soltrol and Soltrol-water are 0.0259 N/m and 0.0364 N/m respectively (Liu et al. 1998). To enhance the contrasts between the fluids, red lipid stain (Sudan Red) was added to Soltrol.

A schematic of the experimental setup is shown in Figure 1. A box container measuring 432 × 51 × 279 mm was used for the experiments. One of two side walls was made of acrylic plate to allow visual observation of fluid movement. Ports to install three fluid control tubes (one for LNAPL injection and two for groundwater table control) were all installed through the other side wall, made of stainless steel. The location of the injection point was at 152 mm from container bottom and 165 mm from the upstream boundary. The distance between the water table and the LNAPL injection point was approximately 100 mm, or 1 m in prototype scale.

A metallic tube was used to introduce the LNAPL into the soil as a line source (a point source for two-dimensional model). The inside of the tube was sectioned into two parts and separated by a rectangular plate. First, the LNAPL that is supplied from a peristaltic pump is pooled into one space. When the LNAPL level surpasses the height of the separating plate, it overflows to the other section of the tube and spilled into the soil through a slit on the bottom. The tube was lined with geotextile which had a greater capillary tension than the sand to aid the distribution of LNAPL as a line source.

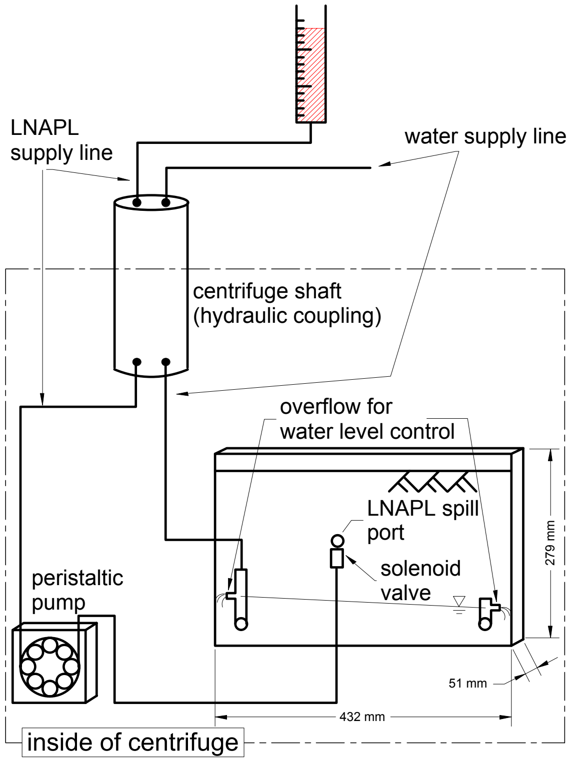

Figure 1. Test setup

Two perforated metal tubes installed at the bottom corners of the container were used to supply or drain water into/out of the soil sample. One tube on upstream side was connected to a water supply line. From the both ports, water was allowed to overflow at predetermined heights to maintain steady groundwater condition during the tests.

2.2 *Model preparation and test procedures*

The sand sample was prepared by pluviating dry sand. The LNAPL injection tube, and the water supply/drainage ports were installed onto the back panel of the container during the pluviation. After packing, porosity was measured and the container was placed into a vacuum chamber to completely saturate the sample. De-aired water was slowly introduced from the water supply/drainage ports under vacuum condition. After the sample saturation process was completed, the LNAPL injection tube and water supply port were connected to LNAPL supply line and water supply line respectively. Water was allowed to drain from the water supply/drainage ports and subsequently the centrifuge test was initiated. On the centrifuge platform, a 45 degree inclined mirror was placed in front of the acrylic window. Once the centrifuge spins and the platform swings up, the video camera mounted on the centrifuge center shaft can capture LNAPL plume migration.

After steady groundwater condition was achieved at 10g, LNAPL was introduced as a pulse flux by operating the peristaltic pump. At each test, migration of LNAPL was monitored approximately for 2 hours which corresponds to 200 hours observation in prototype scale using the centrifuge model scaling relationship for a 1/10 scale model (Arulanandan et al. 1988).

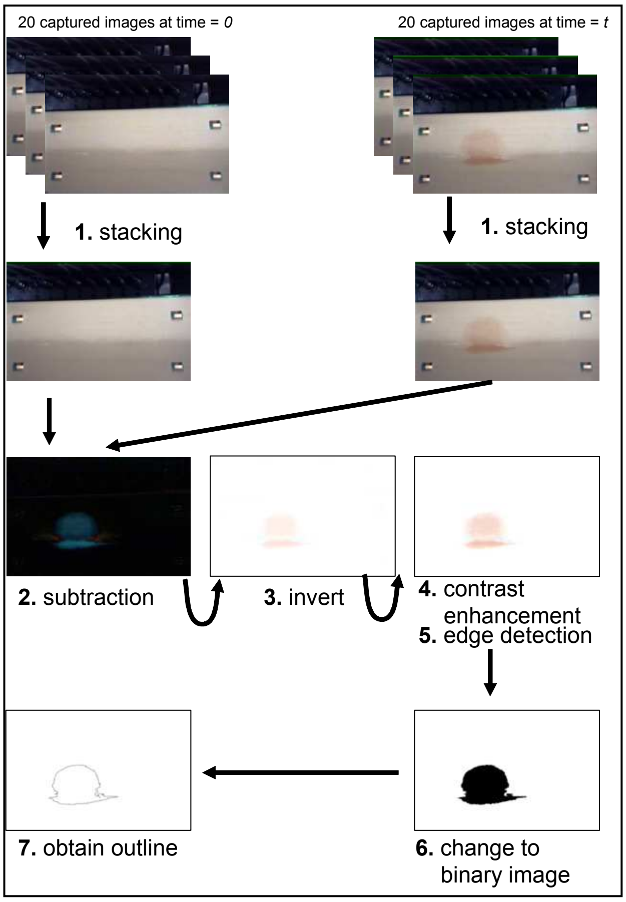

Figure 2. Procedure of image processing

2.3 *Image Processing*

Migration of the LNAPL plume was recorded via a VHS video recorder. Snap shots at given time were captured as 24 bit RGB (Red-Green-Blue) images to identify change of the LNAPL plume size and location. Figure 2 illustrates the image processing procedure. The captured images were processed by (1) image stacking, (2) image arithmetic, (3) edge detection, and (4) scale calculation.

The image stacking was performed to enhance the image quality. An image captured from the video camera consists of two portions, signal level due to the object being imaged and signal level due solely to noise. Under poor lighting condition during centrifuge spin, images may not be always clear enough to perform data analysis. Assuming the noise is randomly distributed in time and space, an averaged image, obtained by stacking, approaches the true image according to the central limit theorem. Twenty images were randomly captured at specific time within ± 1 second and then stacked. A stacked image was generated by averaging pixel values of the twenty images.

Image arithmetic was performed in order to extract the shape of the LNAPL plume from the stacked images. The image arithmetic operation consists of three subtasks: (i) subtraction, (ii) inversion, and (iii) contrast enhancement. The subtraction operation takes two images as input and produces as output a third image whose pixel values are simply those of the first image minus the corresponding pixel values from the second image. Subtraction of an image at arbitrary time from an initial image (i.e., image before the LNAPL spill) generates the change of pixel values caused by the movements of the LNAPL and water.

After inversion and contrast enhancement, the LNAPL plume edge was defined by an arbitrary pixel value threshold, and the image was changed from RGB to binary format to obtain an outline of the LNAPL contaminated area and to calculate the area, perimeter length, and x-y coordinate of the center.

3 TEST RESULTS

Summary of the test series is shown in Table 1. While similar LNAPL injection rate and volume were maintained, groundwater slope was varied at each test. Figure 3 shows the progression of the LNAPL plume front accompanied by an image of the initial condition as a background. Before LNAPL was injected, it was seen that the soil has two visibly distinctive regions. When matric potential becomes more negative than the bubbling pressure, water begins to drain so that saturation decreases. Sudden changes in saturation caused such visibly distinctive wet-dry boundaries.

As a general rule for all the tests regardless of the test conditions, when the injection began, the LNAPL immediately spread in all directions and the plume formed an expanding circular shape with the top coinciding with the injection point. At this stage, the quantity of the LNAPL released into the unsaturated soil was relatively small, thus the capillary force was dominant in the LNAPL movement. When sufficient quantity of the LNAPL was introduced to approach local saturation, the plume began to move mainly vertically downward. The beginning of downward movement was seen during the injection process for all the tests. At this stage, although the LNAPL still continued to diffusively spread in all directions, the movement of the bulk LNAPL was downward. Hence the gravitational force was more dominant than the capillary force. It was seen that when the LNAPL plume reached the vicinity of the wet-dry boundary, the LNAPL began to spread in the lateral direction, and gradually formed a ‘lens’ shaped plume.

Table 1. Test case description

Test Case	Injection Rate, [ml/min/cm]	Injection Volume [ml/cm]	Groundwater condition (hydraulic gradient)
L1	2.77	19.1	0
L2	2.55	17.8	0.5/15
L3	2.64	18.0	1/15

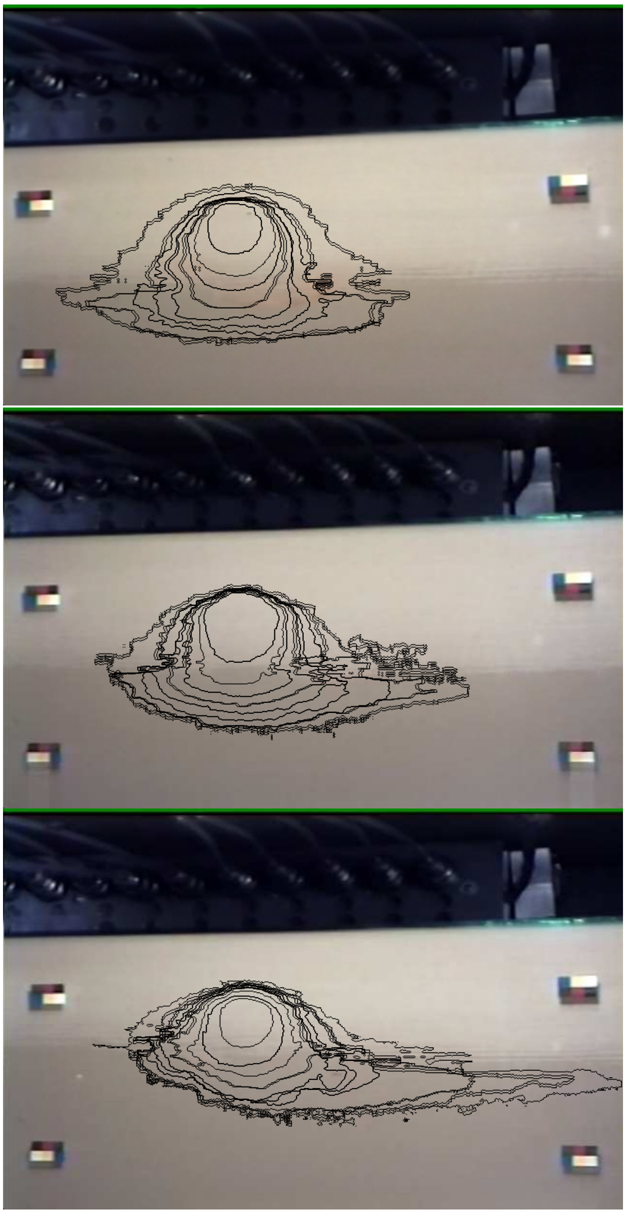

Figure 3. Progression of LNAPL plume up to 200 hours in prototype scale: (top) L1; (middle) L2; (bottom) L3.

For all the tests, the downward LNAPL plume movement in the dry zone was fairly vertical regardless the groundwater condition. However, for the tests in which the water table was sloped, more lateral spreading was seen at the downstream side than that at the upstream side, and the center of the lens-shaped plume (the thickest region) shifted from underneath the injection point to the downstream side. In test L1, the LNAPL plume remained under the injection point but the plume was not completely symmetrical. Lack of symmetry may be explained by local compositional heterogeneity, or possibly, the water table was slightly sloped due to small unintended height difference between the two water outlets.

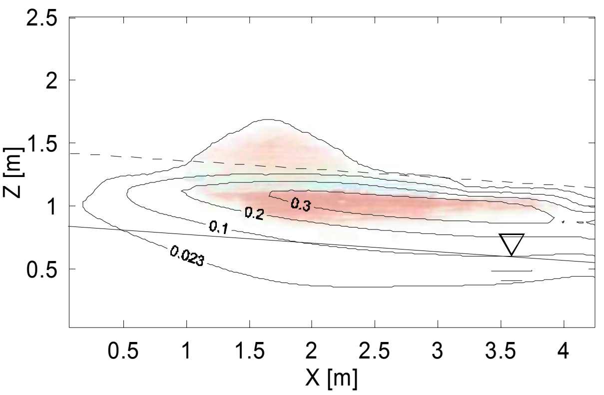

Figure 4. Predicted LNAPL distribution from the STOMP and the centrifuge test L3 (200 hours after spill)

It was seen for all the tests that edge of the lens-shaped plume exhibited many horizontal notches. The sand models were prepared by dry pluviation, and it resulted in the occurrence of many thin stratified layers. It could be considered that the stratification generated local heterogeneity, and consequently the spreading speed in the lateral direction varied in different stratified layer. However, such notched spreading variation was in local scale (1 ~ 3 mm), and at the length scale of the bulk plume ($10^{1\sim2}$ mm), the plume seemed reasonably smooth. Thus it is considered that the bulk LNAPL plume movement was mainly controlled on a macroscopic length scale even though microscopic heterogeneity also influenced on the movement.

Longer lateral extent of the lens-shaped plume in sloped groundwater table conditions causes more contact area between the plume and the water phase. If mass transfer of components in LNAPL to the water phase is of concern, such wider lateral extent will alter the long-term transport process.

4 COMPARISON WITH NUMERICAL MODEL

Numerical model analyses were also undertaken using STOMP (White et al. 1995) to provide comparison with the centrifuge test results. The STOMP simulations correspond to the same initial and boundary conditions of the centrifuge tests but in prototype scale. Air-phase was assumed to be passive and mass-transfer between phases was excluded. The soil unsaturated hydraulic parameters (i.e., retention curve fitting parameters for air-water system) determined from hanging-column tests were used as input data.

As a sample result, Figure 4 shows LNAPL saturation contour at 200 hours after the spill for L3 test case. The contour is overlaid on the plume image captured from L3. A dashed line indicates the wet-dry boundary. The perimeter value of the contour was taken from the experimentally determined irreducible LNAPL saturation value 0.023.

Although the agreements between the STOMP simulations and the centrifuge tests are not exact, LNAPL migration pattern and shape of the plume are very comparable for all three cases. As seen from the centrifuge tests, the LNAPL spreading in the lateral direction starts when the plume reaches slightly below the wet-dry boundary apparent in the window.

The discrepancies between the simulations and the centrifuge test results are found in the migration speed and the size of the plumes. The LNAPL plume movement computed by STOMP is much faster than the corresponding centrifuge test observations. The difference in plume movement speed between the experiments and the STOMP simulations becomes more apparent as the water table slope increases. Steeper water table slopes basically lead to faster and wider movement of the plume than the case of the flat water table. The discrepancy in position of the plume became significant at the lower portion of the lens-shaped plume, where LNAPL saturation was low and water saturation was high, while the residual saturation area above the lens-shaped plume is fairly comparable between the simulations and the centrifuge tests. Better agreement in the area above the lens-shaped plumes is may be explained by the fact that the permeability of LNAPL above the lens-shaped plume was low, so that differences between the experimental observation and the simulation were not clearly detectable. It might be possible that the input intrinsic permeability was larger than the actual value resulting the faster plume movement. The discrepancies at low LNAPL saturation might be attributed to constitutive models that describe permeability-saturation-pressure relations used in the STOMP model. If the decrease in relative permeability with decreasing fluid saturation had been larger, the LNAPL plume movement would have been more similar between the centrifuge test results and the STOMP simulations. It should be noted that a non-wetting fluid (i.e., LNAPL) entry pressure phenomenon was omitted from the saturation-pressure relation in the constitutive models used in the STOMP. As a result, in the STOMP simulations, the LNAPL would enter the pore spaces more readily than the centrifuge tests. This would explain the discrepancies at lower portion of the lens-shaped plume where water saturation was high.

5 SUMMARY AND COCLUSION

The centrifuge model tests simulating LNAPL migration from a point source over the groundwater table formed lens-shape plumes over the water table that spread along the water table slope. Image analysis techniques including stacking and image arithmetic were very useful for defining the plume boundaries in the experiments. The numerical analyses showed faster movements and larger propagation of spilled LNAPL than the centrifuge test results. Nonetheless, the comparison of the simulation results and the centrifuge tests showed good overall agreement, especially in the plume shape and propagation pattern. The agreement lends credence to both the centrifugal modeling technique and the employed numerical procedure.

REFERENCES

Arulanandan, K., Thompson, P. Y., Kutter, B. L., Meegoda, N. J., Muraleetharan, K. K., and Yogachandran, C. 1988. “Centrifuge Modeling of Transport Processes for Pollutants in Soils.” Journal of Geotechnical Engineering. 114(2): 185-205.

Chevalier, L.R. and Petersen, J. 1999. Literature review of 2-D laboratory experiments in NAPL flow, transport, and remediation. Journal of Soil Contamination. 8(1): 149-167.

Liu, Y.P., Hopmans, J.W., Grismer, M.E., and Chen, J.Y. 1998. Direct estimation of air-oil and oil-water capillary pressure and permeability relations from multi-step outflow experiments. Journal of Contaminant Hydrology. 32: 223-245.

Squillace, P.J., Pope, D.A., and Price, C.V. 1995. Occurrence of the gasoline additive MTBE in shallow ground water in urban and agricultural areas. US Geological Survey Fact Sheet FS0114-95.

White, M.D., Oostrom, M., and Lenhard, R.J. 1995. Modeling fluid flow and transport in variably saturated porous media with the STOMP simulator. 1. Nonvolatile three-phase model description. Advances in Water Resources 18(6): 353-364.