Determination of hydrodynamical dispersion factors at the laboratory scale

Détermination des facteurs de dispersion hydrodynamique à l'échelle de laboratoire

P. Conde, C. Frippiat & A. Holeyman

Civil and Environmental Engineering Department, Université catholique de Louvain, Louvain-la-Neuve, Belgium

ABSTRACT

A new laboratory method has been developed to simultaneously determine longitudinal and transversal dispersivities at small scale. A column system, classically used to determine longitudinal dispersivity, has been adapted by dividing the inlet and outlet flasks into three independent concentric zones. Step variations in concentration are performed in the central inlet zone. Time evolution of concentrations in the three outlet zones is measured using electrical sensors. Slope of the S-shaped curves is representative of the longitudinal dispersivity, while final constant concentration levels in each of the concentric zones are mainly affected by transversal dispersivity. Results obtained with hand-compacted Brusselean sand samples of 11 centimeters long are presented in this paper.

RÉSUMÉ

Une nouvelle méthode de laboratoire pour déterminer simultanément les dispersivités longitudinale et transversale à petite échelle a été développée. Un dispositif de colonne, classiquement utilisé pour déterminer la dispersivité longitudinale, a été adapté en divisant les flasques d'entrée et de sortie en trois zones concentriques indépendantes. Des variations de concentration sont réalisées sur la zone d'alimentation centrale. L'évolution temporelle des concentrations à la sortie est mesurée à l'aide de capteurs électriques. La pente des courbes de transfert est représentative de la dispersivité longitudinale, tandis que les niveaux de concentration finale dans chacune des zones de sortie sont directement liés à la dispersivité transversale. Des résultats obtenus sur des échantillons de sable Bruxellien compactés de 11 centimètres de long sont présentés dans cet article.

1 INTRODUCTION

Soil and aquifer contamination remain nowadays crucial problems too frequently encountered by civil engineers. In order to predict the expansion of a contaminant plume in the soil and in order to correctly design the remediation technique to be used, one needs to understand how will the contaminant move through the porous media. A good knowledge of the main transport parameters, including longitudinal and transversal dispersivities, is then required.

The determination of the dispersive characteristics of soils can be made either on site (e.g. by tracer tests) or in the laboratory (generally on soil monoliths). However, existing methods to quantify transversal dispersivity generally require plume mapping, which is only possible when using geophysical instruments, or point measurements of breakthrough curves, which may not be representative of the global behavior of the particle cloud. In this paper, a new laboratory method is developed to determine both longitudinal and transversal dispersivities at small scale. Classically, at this scale, longitudinal dispersivity can be determined by one-dimensional tracer test into soil columns. Adaptations to this system allow one to conduct two-dimensional tracer experiments from which transversal dispersivity can also be deduced.

2 EXPERIMENTAL SETUP

The method is based on two-dimensional tracer tests into soil columns (fig 1). In order to perform this kind of experiments, the inlet flask of the cylindrical column is divided in three independent concentric zones. Each zone has the same surface and is supplied by two specific tubes, one being the inlet solution feeding tube and the other one allowing one to perform pressure measurements. The outlet flask is similarly modified, so that a two-dimensional image of the response of the system can be recorded.
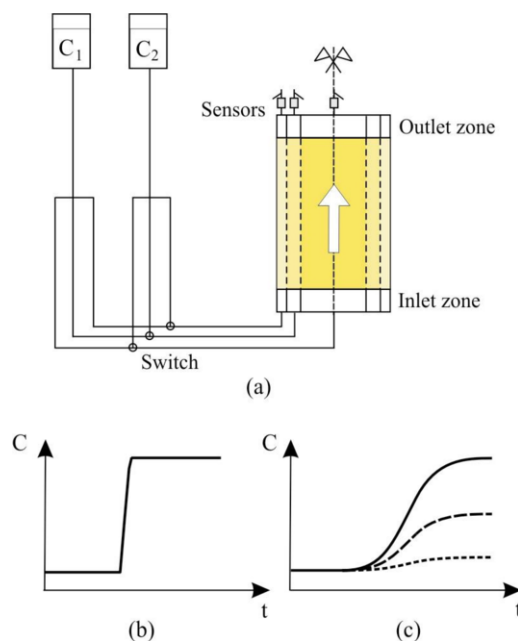

Figure 1. (a) Experimental setup. (b) Initial condition in the central zone of the inlet flask. (c) Time variation of concentration in the three zones of the outlet flask.

The concentration of the inlet solution and the hydraulic head can be imposed different in each zone of the column. Many two-dimensional injection schemes can then be performed with this new experimental device. Although the system allows one to simulate non-uniform flow, only constant mean velocity situations are investigated in this study.

Evolution of effluent concentration in the three outlet zones is measured with external on line electrical sensors. The solu-

tion passes through a stainless steel tube being the first electrode of the sensor. The other one is a perpendicular needle, electrically isolated from the first one (fig 2). Sensors are supplied by a sinusoidal current (1 mA of intensity and 1 kHz of frequency).
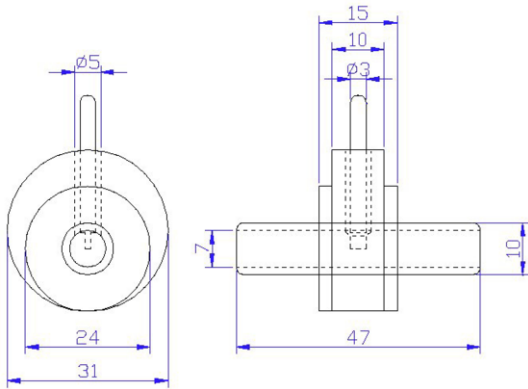

Figure 2. Electrical sensor plan in [mm].

The sensors have been calibrated with NaCl solutions within the range of measured concentrations (0.1 to 0.6 g/l of NaCl) and the range of normal use temperatures (20 to 25.5°C). Quadratic regressions were used to link concentration C with the inverse of measured tension drop V. Coefficients of the regression were found to be temperature dependent and a quadratic law was also adopted for these coefficients.

The measured values of concentration correspond to the averaged concentrations in the three outlet zones. That means the effluent concentration can be followed at the end of the column.

Laboratory experiments were performed on hand-compacted and saturated Brusselean sand samples of 11 cm long and 10.4 cm of diameter. The main characteristics of this sand are summarized on table 1.

Table 1 : Main characteristics of Brusselean sand

Property	Unit	Values
Specific weight	kN/m³	25.98
Lime content	%	0.62 – 0.79
Organic content	%	0.14 – 0.17
Mean diameter	mm	0.3
Uniformity coefficient	-	2.43
Porosity range	%	35.3 – 52.4
Permeability	m/s	$1.2 – 3.6 \ 10^{-4}$

In order to validate the basic experimental setup, homogeneous injections (one-dimensional problems) were first realized. After saturating the soil column with a NaCl solution at 0.1 g/l, the inlet solution was rapidly replaced by a solution at 0.6 g/l in all of the three zones. That kind of tracer test only allows the determination of the longitudinal dispersivity. Unavoidable small variations (under the millimeter) of the hydraulic head in the three outlet zones made difficult to maintain a homogeneous velocity in all the soil sample.

Then, step variations in concentration of NaCl solutions were performed in the central inlet zone only (two-dimensional axi-symmetrical problem) while the time evolution of effluent concentrations were recorded in the three outlet zones (fig 1c).

While the longitudinal dispersivity α_L [m] influences the slope of the S-shaped curves, the transversal dispersivity α_T [m] mainly affects the final constant concentration levels in each of the concentric zones.

In both cases, up and down step of concentration from 0.1 g/l to 0.6 g/l were performed.

3 INTERPRETATION METHODS

The dispersive characteristics of the tested soils are determined by inverse modeling of the tracer transport events into the column. Depending on the type of tracer test, the model can be analytical or numerical. In the case of homogeneous injection (one-dimensional problem), exact analytical solutions to the solute transport equation in semi-infinite homogeneous soil columns are often applied to finite geometry. This approximation is valid provided that flow velocity is sufficient. That means when Peclet number is greater than 10 (Van Genuchten and Parker, 1984).

Another way to approximate the flow and transport solutions is to use a numerical model. Two models were developed, one in finite differences using Modflow® and MT3D®, and another one in finite elements using Seep® and Ctran® of the GeoSlope® series. Both models give a good agreement with each other and with the analytical solution of Lindstrom et al. (Van Genuchten and Parker, 1984), when applied to an injection in flux in a semi-infinite media (fig 3). The solution proposed by Lindtrom et al. is :

$$\frac{C(x,t)}{C_0} = \frac{1}{2} \cdot \left\{ \begin{array}{l} erfc\left(\dfrac{x-v.t}{2\sqrt{D_L.t}}\right) + 2\sqrt{\dfrac{v^2.t}{\pi.D_L}}.exp\left[\dfrac{(x-v.t)^2}{D_L.t}\right] \\ -\left(1+\dfrac{v.x}{D_L}+\dfrac{v^2.t}{D_L}\right)exp\left(\dfrac{v.x}{D_L}\right).erfc\left(\dfrac{x+v.t}{2\sqrt{D_L.t}}\right) \end{array} \right\} \quad (1)$$

where $C(x,t)$ is the measured concentration depending on position x and time t, C_0 is the concentration of the inflow solution, erfc is the complementary error function, v the migration velocity and $D_L = \alpha_L \cdot v + D^*$ is the longitudinal dispersion coefficient with D^*, the effective diffusion coefficient.
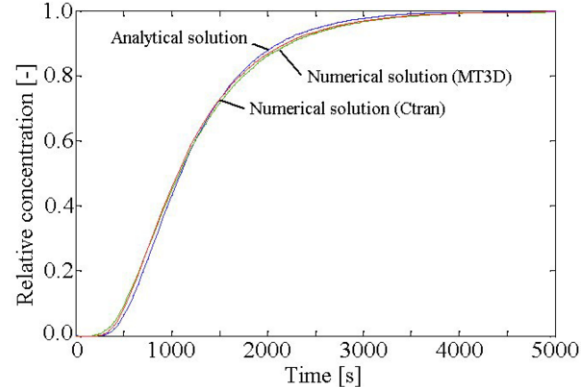

Figure 3. Comparison of the analytical solution of Lindstrom and those obtained by numerical modeling (under MT3D® and Ctran®).

In the case of two-dimensional problems, analytical solutions for the solute transport equation in finite soil columns are very rare. Pisani and Tosi (1994) developed a solution for point step injection but the radius of the soil column is assumed to be infinity. Assuming a uniform flow in the x direction and a point step injection in (0,0), and knowing the concentration C_1 at $(x,0)$ and C_2 at (x,y), the transversal dispersivity α_T can be deduced from the following relationship (eq. 2).

$$\alpha_T = \frac{y^2/(4.x)}{\log(C_1/C_2)} \quad (2)$$

To handle two-dimensional problems, a numerical approach is then necessary. Due to the geometry of the experimental setup, Seep® and Ctran® were selected, using an axi-symmetrical resolution scheme. The soil column is defined by

rectangular finite elements of homogeneous media mainly characterized with a porosity n [%] and a permeability k [m/s]. The transport boundary conditions are of the first order (as the concentration is measured in flux).

The first step is to define water flow conditions under Seep®, by introducing the hydraulic heads measured in the three inlet and the three outlet zones. Once the observed discharges in the outlet zones are correctly modeled, the flow lines are transferred into Ctran® and water quality conditions (concentration of the NaCl solution) are introduced. Modifying the values of the dispersivities of tested soil samples, the best fit of numerical and measured transfer curves is obtained. First, the value of the longitudinal dispersivity α_L [m] is found by fitting the numerical curve to the experimental one in the central outlet zone. Then, the value of the transversal dispersivity α_T [m] is modified to have the best matching of the other outlet curves (using least square methods). The retardation factor is assumed to be 1 (no interaction between NaCl and soil particles).

4 RESULTS

All tracer tests were analyzed using the inverse numerical modeling methodology described in section 3. Experimental results, curve-fittings and deduced values of the hydrodynamical dispersion factors are presented for both one- and two-dimensional tests.

4.1 Homogeneous injection test

Even if deduced global values of the longitudinal dispersivity are similar in each of the three outlet zones (α_L about 0.45 cm), differences appear (fig 4). That could be explained by two reasons. First, the difficulty to maintain the same hydraulic head in the three outlet zones could led to variation in the flow lines. Secondly, the time necessary to replace the solution quality into the inlet zones vary for each one and could explain part of the shift between the curves.
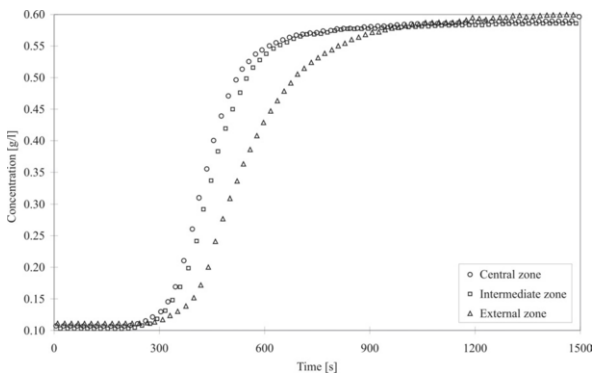

Figure 4. Time evolution of concentration in the outlet zones for an homogeneous injection test (divided inlet flask).

Performing homogeneous injection test with one single volume inlet flask give more uniform results (fig 5).

If we compare the longitudinal dispersivity values deduced from the mean outlet concentration and from the central outlet concentration, no significant difference appears.
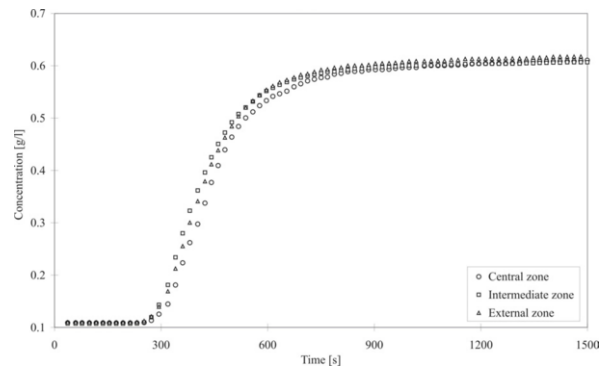

Figure 5. Time evolution of concentration in the outlet zones for an homogeneous injection test (single-volume inlet flask).

4.2 Central injection test

Central injection tests were performed varying shortly the concentration in the central inlet zone (from 0.1 to 0.6 g/l) while maintaining the same value in the other zones (0.1 g/l). The longitudinal dispersivity values determined by inverse modeling (fig 6) are similar to those deduced from the homogeneous injection test (α_L about 0.45 cm). That makes one more confident about the values of transversal dispersivity obtained by the same way.

The best fit is obtained for transversal dispersivity values of the Brusselean sand ranging between 25 to 30 times lower than longitudinal dispersivities (i.e. α_T from 0.15 to 0.2 mm).

When modeling the step down in concentration (from 0.6 to 0.1 g/l) with the parameters deduced from the step up (from 0.1 to 0.6 g/l), the curve-fitting is not so good anymore (fig 7). The dispersivities must be greater (α_L from 0.5 to 0.8 cm).
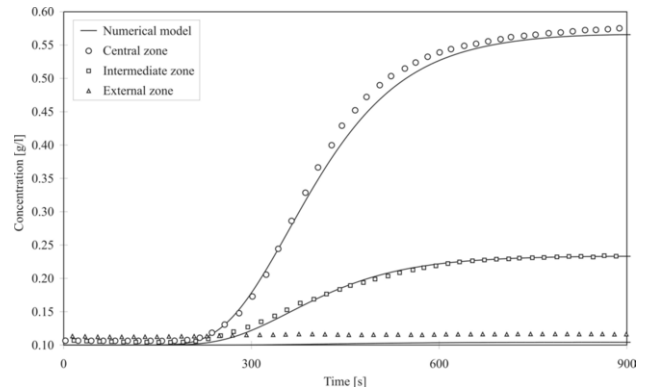

Figure 6. Time evolution of concentration in the outlet zones for central injection test (from 0.1 to 0.6 g/l).
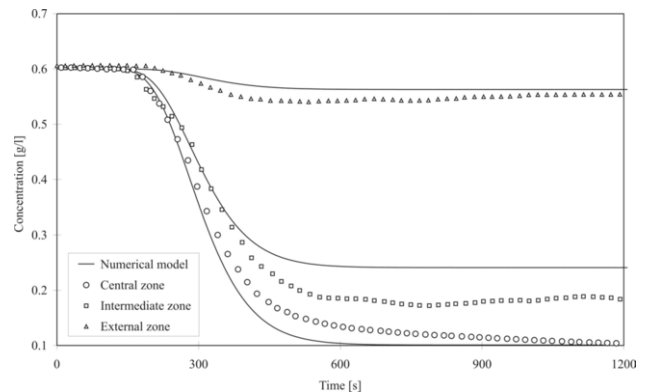

Figure 7. Time evolution of concentration in the outlet zones for central injection test (from 0.6 to 0.1 g/l).

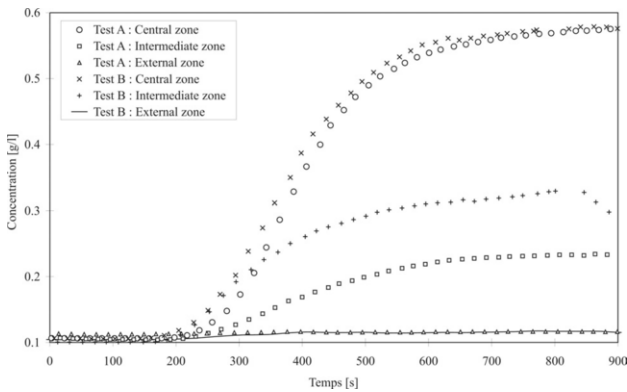Once more, the influence of small variations in hydraulic outlet heads are visible (fig 8).

Figure 8. Influence of hydraulic charges on the outlet concentrations for central injection tests.

5 CONCLUSIONS

A new laboratory method is suggested to determine the transversal dispersivity of soils at small scale. The inlet and the outlet flasks of a column experiment systems classically used to determine longitudinal dispersivity are divided into three independent concentric zones. Many kinds of two-dimensional tracer tests schemes can be investigated, including non-uniform flow. This first approach only considers constant mean velocity situations and central injection tracer tests. A numerical model developed using Seep® and Ctran® of the GeoSlope® series is used to determine dispersivity values by inverse modeling.

Both one- and two-dimensional tracer tests were performed on hand-compacted and saturated Brusselean sand samples of 11 cm long and 10.4 cm of diameter. The longitudinal dispersivity value deduced from both tests is about 0.45 cm. Two-dimensional tracer test into soil columns seems to be at least as efficient as more classical one-dimensional tracer test in terms of longitudinal dispersivity. The transversal dispersivity is about 1/30 of the longitudinal dispersivity. More tests on higher soil columns will be performed to verify those first values. Special care will be taken on the hydraulic head control.

REFERENCES

Bear, J. 1972. *Dynamics of fluids in porous media*, Amsterdam: Elsevier Publishing Company. 767 p.

Conde Pérez, P. 2000. Laboratory tests to determine hydro dynamical dispersion factor in a fine saturated sand., I International Young Geotechnical Engineers Conference, Southampton.

Fetter, C.W. 1993. *Contaminant hydrogeology*, New Jersey: Macmillian Publishing Company. 500 p.

Gillet, G., Louppe, S. 2004. Développement d'une cellule de laboratoire propre à mettre en évidence la dispersivité transversale d'un sol. Final-year thesis, UCL, GCE, Belgium. 165 p.

Van Genuchten, M., Parker, J.C. 1984. Boundary conditions for displacement experiments through short laboratory soil columns, *Soil Science Society of America Journal*, 48: 703-708.