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Comparison of single-well and two-well tracer tests at the laboratory scale

Comparaison d'essais de traçage à un et à deux puits à l'échelle du laboratoire

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ABSTRACT
The aim of this paper is to verify whether hydrodispersive parameters obtained from a rapid and widely used tracer test such as the single-well injection-withdrawal test can be used confidently when designing remediation techniques such as two-well injection-recovery. Although previous work tends to be pessimistic regarding this issue, experimental results obtained during this study using an intermediate-scale laboratory device modelling a confined aquifer come to moderate these pessimistic assertions.

RÉSUMÉ
L'objectif de ce travail est de vérifier dans quelle mesure des paramètres hydrodispersifs obtenus à partir d'un essai rapide et répandu tel que l'essai d'injection-récupération à un puits peuvent être utilisés pour dimensionner des techniques de remédiation faisant appel à des géométries d'écoulement plus complexes (résultant par exemple d'un système d'injection-récupération à deux puits). Bien que de précédents travaux soient assez pessimistes quant à cette possibilité, les résultats expérimentaux obtenus dans cette étude à l'aide d'un modèle de laboratoire de dimension intermédiaire viennent nuancer ces propos.

1 INTRODUCTION

Current remediation techniques require an in-depth knowledge of the contaminated site and reliable data to base remediation modelling on. Site characterization often includes tracer tests, if possible using existing wells and piezometers, and generally implying forced-gradient conditions in order to get quick results. The issue is then to choose the type of tracer test with reference to the type of remediation technique that is contemplated. The subsequent problem is then to transpose results of the tracer test to other flow configurations.

Some authors have already investigated the use of different pumping schemes on the same heterogeneous sampling zone. Pickens and Grisak (1981) investigated the magnitude of longitudinal dispersivity in a sandy stratified aquifer using single-well injection-withdrawal and two-well recirculating injection-withdrawal tracer tests. They found much greater dispersivities using two-well tests. Tiedeman et Hsieh (2004) performed 2D numerical simulations on randomly heterogeneous aquifers and compared three types of forced-gradient tracer tests with a natural-gradient test. They also found that two-well tests yield a higher apparent dispersivity value.

Gelhar et al. (1992) reported a high number of in situ and small-scale laboratory experiments. However, to the knowledge of the authors, very few field-scale-imitating tracer experiments have been reported in the laboratory at an intermediate scale. The aim of this study is to start to fill this gap by performing single-well and two-well tracer tests under controlled flow and transport conditions and to compare apparent hydrodispersive transport parameters with each other.

In a first section, the experimental setup and its specificities will be described, as well as the type of tracer test investigated. Then, interpretation methods and results for three types of tracer tests will be presented. Finally, those results will be discussed, with a particular emphasis on the validation of the analytical modelling tools that were used and on the comparison of the tests results.

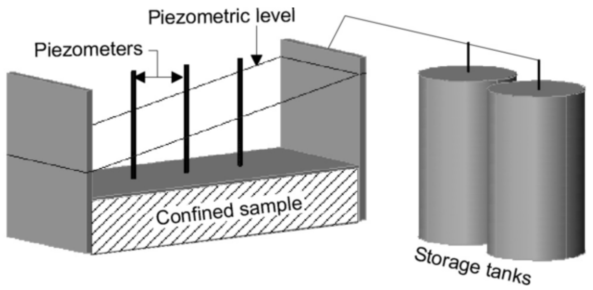

Figure 1 : Schematic view of the laboratory device.

2 MATERIALS AND METHODS

The experimental device, schematically illustrated on Figure 1, consists of a 2m long, 80 cm wide and 32 cm high sand-box flanked by two water reservoirs used to impose fixed-head upstream and downstream flow conditions (Frippiat et al., 2003a). This device allows one to impose confined flow conditions on intermediate-scale soil samples.

Experiments were conducted on Brusselean sand, which is a relatively coarse sand (d_{50} = 315 µm) with a very low clay content (less than 0.5 % in weight). The sample was compacted manually in three layers of about 10 cm each, in order to reach a mean total porosity of about 40 %.

In order to avoid preferential paths between the sample and the covering panel of the model, a bentonite layer was pasted on the sand sample. When saturating the sample, the swelling bentonite filled the space left under the covering panel and prevented any flow short circuit, ensuring the confined condition of the modelled aquifer.

The tracer was a low concentration saline solution (less than 1 mg/l of NaCl). Preliminary tests showed that cation exchange between bentonite and the tracer could be limited by feeding a continuous clear water flow to the sample prior to any tracer experiment.

Measurements were mainly performed using buried electrical sensors allowing one to obtain local-scale soil apparent conductivity values (Frippiat et al., 2003b). Analysis of samples taken in piezometers and in the upstream and downstream reservoirs was also achieved using a commercial conductimeter. Moreover, three thermocouples were inserted into the sample in order to measure local temperature variations. Bulk electrical conductivity measurements were first corrected according to temperature variations recorded by thermocouples, using linear temperature-dependent laws. Then, that data was transformed to liquid phase electrical conductivity values using a linear calibration curve. As solute concentration is very low, it is assumed to linearly depend on the liquid phase electrical conductivity, and this latter will remain the principal variable of interest along this study.

Locations of sensors, piezometers and thermocouples are illustrated on the plan view on Figure 2.

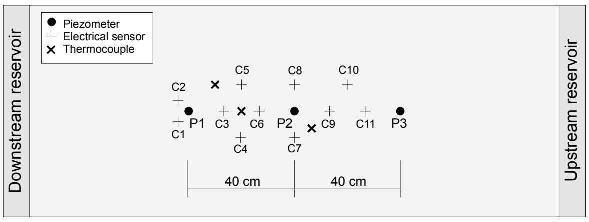

Figure 2 : Piezometers, electrical sensors and thermocouples locations.

As a preliminary step, one-dimensional tests were performed under prismatic flow conditions (from upstream to downstream reservoirs, with a mean gradient of 20 % in order to achieve a relatively short experiment duration). These tests included several rapid variations in conductivity of the upstream reservoir solution and were used to calibrate the sensors. Indeed, each step experiment allows one to draw for each sensor two points on a conductivity-tension drop graph. After a few experiments at varying conductivity levels, a regression curve can be plotted, that will be used to calibrate the sensors.

Then, various combinations of two-well tracer tests were investigated (without "regional" water flow). Table 1 summarizes the various experimental configurations. C_b is the background conductivity at the beginning of the experiment and C_i is the conductivity of the tracer solution. For each experiment, the injection rate was maintained as close as possible to the withdrawal rate. In case of three-well Experiment F, injection rates were kept as similar as possible and equal to half of the pumping rate in piezometer P2. One single-well injection-withdrawal test was also performed in piezometer P2 (Experiment E).

Table 1 : Experimental configurations

Label	Injection	Recovery	C_b [µS/cm]	C_i [µS/cm]
step 1	Ups. Res.	Downs. Res.	1000	1300
step 2	Ups. Res.	Downs. Res.	1300	1500
step 3	Ups. Res.	Downs. Res.	1500	1000
step 4*	Ups. Res.	Downs. Res.	1000	3000
A*	P2	P1	1000	3000
B	P1	P2	1000	3000
C	P1	P3	1000	3000
D	P2	P3	1000	3000
E	P2	P2	1000	3000
F	P1 & P3	P2	1000	3000

* not presented in this paper

3 RESULTS

Conductivity curves were analysed using analytical models. Indeed, as local dispersivities were expected to be very low, numerical modelling would have required a very fine spatial discretization, implying a relatively high computation time. In the case of an inverse modelling procedure implying successive evaluations of the direct model for refining transport parameter values, computation time would have become prohibitively long.

3.1 *One-dimensional tests*

Resident-concentration curves obtained during the calibration phase from electrical sensors were analysed using the analytical model recommended by Kreft and Zuber (1978) :

$$\frac{C(x,t)}{C_0} = \frac{1}{2}\left[erfc\left(\frac{x-vt}{2\sqrt{\alpha_L vt}}\right) + exp\left(\frac{x}{\alpha_L}\right)\ erfc\left(\frac{x+vt}{2\sqrt{\alpha_L vt}}\right)\right] \quad (1)$$

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 is the migration velocity and α_L the apparent longitudinal dispersivity.

Non negligible spatial variations in mean migration velocity were observed, reflecting the heterogeneous nature of the sample. Apparent longitudinal dispersivity, represented on Figure 3, was found to continuously increase with the mean travel distance of the tracer front.

A sensitivity analysis was performed to assess parameter uncertainty. A relatively high level of confidence could generally be obtained for velocity values as well as for dispersivity values. Results from step experiment 3 are however generally of reduced quality (higher mean discrepancy between data and fitted model), probably due to less controlled injection conditions. This could explain the higher dispersivity values shown on Figure 3.

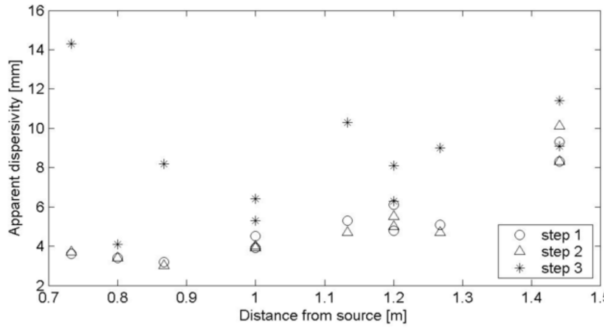

Figure 3 : Results of one-dimensional calibration tests.

3.2 *Two-well tracer tests*

A well-known analytical solution to the transport problem corresponding to a continuous tracer injection in the case of a two-well injection-recovery test is the one proposed by Hoopes and Harleman (1967). This solution is however only valid for measurements performed along the axis joining both wells. Instead, it is proposed to use the more recent solution by Maloof and Protopapas (2001) which overcomes this limitation :

$$\frac{C(x,t)}{C_0} = \frac{1}{2} erfc\left(\frac{a-\tau}{2\sqrt{b}}\right) \quad (2)$$

where

$$a = \int_{-\infty}^{\eta} \frac{d\eta}{\left(cosh(\eta)+cos(\xi)\right)^2} \quad (3)$$

$$b = \int_{-\infty}^{\eta} \frac{(\alpha_L/e)\ d\eta}{\left(cosh(\eta)+cos(\xi)\right)^3} \quad (4)$$

and

$$\eta = tanh^{-1}\left[\frac{2ex}{e^2+(x^2+y^2)}\right] \quad (5)$$

$$\xi = tan^{-1}\left[\frac{2ey}{e^2-(x^2+y^2)}\right] \quad (6)$$

with $\tau = At/e^2$ and $A = Q/(2\pi b n_e)$. x and y are spatial coordinates expressed in a referential centered between both wells, x-axis being aligned with the mean flow direction. *(e,0)* and *(–e,0)* are respectively the coordinates of the injection and the recovery well. Q is the injection and pumping rate, b is the aquifer thickness and n_e is its effective porosity. Molecular diffusion is neglected. Integration was performed using the trapezoidal rule.

As concentration pulses were used rather than continuous injections, a combination of two continuous injections shifted in time and reversed in concentration was used to perform inverse modelling on injection rates and apparent dispersivities.

Results from Experiment A were not included in this analysis, as an experimental error occurred during this test. Results of two-well tracer tests B and D, plotted on Figure 4, are relatively similar, leading to apparent dispersivity values of about 2 mm, irrespective of the measurement scale between 10 cm and 30 cm. A sensitivity analysis led to an estimation of the error on this value of about 12 %. Experiment F led to similar results, except that sensor C11 provided data that led to an unexpected and unexplained high value of longitudinal dispersivity (7 mm for a mean travel distance of about 13 cm).

Results of Experiment C, also plotted on Figure 4, show a scale effect of the same order of magnitude as the one observed during the calibration phase. A sensitivity analysis also led to an error on apparent dispersivities of about 12 %.

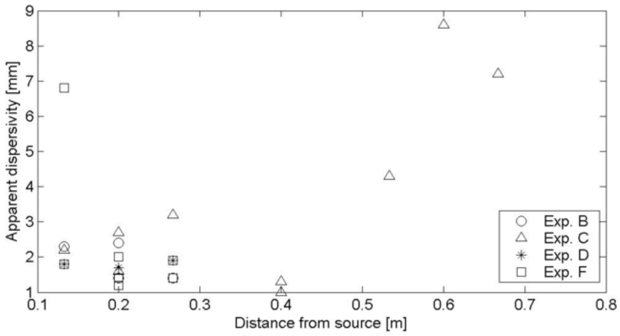

Figure 4 : Results of two-well tracer tests.

3.3 *Single-well tracer tests*

Analysis of breakthrough curve recorded by electrical sensors during the injection phase were performed using the analytical model of Bear (1972) :

$$\frac{C(r,t)}{C_0} = \frac{1}{2} erfc\left(\frac{r-R^*}{4/3\,\alpha_L\sqrt{R^*}}\right) \quad (7)$$

where r is the radial position and R^* is the mean radial displacement of the tracer front and can be calculated according to

$$R^* = \sqrt{\frac{Qt}{\pi b n_e}} \quad (8)$$

This model assumes that the well radius is negligible compared to the radial measurement distance. This will be further discussed in next section.

In order to limit border effects due to the lateral impervious boundaries of the model, injection was performed during 2400 s, leading to $R^*\sim$ 18 cm. Dispersivities were found to be around the value of 2 mm.

Concentration measurements at the recovery well were analysed using the analytical model of Gelhar and Collins (1971) :

$$\frac{C(t)}{C_0} = \frac{1}{2} erfc\left[\frac{(U_R-1)}{\sqrt{\frac{16}{3}\frac{\alpha_L}{R}\left(2-\sqrt{|1-U_R|}\,(1-U_R)\right)}}\right] \quad (9)$$

where $U_r = U_p(t)/U_i$ and R represents the mean radial position of the plume at the end of the injection phase, calculated according to Equation 8 (in which Q must be the injection rate and t the injection duration). In Equation 9, t is the time starting from pumping, $U_p(t)$ is the volume of pumped solution, U_i is the total volume injected.

Figure 5 shows the measured recovery curve as well as the best-fitted Equation 9. A good agreement can be observed between both curves. About 97.2 % of the injected tracer was recovered and apparent dispersivity was found to be equal to 1.8 mm. This value is one of the smallest dispersivity value although of the same order of magnitude as the smallest values shown on Figure 4.

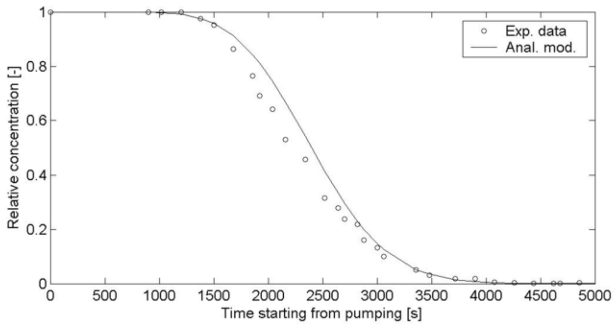

Figure 5 : Concentration recovery during single-well test.

4 DISCUSSION

Two types of problem will be addressed in this section. First, the validity of the analytical models used to infer transport parameters values will be discussed using numerical tools. Then, a comparison of the various experiments will be undertaken to assess to which extent results of single-well tracer tests can be upscaled to two-well tracer tests data.

4.1 *Inverse modelling procedure*

Analytical models in Equations 1, 2, 7 and 9 are strictly valid for unbounded media. Although this limitation has generally little influence in the case of one-dimensional tests (van Genuchten and Parker, 1984), one expects it to be of greater importance in the case of radial and 2D configurations.

First, a 2D numerical model corresponding to the geometry of the physical model in the case of Experiments A, B and D was set up using GeoSlope®. Flow and transport were solved for a longitudinal dispersivity of 1.3 cm (higher than measured) and injection and pumping rates of 9.6 10^{-6} m^3/s. Transversal dispersivity was set equal to the longitudinal one, whereas the analytical solution in Equation 2 assumes no diffusion nor dispersion across flow lines. Effective porosity was set equal to 40 %. Breakthrough curves simulated for Experiment B at sensors C3 and C4 are plotted on Figure 6, as well as the corresponding analytical solution in Equation 2.

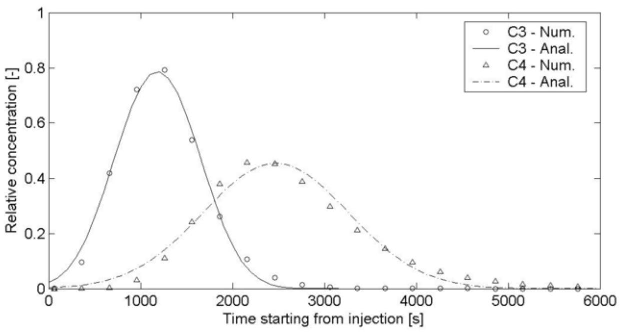

Figure 6 : Comparison of analytical and numerical two-well transport models

A good agreement can be observed between numerical and analytical curves. Only a slight shift and an increased spreading of the analytical curve appear for sensors not placed on the axis of symmetry, such as sensor C4. This effect is due to the narrowing of the current lines between both wells, caused by the impervious lateral boundaries. Dispersivity values obtained from the inversion of Equation 2 are thus expected to be slightly underestimated.

A similar methodology was applied to assess the validity of the single-well experiment analytical modelling. Due to lateral impervious boundaries re-directing current lines towards water reservoirs, the assumption of a radial flow field was found to be valid only at very close distances from the injection well. This made the analysis of the data obtained with the electrical sensors erroneous. However the numerical concentration curve at the recovery well was found relatively close to the analytical one. It only appeared that fitting the analytical curve on experimental data could lead to an underestimation of the apparent dispersivity. One should then expect the true apparent dispersivity value at the recovery well to be around 2 mm.

4.2 *Comparison of tracer tests*

Merging results of one-dimensional and of two-well tests allows one to observe a very clear scale-effect for travel distances larger than 30 cm. For smaller distances, apparent dispersivity was found constant and equal to about 2 mm.

If the dispersivity value obtained from the single-well test is one of the smallest, a clear difference does not appear between single-well and two-well results. It must be however noted that only one single-well experiment was performed. Moreover, injection and pumping rates were maintained constant with great difficulties during two-well tests, so that these parameters are affected by an error that was not possible to quantify so far.

Tiedeman and Hsieh (2004) have performed numerical tracer experiment on heterogeneous 2D permeability fields. They have compared two-well injection-recovery tests with radially converging tracer tests. They found an apparent dispersivity value much greater in the case of two-well tests. They explained qualitatively the difference by considering the sampled aquifer area. A converging radial-flow test samples a small area and the tracer undergoes a low degree of spreading and mixing. As a two-well test samples a much greater area, the tracer is spread and mixed to a greater degree.

The experiments conducted within the framework of this study involve roughly equal sampling areas. Two-well tests B, D and F sample a circular area of about 40 cm in diameter. Mean radial position of the tracer front at the end of the injection phase during single-well test E is about 18 cm, leading to a circular sample area of about 36 cm in diameter This value is rather similar to that of the two-well tracer tests, leading to a similar degree of spreading and mixing for the tracer plume and to similar apparent dispersivity values.

5 CONCLUSIONS

Gelhar et al. (1992) stated that two-well recirculating tracer tests could not yield valuable apparent dispersivity values as the resulting breakthrough curve in the recovery well is not strongly influenced by dispersion but is rather determined by the difference in travel time along current lines. This raises the issue of the transport parameters to use when designing remediation techniques requiring this type of flow configuration.

Tiedeman and Hsieh (2004) have indeed highlighted using numerical simulations that apparent transport parameters deduced from radially converging tracer tests could generally not be upscaled to two-well tracer tests.

Although Gelhar et al. (1992) tends to consider the single-well injection-withdrawal test as less reliable and leading to underestimated apparent dispersivity values, this study tends to show that results from this type of tracer test yield apparent transport parameters applicable to two-well recirculating tests conducted on similar sampling areas. Regarding this observation, the single-well injection-withdrawal test should be preferred to radially converging tests when designing two-well injection-recovery systems.

ACKNOWLEDGEMENTS

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