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STUDY OF AIR RELATIVE PERMEABILITY EVOLUTION DURING SOILS DECONTAMINATION BY SOIL VAPOUR EXTRACTION

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ABSTRACT
Soil vapour extraction (SVE), is the primary method used in the world to remove volatile organic compounds (VOCs) from unsaturated subsurface porous media.
The objective of this work is to study the change of the soil air relative permeability during continuous venting and removal of contaminant from a polluted soil. Once the flow starts, the contaminants will volatilize and the volume of liquid phases (Non aqueous phase liquid NAPL and water) will decreases with time accordingly as long as the venting process is continuous. A correlation that describes the evolution of the relative air permeability as a function of the gas saturation degree has been established by fitting pneumatic tests data, conducted a small-scale laboratory pilot, to an analytical gas flow model.
The experimental correlation were compared to models developed previously [1,2]. A significant difference between simulated breakthrough curves, which illustrate evolution of contaminant concentration in the extracted gas, based firstly on the relationship established experimentally and on the other hand on the two other correlations was observed. The difference between the three curves becomes more important when the PLNA initial saturation in soil is high.
These results lead us to say that the evolution of air relative permeability according to the total liquids saturation degree should be determined experimentally. Inadequate characterization of this evolution may generate significant errors in removal rate and closer time estimates.
Keywords: Soil vapour extraction, Air relative permeability, Liquids saturation degree, SVE modelling.

1. INTRODUCTION
Soil Vapour Extraction (SVE) is an in-situ remediation method that has been extensively used for removal of volatile organic contaminants (VOCs) from the unsaturated zone due to low installation and maintenance costs combined with height efficiency. The movement of vapour in the subsurface is caused primarily by advection, which is related to the existence of pressure gradients that are developed during the operation of vapour extraction wells [3]. The primary design parameter of an SVE system is the air permeability of the soil, in both the vertical and horizontal directions, which is used in determining the "zone of effective air exchange" at a given applied vacuum [4]. Because air-filled porosity determines the pore volume available for air transport, air relative permeability is a function of saturation. Contaminants removal during soil venting leads to a reduction in the volume of the VOCs trapped in the soil pore space, and a widening of air flow channels, which increases soil air relative permeability [5]. The assumption of constant air permeability in SVE modeling will then generate significant errors in estimation of contaminant removal rate.
Several methods have been done in order to correlate relative permeability evolution as a function of pore gas filled porosity [1,2,5,6] by estimating soil parameters like water residual saturation or pore

distribution index, etc. However, the difficulty and the time consuming of parameters estimating tests make these methods undesirable for engineering applications [1]. Furthermore, most of these relationships have been obtained by conducting air permeability measurements on unidirectional laboratory columns under different conditions from those met in field venting applications.

The purpose of this work is to develop a relationship between relative permeability and total liquid saturation degree by measuring air permeability using pneumatic pump tests conducted on a laboratory pilot. The established equations were then compared to existing models. Two correlations were selected for testing in this work due to their convenient formulation, which allows them to be readily compared to the measured permeability.

2. MATERIALS AND METHODS

2.1. Soil characterization

Sand was selected for the present study to ensure a good homogeneity of the medium. It was composed of almost pure rounded quartz particles with a specific gravity of 2.65. The apparent density of the used sand was equal to 1.36 g/cm^3 and its porosity was equal to 48.56%.

2.2. Experimental apparatus and soil preparation

The pilot consists of an aluminium cylindrical tank which has a diameter of 56 cm and a height of 26 cm. In the middle of the tank, an extraction well of 3 cm in diameter and screened in the bottom, is installed to induce the desired vacuum with the aid of a Teflon KNF vacuum pump. The determination of soil air radial and vertical permeability was done by measuring pressure in several positions using six pressure transmitters based on ceramic thick film technology.

Experiments, conducted using the laboratory pilot, comprised three stages: (1) soil preparation (2) introduction of the soil into the tank; (3) carrying out steady-state pneumatic tests.

The first stage consisted of preparing soil at the desired moisture saturation. The degree of saturation (S) was calculated as the percent of volume of the contaminant in the sample divided by the volume of the pore space. The second stage consisted of filling the column with soil. A basic requirement for all the samples was their homogeneity. The pneumatic tests, which were realised in the third stage, consist of applying four different flow rates to the soil by changing the vacuum at each test. For the steady state measurements, pressures were measured after a period of 30 minutes, estimated to be enough for the system to reach the steady state regime.

In order to limit water movement during vacuum and its drainage under the gravity which may cause non-uniform conditions, we were limited to a saturation degree of 40% as a maximum. Furthermore, SVE is not adequate under liquids saturated conditions, and hence the practical significance of the results in this range is not important.

2.3. Air permeability measurements

Different analytical solutions have been compared in a previous work in order to determine which the best method that should be used to determine radial and vertical air permeability under laboratory pilot conditions. It was found that this soil characteristics can be properly calculated by fitting pressure data, measured with the laboratory pilot, to the analytical solution that describe air flow in the steady-state under unconfined (open to the atmosphere) conditions (equation 1).

$$k_{rel}k_r\left[\frac{\partial^2 P^2}{\partial r^2}+\frac{1}{r}\frac{\partial P^2}{\partial r}\right]+k_{rel}k_z\,\frac{\partial^2 P^2}{\partial z^2}=0 \qquad (1)$$

Where r is the radial distance from the centre of the well, z is the vertical distance below land surface, k_{rel} is the relative air permeability, k_r is the intrinsic radial permeability, k_z is the intrinsic vertical permeability and P is the air pressure.

3. RESULTS AND DISCUSSIONS

3.1. Comparison of relative air permeability evolution

Figure 1 illustrates relative air permeability as a function of water saturation degree. Relative air permeability was calculated using the average of radial and vertical permeability values. As it shows, air permeability decreases when water saturation degree increases. Air permeability decreases slightly till water occupies more than 10% of the soil pore space; the relative air permeability measured at this liquid saturation degree is equal to 0.984.

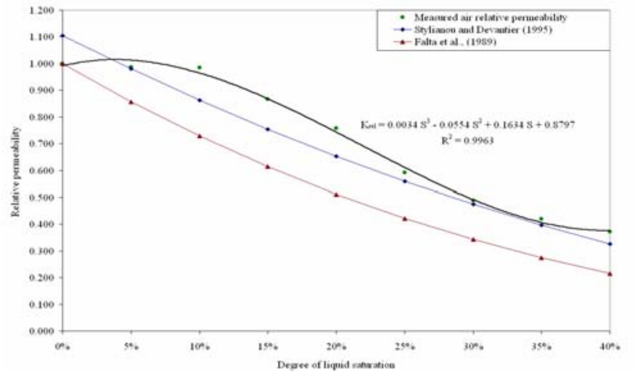

Figure 1. Relative air permeability evolution as a function of total liquid saturation

The functional relationships that best fit the experimental data is:

$$k_{rel} = 0.8797 + 0.1634\,S - 0.0554\,S^2 + 0.0034\,S^3 \quad (2)$$

Figure 1 compares measured relative permeabilities to the two correlations established by Stylianou and Devantier, 1995 and by Falta, 1989. Falta et al. (1989) expressed relative air permeability as a third-order function of degree of liquid saturation:

$$k_{rel} = (1 - S)^3 \quad (3)$$

This simplified equation was used by the venting model VENT2D to update the effective air permeability during the venting process.

Stylianou and Devantier (1995) proposed a polynomial expression that represents a relationship between relative permeability and total liquid saturation:

$$k_{rel} = 1.105 - 2.576S + 1.577S^2 \quad (4)$$

As it shows, Stylianou's polynomial fits approximately experimental results when the liquid saturation degree is higher than 30%. This means that air permeability will be underestimated in the final stage of venting. In this case, calculated pore-gas velocities will be lower than those occurred in field which may cause mass transfer retardation as a consequence of higher pore-gas velocities.

Falta's relationship doesn't fit the evolution of measured relative air permeability for the soil tested here. A difference of almost 20% is observed between measured relative permeability points and those obtained with Falta's relationship. The same result will be obtained as with the previous relationship; mass transfer retardation will occur and closer time will be higher than expected which will cause additional costs. Low liquid saturation degrees may not affect air flow since large pore space still available for air transport. This result confirms cited previously and which say that changes in air relative permeability or in air-filled porosity, caused by liquids removal, can be neglected when total liquid saturation is lower than 20% [8].

The inadequate estimation of air permeability will engender a wrong assessment of cleanup degree and length of the zone of effective air exchange. The zone of effective air exchange corresponds to the volume of soil that can be remediated within an acceptable time frame and where a minimum value of vacuum and pore gas velocity is reached.

3.2. Comparison of prediction capabilities

3D-SVE model [9] was used in order to study the influence of soil air relative permeability variation on prediction capacities. This mathematical model couple air flow multicomponent transport with nonequilibrium mass transfer. The experimental correlation and the two other ones were integrated to the mathematical model in order to compare the breakthrough curves obtained for each method. Figure 2 illustrates the three breakthrough curves of a toluene polluted soil (S = 20%). As it shows, a large difference is obtained between the experimental curve and the two other ones especially in the first

stage of treatment which correspond to the evacuation step. Contaminant concentration in the extracted gas can be then improperly estimated if the used correlation of air relative permeability doesn’t fit exactly its evolution during treatment process.
In order to demonstrate this effect on prediction capabilities of SVE mathematical models, closer time was calculated for the three methods by calculating the efficiency *E* which is defined as the ratio between the relative slope of the breakthrough curve on time [9].

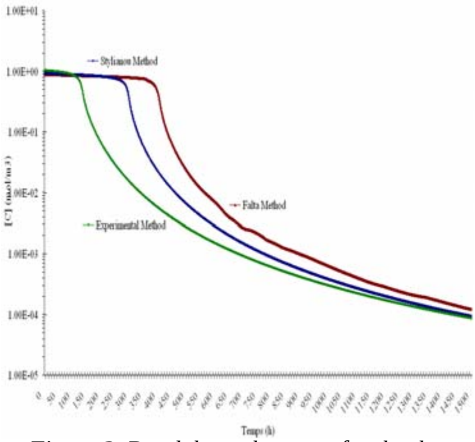

Figure 2. Breakthrough curves for the three methods

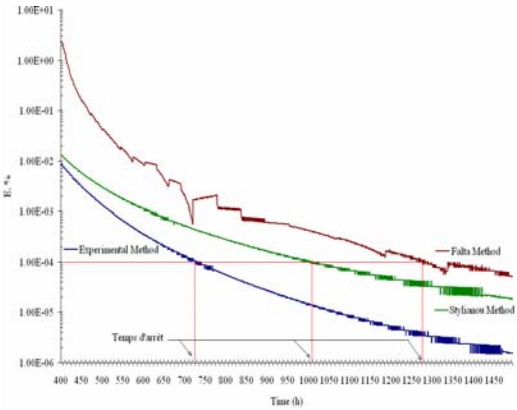

Figure 3. Treatment efficiency evolution as a function of time

Figure 3 illustrate the evolution of the treatment efficiency for the three methods compared in this work. As it shows, the closer time was found to be equal to about 750 h for the experimental method, 1000 h for Stylianou’s method and 1250 h for Falta’s method. The optimal close time well then misestimated if the evolution of relative air permeability is not well determined and integrated in the SVE mathematical model.

4. CONCLUSION

Results obtained in this work lead us to say that air relative permeability variation as a function of liquid saturation should be determined experimentally as existed correlations don’t give good estimation which may generate significant errors in calculation of removal rate by modelling mass transfer from soil phases to vapour phase.

5. REFERENCES

[1] Stylianou, C., and DeVantier, B. A.: Relative air permeability as a function of saturation in soil venting. Journal of Environmental Engineering, 121(4), 337–347, 1995.
[2] Falta, R. W., Javandel, J., Pruess, K., and Witherspoon, P. A.: Density-driven flow of gas in the unsaturated zone due to the evaporation of volatile organic compounds. Water Resources Research, 25(10), 2159–2169, 1989.
[3] Nobre M.M. and Nobre R.C.: Soil vapour extraction of chlorinated solvents at an industrial site in Brazil. Journal of Hazardous Materials 110, 119–127, 2004.
[4] U.S. Army Corps of Engineers (USACE): Engineering and Design: Soil Vapor Extraction and Bioventing, DC 20314-1000, p.425, Washington , 2002.
[5] Farhan, S., Holsen, T., and Budiman, J.: Interaction of soil air permeability and soil vapor extraction. Journal of Environmental Engineering, 127(1), 32–37, 2001.
[6] Garcia-Herruzo, F., Gomez-Lahoz, C., Rodriguez-Jimenez, J. J., Wilson, D. J., Garcia-Delgado, R. A., and Rodriguez-Maroto, J. M.: Influence of water evaporation on soil vapor extraction SVE. Water Science Technology, 30(7), 115-118, 1994.
[7] DiGiulio, D.C. and Varadhan, R.: Development of Recommendations and Methods to Support Assessment of Soil Venting Performance and Closure. U. S. Environmental Protection Agency. Office of Research and Development Washington DC 20460, 2001.
[8] Johnson, P. C., Stanley, C. C., Kemblowski, M. W., Byers D. L., and Clothart, J. D.: A practical approach to the design, operation, and monitoring of in situ soil-venting systems. Ground Water Monitoring Review, Spring, 1990.
[9] Zhao L.: Three dimensional soil vapour extraction modeling, Doctoral thesis, University of Guelph, 2007.