Optimizing the experimental design of unsaturated soil columns

Jeffrey Lewis, Jan Sjöstrom

Totalförsvarets forskningsinstitut FOI-CBRN, Umeå, Sweden

Abstract
The apparent simplicity of constructing soil columns conceals a number of technical issues which can seriously affect the outcome of an experiment. This review examines the literature to provide an analysis of the state of the art for constructing both saturated and unsaturated soil columns. Common design challenges are discussed and best practices for potential solutions are presented. This review will assist soil scientists, and other environmental professionals in optimizing the construction and operation of soil column set-ups in order to achieve their experimental objectives while avoiding serious design flaws which can compromise the integrity of their results.

Key Words
Lysimeters, construction, best practices

Introduction
Soil columns have been used for over a century in the study of hydrogeological properties (Darcy, 1856). More recently, soil columns and lysimeters have been used to evaluate transport models, to monitor the fate and mobility of contaminants in soil and for evapotranspiration studies. For the purposes of this review, a soil column is characterized as a discrete block of soil located either outdoors or in a laboratory, which allows control or measurement of the infiltration and which incorporates equipment for the total recovery of the effluent. This is usually achieved by encasing the soil column in a rigid and impermeable shell material, both for structural reasons and to prevent fluid loss.

There is considerable variation in the soil columns which have been reported in the literature. Some of the smallest measure 1 cm diameter and 1.4 cm in length (Voegelin *et al.* 2003) while some of the largest measure 2 m x 2 m x 5 m (Mali *et al.* 2002). Despite the ubiquitous use of soil columns no attempt has ever been made to outline the best practices for constructing these useful pieces of equipment. The apparent simplicity in constructing lysimeters conceals several critical design issues which could seriously compromise subsequent experimental results. The purpose of this article is to review and summarize the literature and provide practical guidance concerning the state of the art in their construction.

Repacked soil columns
Although the repacking of laboratory columns has received relatively little attention in the literature, Bromly *et al.* (2007) have shown that it will significantly influence the resulting solute transport behaviour of the columns. The goal of repacking is to restore the bulk density of the soil to a value similar to that observed naturally, while avoiding the formation of preferential flow pathways. Several repacking methods have been reported in the literature. The most common approach is dry or damp packing.

Dry or damp packing involves loading small discrete amounts or "lifts" of dry or damp soil into the column and then mechanically packing it either by hand or with some type of ram or pestle. Oliviera *et al.* (1996) demonstrated that in order to produce homogeneous sand packing, dry deposition must be in increments of 0.2 cm followed by compaction with a metal pestle. However, the literature shows few studies in which dry deposition is done in lifts smaller than 1 cm and some in which the lifts were as much as 15 cm (Plummer 2004). Several studies which employed dry or damp packing also noted the importance of lightly scarifying the soil surface after compaction and before addition of another lift in order to ensure hydraulic connectivity between the layers (Plummer 2004).

Another common approach is slurry packing (Sentenac 2001). Slurry packing involves saturating the soil with an excess of water, then letting it settle at the bottom of the column. Saturation is achieved either by stirring the soil into the water prior to pouring it into the column as a slurry, or by filling the column with water and then slowly pouring or sprinkling dry soil into the column while stirring. Oliviera *et al.* (1996) found that the best wet packing technique involved depositing thin layers of saturated sand into water while vibrating the column. They observed that this technique produced the highest density uniform packing without causing any lateral particle size segregation.

Lysimeter design issues

The most critical design issue with homogeneous, unsaturated soil columns is to avoid unnatural preferential flow paths. While natural preferential flow paths are expected or even desirable in monoliths, they may also be formed unintentionally in the construction of unsaturated soil columns, and these must be avoided. These flow paths will cause spatial heterogeneity in the transport of solutes through a porous medium and will therefore significantly bias any experimental results. Sidewall flow refers to a preferential flow of fluid in proximity to the rigid outer wall of a soil column (Sentenac *et al*. 2001; Corwin 2000). In repacked soil columns, other undesirable forms of preferential flow include macropore flow or fingering (Wilson *et al*. 1995).

Sidewall flow may be caused by improper packing of the column or flexing of the column walls during or after the soil has been repacked. However, there is evidence that preferential sidewall flow occurs even when no space or gap exists due to an increase in the permeability of the soil in contact with the sidewall (Schoen *et al*. 1999). Sentenac *et al*. (2001) observed that the flow velocity at a column wall can be between 1.11 and 1.45 times the flow velocity in the column center. They also observed that sidewall flow increased with larger soil particle sizes and that it is more exaggerated at small hydraulic gradients.

Various strategies have been proposed in the literature to overcome sidewall flow including roughening the sidewall (Smajstrla 1985), gluing sand to it (Sentenac *et al*. 2001) or by installing annular rings on the interior surface of the column prior to the addition of soil (Corwin 2000). Another (unpublished) approach advocated by the United States Department of Agriculture recommends wetting the inside of the column then packing it with a swelling clay such as montmorillionite. The excess (dry) clay is allowed to fall out of the column while the hydrated clay forms a liner on the column wall. The soil to be investigated is then carefully packed into the column without disturbing the clay layer.

Macropore flow refers to any flow which takes place outside of the normal pore structure of the soil, such as in wormholes or decayed roots. While these may play a more significant role in monolith-type soil columns, macropores still exist in apparently homogeneous repacked soil columns on account of the heterogeneity of the soil grains themselves (Cortis and Berkowitz 2004).

Fingering occurs when instability develops in the wetting front as it moves through coarse unsaturated soils such as sands (Selker *et al*. 1999). Parlange *et al*. (1990) showed that the size of the finger width were a function of the soil grain size, with silts having fingers on the order of 1 m in diameter and coarse sands having fingers on the order of 1 cm. While fingering has generally only been observed in practice in soils that are predominantly sand, water-repellency of the soil has also being implicated (Bauters *et al*. 1998). Selker *et al*. (1999) suggest that finger width is not strongly influenced by the flux through the system so long as the rate of infiltration is well below the saturated conductivity. When the flux is increased up to the rate of the saturated hydraulic conductivity of the soil, fingers will grow in width and frequency until they finally merge into a single wetted front without fingers. Since it has been demonstrated that once a finger a formed in a particular location it will persist until the soil has either been dried or saturated completely (Glass *et al*. 1989), they can strongly influence the results of an experiment. Fingering is most likely to occur when the soil being infiltrated is initially extremely dry (Lui *et al*. 1993).

One other significant issue in unsaturated columns is obtaining the effluent in such a way that the column remains unsaturated. The pressure potential in unsaturated soil is always negative due to capillary and other forces, becomes zero at the water table and increases below the water table due to the pressure from the overlying water (Wierenga 1995). This means that suction must be applied to unsaturated soil in order to extract the pore water. However, attempting to sample pore water by applying suction to an open ended pipe attached to the base of a soil column will fail because only air will be drawn in (Wilson *et al*. 1995). For this reason, a porous material is used as an interface to ensure that pore liquids in the soil are in hydraulic contact with liquid within the sampling device (Plummer *et al*. 2004).

Porous materials which have been used experimentally include ceramic, porous PTFE, fritted glass, porous stainless steel, porous plastic and fibreglass wicks. Two key considerations in the choice of a porous material is the bubbling pressure of the material (Everett and McMillion 1985) and whether or not the material is chemically compatible with the solute under consideration.

The bubbling pressure is the maximum suction that can be applied to soil water by a porous plate before air will begin to enter the plate instead of pore water. In most applications, the vacuum applied to the porous material need not be very high. The maximum theoretical suction that can be applied to the soil is 1 bar. However, the hydraulic conductivity of a soil at 1 bar matric potential is so low that any column experiment would take a prohibitively long time (Wilson *et al*. 1995). As a result, most unsaturated soil column studies are conducted at or near the field capacity of the soil. In coarse textured soils, this means that the soil matric potential will be between 0.04 to 0.06 bars and from 0.06 to 0.1 bars in fine textured soils (Wierenga 1995).

These pressures can be easily achieved without pumps by using a hanging column of water. It should also be noted that even under these favourable conditions, PTFE porous materials may not be able to achieve a sufficiently high operational suction to bring the water content of a soil down to field capacity. In finer textured soils such as silts and clays, the operational suction of porous PTFE is unlikely to successfully withdraw pore water. How much suction should be applied is still under some debate, but a consensus is emerging that the methodology to obtain the most representative soil water samples is to apply a suction equivalent to the ambient matric potential which exists at the same depth in the soil (Kosugi and Katsuyama 2004). However, higher-than-ambient suctions will allow a faster collection of leachate. While this will create an artificial flow field within the column, this may be an acceptable tradeoff depending on the experimental objectives, particularly in soils which have very low permeabilities. In general, the suction applied will be dependent on the soil type, the amount of water required for analysis, the soil water content and the time of the applied suction.

One serious problem with the use of porous materials in soil column experiments is pore clogging, and Everett and McMillan (1985) recommend the use of a silica flour pack between the porous material and the soil to be tested to prevent colloids in the soil from reaching and plugging the porous surface. They found that the use of a silica flour pack was essential when using PTFE porous materials. Clogging of porous surfaces in lysimeters may also be caused by biofilms.

Another experimental approach which is encountered frequently in the literature is to allow the free drainage of soil pore water from the base of the soil column without any applied suction (Derby *et al*. 2002). Frequently, the soil column will be installed on a layer of gravel or on a metal screen. In these experimental setups, the soil matric potential must increase to 1 bar before drainage begins, which means by definition that a saturated zone must form at the base of the soil column before flow can occur. This experimental approach is particularly common in large and very large unsaturated soil columns (Mali *et al*. 2002). However, Derby *et al*. (2002) point out that gravity drainage may cause an unrealistic moisture regime, and Flury *et al*. (1999) showed with numerical simulations that the saturated seepage face conditions influence both the water flow and solute concentration in the sampled leachate.

One final issue affecting the operation of unsaturated soil columns concerns unsaturated dispersion. At the microscopic scale, water moves through pores of a homogeneous porous material with some velocity that varies according to the geometry of the individual pore spaces. However, the macroscopic water velocity measured in the lab represents an average movement of water through a representative volume (Fogg *et al*. 1995). The deviations of fluid velocity in the individual pore spaces from the overall average produces spreading and dilution, which is called dispersion. This behaviour is modelled by assuming that it is analogous to Fick's law of diffusion (Bear 1972). However, Fick's law can only be valid when a fluid or solute has passed through enough micro scale heterogeneities that the overall behaviour becomes representative of the volume as a whole (Selker 1999). In a homogeneous saturated soil, this distance is on the order of several thousand soil grains (Yeh 1998) and therefore it is rarely an issue experimentally. However, because there are fewer flow pathways in unsaturated conditions, a solute must pass through a much larger representative volume before its behaviour becomes representative of the soil column as a whole. Often, this distance is longer than the experimental soil column itself (Yeh 1998). As a result, the concentration of solutes which are detected in the effluent is characterized by an early breakthrough and multiple peaks. This is even truer in situations where the heterogeneities are not micro-scale, but are macro-scale themselves, as is explicitly the case with monoliths.

Conclusions

While construction of a lysimeter for theoretical or applied studies appears to be straightforward, there exist a number of technical issues which could seriously bias results. This review article provided insight into the state of the art for the construction and manufacture of these useful experimental tools in order to provide researchers with the best practices available to construct soil columns which will meet their experimental needs.

References

Bauters TWJ, DiCarlo DA, Steenhuis TS, Parlange JY (1998) Preferential flow in water-repellent sands. *Soil Science Society of America Journal* **62**(5), 1185-1190.

Bear J (1972) 'Dynamics of fluids in porous media.' (American Elsevier Pub. Co.: New York,) xvii, 764 p.

Bromly M, Hinz C, Aylmore LAG (2007) Relation of dispersivity to properties of homogeneous saturated repacked soil columns. *European Journal of Soil Science* **58**(1), 293-301.

Cortis A, Berkowitz B (2004) Anomalous transport in "classical" soil and sand columns. *Soil Science Society of America Journal* **68**(5), 1539-1548.

Corwin DL (2000) Evaluation of a simple lysimeter-design modification to minimize sidewall flow. *Journal of Contaminant Hydrology* **42**(1), 35-49.

Darcy H 'Les fontaines publiques de la ville de Dijon: Exposition et application des principes a suivre et des formules a employer dans les questions de distribution d'eau.' ([s.n.]: [S.l.]) microfilm.

Derby NE, Knighton RE, Montgomery BR (2002) Construction and performance of large soil core lysimeters. *Soil Science Society of America Journal* **66**(5), 1446-1453.

Everett L, McMillion L (1985) Operational ranges for suction lysimeters. *Ground water monitoring review* **51**(5), 51-60.

Fogg G, Nielsen D, Shibberu D (1995) Modeling Contaminant Transport in the Vadose Zone: Perspective on State of the Art. In 'Handbook of vadose zone characterization and monitoring'. (Eds. Wilson L, Everett L,Cullen S), pp. 249-266. (Lewis Publishers: Boca Raton).

Glass R, Steenhuis T, Parlange, J-Y (1989) Mechanism for finger persistence in homogeneous, unsaturated, porous media: theory and verification. *Soil Science* **148**(1), 60-70.

Kosugi K, Katsuyama M (2004) Controlled-suction period lysimeter for measuring vertical water flux and convective chemical fluxes. *Soil Science Society of America Journal* **68**(2), 371-382.

Liu CM, Zhang XY, Zhang YQ (2002) Determination of daily evaporation and evapotranspiration of winter wheat and maize by large-scale weighing lysimeter and micro-lysimeter. *Agricultural and Forest Meteorology* **111**(2), 109-120.

Mali N, Urbanc J, Leis A (2007) Tracing of water movement through the unsaturated zone of a coarse gravel aquifer by means of dye and deuterated water. *Environmental Geology* **51**(8), 1401-1412. [In English]

Oliveira IB, Demond AH, Salehzadeh A (1996) Packing of sands for the production of homogeneous porous media. *Soil Science Society of America Journal* **60**(1), 49-53.

Plummer MA, Hull LC, Fox DT (2004) Transport of carbon-14 in a large unsaturated soil column. *Vadose Zone Journal* **3**(1), 109-121.

Schoen R, Gaudet JP, Elrick DE (1999) Modelling of solute transport in a large undisturbed lysimeter, during steady-state water flux. *Journal of Hydrology* **215**(1-4), 82-93.

Selker JS, Keller CK, McCord JT (1999) Vadose zone processes. (Lewis: Boca Raton, FL)

Sentenac P, Lynch R, Bolton M (2001) Measurement of the side-wall boundary effect in soil columns using fibre-optics sensing. *International Journal of Physical Modelling in Geotechnics* **4**, 35-41.

Smajstrla A (1985) A field lysimeter system for crop water use and water stress studies in humid regions. *Soil & Crop Science Society of Florida - Proceedings* **28**.

Wierenga P (1995) Water and Solute Transport and Storage. In 'Handbook of vadose zone characterization and monitoring'. (Eds. Wilson L, Everett L,Cullen S). (Lewis Publishers, Boca Raton).

Wilson LG, Everett LG, Cullen SJ (1995) Handbook of vadose zone characterization and monitoring. (Lewis, Boca Raton, Fla.) xii,730p.

Yeh T (1998) Scale issues of heterogeneity in vadose-zone hydrology and practical solutions. In 'Scale Dependence and Scale Invariance in Hydrology' (Ed. Sposito G), pp. 224-265. (Cambridge University Press, Cambridge).