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Review article

Optimizing the experimental design of soil columns in saturated and unsaturated transport experiments ☆

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ABSTRACT

Soil column experiments in both the saturated and unsaturated regimes are widely used for applied and theoretical studies in such diverse fields as transport model evaluation, fate and transport of pesticides, explosives, microbes, heavy metals and non aqueous phase liquids, and for evapotranspiration studies. The apparent simplicity of constructing soil columns conceals a number of technical issues which can seriously affect the outcome of an experiment, such as the presence or absence of macropores, artificial preferential flow paths, non-ideal infiltrate injection and unrealistic moisture regimes. 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 article discusses both basic principles and the practical advantages and disadvantages of various experimental approaches. Both repacked and monolith-type columns are discussed. The information in this review will assist soil scientists, hydrogeologists and environmental professionals in optimizing the construction and operation of soil column experiments in order to achieve their objectives, while avoiding serious design flaws which can compromise the integrity of their results.

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☆ The paper is a review of the literature to summarize the best practices and state of the art in designing and operating unsaturated and saturated soil columns.

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1. Introduction

Soil columns have been used for over three centuries in the study of hydrogeological properties (De la Hire, 1703). More recently, soil columns and lysimeters have been used to evaluate transport models (Klein et al., 1997; Butler et al., 1999), to monitor the fate and mobility of contaminants in soil (Jin et al., 1997; Hrapovic et al., 2005; Dontsova et al., 2006) and for evapotranspiration studies (Liu et al., 2002; Prueger et al., 1997; Sahoo et al., 2009). For the purposes of this review, a soil column is characterized as a discrete block of soil located either outdoors or in a laboratory, allows control or measurement of the infiltration, incorporates equipment for the total recovery of the effluent and models one-dimensional flow. 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.

With the exception of the groundbreaking work by Darcy (1856), most early studies involving soil columns were performed using unsaturated soil columns or lysimeters. An exhaustive bibliography and history of early experimental work involving lysimeters was compiled by Kohnke et al. (1940). Early work was largely concerned with the rate and amount of percolate passing through the soil (Dalton, 1802; De la Hire, 1703; Lawes et. al., 1882). Soil column studies concerning the chemistry and movement of solutes in the pore water began to appear in the early 20th century (Burgess, 1921; Parker, 1921; Schreiner and Failyer, 1906) and soil column analyses of the mechanics of flow and permeability in porous media were being published by the 1940s (Christiansen, 1944; Fireman, 1944; Kirkham and Feng, 1948). A vast number of articles have been published since 1950 in the fields of hydrogeology, agriculture and soil sciences which rely primarily on results obtained from soil column experiments. Despite this, no attempt has ever been made to standardise or compile the best practices for constructing soil columns and a review of the literature reveals a bewildering array of technical approaches. Some of the smallest columns reported in the literature measure 1 cm in diameter and 1.4 cm in length (Voegelin et al., 2003) while the largest measure up to 2 m × 2 m × 5 m (Mali et al., 2007) and weigh over 50 tonnes.

The purpose of this article is to review the state of the art for soil column design, rather than to provide a rigorous review of the history of soil column experimentation. Given the thousands of publications which describe results obtained from soil columns, it would be impossible to cite even a small fraction of them in a single article. Therefore, citations have been limited to those which concisely illustrate a given concept. A great many other references may exist which are historically and factually valid.

Soil columns operating in the unsaturated regime are generally and historically referred to as lysimeters. This term has usually been applied to large outdoor soil columns, although no definition exists which establishes minimum size requirements. These columns are characterized as having both air and water (or another liquid) in their pore spaces and they are typically used to reproduce conditions encountered in soil found between the earth's surface and the top of the groundwater table, otherwise known as the vadose zone or unsaturated zone.

In contrast, soil columns which operate in the saturated regime have no air or gaseous phase present in their pore spaces. In such a situation, the pores are entirely filled with a liquid such as water or a non aqueous phase liquid such as oil. These soil columns are typically used to reproduce the conditions found in an aquifer. Substantial design differences exist between soil columns used to reproduce saturated and unsaturated conditions.

Soil columns may be classified either according to their level of saturation as discussed above, or according to the method of their construction. Two broad categories of construction have been reported in the literature: packed columns that use disturbed soil and monolithic columns that use undisturbed soil. Packed soil columns are built using soils which have been excavated or “disturbed”, then backfilled into a rigid container and compacted. In contrast, monoliths are extracted whole and intact from natural soil. Packed columns are typically much more homogeneous than monoliths, which may or may not be desirable depending on the experimental objectives. It has been shown that the choice of packed or monolithic columns will have a direct impact on the experimental results. For example, Camabreco et al. (1996) showed that there is a lower leaching rate of trace metals and dissolved organic matter from packed columns than in intact soil columns. Similarly, Smith et al. (1985) reported less leaching of *Escherichia coli* from packed soil columns than undisturbed soil columns.

The selection of methodology in soil column construction will therefore have an impact upon the results obtained and investigators need to reflect on how their choice of methodology relates to the hypothesis they are attempting to prove or disprove. Packed soil columns using screened, homogenized soils can be expected to have fewer macropores, which will result in better reproducibility at the expense of realism. Use of intact monoliths may better reproduce field conditions at the possible expense of reproducibility.

If the behaviour of the soil columns is to be modelled numerically, the boundary and initial conditions must be well defined. In most cases, the boundary conditions of soil column experiments involve no-flow boundaries along the column walls and constant head boundaries of different values at each end of the column. This arrangement forces steady-state one-dimensional flow along the longitudinal axis of the soil column. In most soil column experiments, the objective of the initial conditions is to reproduce the