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ScienceDirect
Journal of Contaminant Hydrology 92 (2007) 109 – 128
JOURNAL OF Contaminant Hydrology
www.elsevier.com/locate/jconhyd

Multidimensional validation of a numerical model for simulating a DNAPL release in heterogeneous porous media

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Received 31 January 2006; received in revised form 16 October 2006; accepted 3 January 2007

Abstract

A fixed-volume release of 1,2-DCE, tracked in space and time with a light transmission/image analysis system, provided a data set for the infiltration, redistribution, and immobilisation of a dense non-aqueous phase liquid (DNAPL) in a heterogeneous porous medium. The two-dimensional bench scale flow cell was packed with a spatially correlated, random heterogeneous distribution of six sand types. In order to provide the necessary modelling parameters, detailed constitutive relationships were measured at the local scale for the six sands. These experiments revealed that nonwetting phase (NWP) relative permeability–saturation (k_{rN}–S_W) relationships are strongly correlated to sand type. Trends in the best-fit k_{rN}–S_W parameters reflected a positive correlation between mean grain diameter and the maximum NWP relative permeability, k_{rN}^{max}. Multiphase flow simulations of the bench scale experiment best reproduced the experimental observations, producing excellent matches in both time and space, when the measured, correlated local scale k_{rN}–S_W relationships were employed.

Keywords: Relative permeability; Multiphase flow; Nonwetting phase; Migration rates; Model validation; Constitutive relationships

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1. Introduction

Numerous physical experiments (Schwille, 1988; Kueper et al., 1989; Illangasekare et al., 1995; Oostrom et al., 1999; O'Carroll et al., 2004) and field studies (Kueper et al., 1993; Brewster et al.,

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doi:10.1016/j.jconhyd.2007.01.003

1995) have examined the factors that govern the final spatial distribution of a dense, non-aqueous phase liquid (DNAPL) body following a finite volume, near-surface release. However, few studies (e.g., Illangasekare et al., 1995; Gerhard and Kueper, 2003b; O'Carroll et al., 2004) have collected the transient data necessary for examining the temporal behaviour of such releases. Kueper and Frind (1991b) validated a multiphase flow model for drainage processes by tracking DNAPL migration in a two-dimensional, heterogeneous bench scale cell with a continuously active source. Gerhard and Kueper (2003a,b) validated a multiphase flow model for drainage, imbibition, and trapping processes by tracking hysteretic DNAPL migration and immobilization in one-dimensional, homogeneous column experiments. Few data sets are available for the rigorous multidimensional validation of models for a complete DNAPL release (i.e., from onset of source to final hydrostatic distribution) in space and time (e.g., Kueper et al., 1989; Oostrom et al., 1999).

Predictions of DNAPL migration in heterogeneous porous media are known to be sensitive to the macroscopic constitutive relationship submodels employed (e.g., Lenhard and Parker, 1987; Kueper and Frind, 1991b; White and Oostrom, 1998; Dekker and Abriola, 2000; Gerhard and Kueper, 2003c; Lemke et al., 2004). While the role of capillary pressure relationships in dictating the predicted spatial distribution of DNAPL is well documented (e.g., Lenhard and Parker, 1987; Kueper and Frind, 1991b; White and Oostrom, 1998; Dekker and Abriola, 2000; Gerhard and Kueper, 2003a,c; Lemke et al., 2004), less is known about the role of relative permeability relationships in determining the predicted rates of DNAPL migration. Relative permeability is defined as the ratio of effective permeability to absolute permeability (k_{abs}) for a given phase in a multiphase system. This REV-scale parameter, a function of both saturation and saturation history, can be difficult to measure; as a result, very few laboratory studies (Naar et al., 1962; Lin et al., 1982; Stonestrom and Rubin, 1989; Demond and Roberts, 1993; Dury et al., 1999; Gerhard and Kueper, 2003b) provide relative permeability data for unconsolidated porous media. This has prompted researchers to devise new methods of measuring relative permeability curves (Dane et al., 1998; Kamon et al., 2003), with varying degrees of success. Relative permeability has also been examined in the oil engineering literature (e.g., Osoba et al., 1951; Land, 1971; Lefebvre du Prey, 1973; Amaefule and Handy, 1982; Fulcher et al., 1984; Braun and Holland, 1994). However, the porous media characteristics that influence relative permeability curves – in particular, coordination number and pore aspect ratio – exhibit values in oil reservoir rock (Morgan and Gordon, 1970; Dixit et al., 1997) that preclude applying this data to the unconsolidated porous media relevant in near-surface DNAPL releases.

Nonwetting phase (NWP) relative permeability (k_{rN}) has been shown to be a function of wetting phase (WP) saturation, S_{W}, and saturation history, with distinct non-zero endpoints coinciding with the emergence saturation, $S_{\mathrm{W}}^{\mathrm{M}}$, and the extinction saturation, $S_{\mathrm{W}}^{\mathrm{X}}$ (see Gerhard and Kueper, 2003b for a detailed description of the characteristics of NWP relative permeability curves). In unconsolidated porous media, NWP relative permeability (k_{rN}–S_{W}) functions often exhibit a "reverse hysteresis pattern" where imbibition k_{rN} is greater than drainage k_{rN} for some or all of the relevant S_{W} range. Note that throughout this study, the term 'drainage' refers to relative permeability and capillary pressure conditions (for both the NWP and the WP) that occur as WP saturations are decreasing, and that 'imbibition' refers to these parameters under increasing WP saturation conditions.

"Reverse hysteresis pattern" NWP relative permeability curves are common in narrow pore-size distribution sands (e.g., Naar et al., 1962; Stonestrom and Rubin, 1989; Wei and Lile, 1992; Gerhard and Kueper, 2003b). Increasing NWP saturations on drainage lead to the advancement of NWP into previously uninvaded nodes, whereas imbibition processes in such sands result in decreasing saturations within the previously invaded NWP pathway network. Therefore, for a given saturation, the number of NWP pathways for migration through an REV on imbibition is