Computers & Geosciences 78 (2015) 96–109

Contents lists available at ScienceDirect

Computers & Geosciences

journal homepage: www.elsevier.com/locate/cageo

Reconstruction of three dimensional convex zones using images at model boundaries

Sina Kashuk [a], Magued Iskander [b,*]

[a] NOAA-CREST Institute, CUNY, USA
[b] Civil & Urban Engineering Department, NYU, USA

ARTICLE INFO

Article history:
Received 18 June 2014
Received in revised form
2 February 2015
Accepted 12 February 2015
Available online 25 February 2015

Keywords:
Model studies
Optical image processing
Colorimetery
3D reconstruction
Contaminant transport
Regression analysis

ABSTRACT

This paper presents a method for predicting positions of color cubes inside a square transparent solid object from images taken at the orthogonal boundary surfaces. The work is developed for use in mapping flow of non-aqueous phase liquids (NAPL) in transparent soils. Transparent soil models have been developed to study the flow of contaminants through porous media, in bench scale tests. Yellow transparent cubes are used to represent NAPL plumes and clear transparent cubes are used as representations of transparent soil in order to definitively validate the algorithm. Color space information is used to relate concentration and image intensity. The new algorithm employs a so-called 3D carving method to iteratively reconstruct a 3D model using images taken at three orthogonal boundaries. The methodology presented in this paper is a fast, relatively accurate, non-intrusive and inexpensive method for quantifying NAPL zones in transparent soil models.

1. Introduction

Contamination of soil and groundwater are major environmental concerns. In the United States, over 50% of the potable water comes from groundwater (Harwell et al., 1999). In 1980, Congress established the *Superfund Program* to locate, investigate, and clean up hazardous sites nationwide. Since its creation, this program has been responsible for the location and analysis of tens of thousands of contaminated groundwater sites (EPA, 2012). To date, there are approximately 126,000 contaminated sites that remain polluted in the United States, with an estimated cost of remediation exceeding $110 billion (ERC, 2012).

A common form of soil and groundwater pollution is spilled non-aqueous phase liquids (NAPLs) (Freeze and Cherry, 1979). These liquids are immiscible in water and cannot be easily remediated (Riser-Roberts, 1998). One of the major concerns in the remediation processes is mapping the locations and volumes of NAPLs, especially as NAPLs migrate from their initial point sources under hydraulic gradients. Bench scale models are commonly employed to study the distribution of contamination, calibrate numerical models, and devise plans for remediation (Werth et al., 2010). Determining the concentration and distribution of contaminants using sampling from inside a contaminated model is intrusive and often impractical. As an alternative, non-intrusive imaging techniques are increasingly being used to extract data from bench scale models of porous media (Lo et al., 2010; Kechavarzi et al., 2000; Flores et al., 2009). However, the use of these techniques, for example CT scan or NMR imaging, is usually difficult and expensive, which gave rise to modeling of contamination using transparent synthetic soil surrogates (Kashuk et al., in press). Transparent soils (Fig. 1) can be used to visualize NAPL transport in subsurface media and confirm inferences made from numerical models (Iskander, 2010). The use of optical image processing techniques to map NAPL transport in transparent soils is advantageous due to the significant advancement in digital imaging and computing power in the last decade.

The methodology presented in this study has been motivated by the limitations encountered in bench scale multiphase flow studies, particularly those involving modeling of NAPLs spills and remediation. The resulting algorithm can be used in model studies to investigate remediation technologies such pump and treat. It can also be used to investigate flow of contaminants due to natural factors such as tidal variations or construction activities such as dewatering. Moreover, using three orthogonal projections, the shape, position, and volume of contamination can be reconstructed. Thus contamination volume can be measured to verify inferences derived from numerical models. Finally, because the technology is inexpensive and safe it can easily be introduced in educational settings including undergraduate labs and even K-12 outreach programs.

---

* Corresponding author.
E-mail addresses: skashuk@ccny.cuny.edu (S. Kashuk), Iskander@nyu.edu (M. Iskander).

http://dx.doi.org/10.1016/j.cageo.2015.02.008
0098-3004/

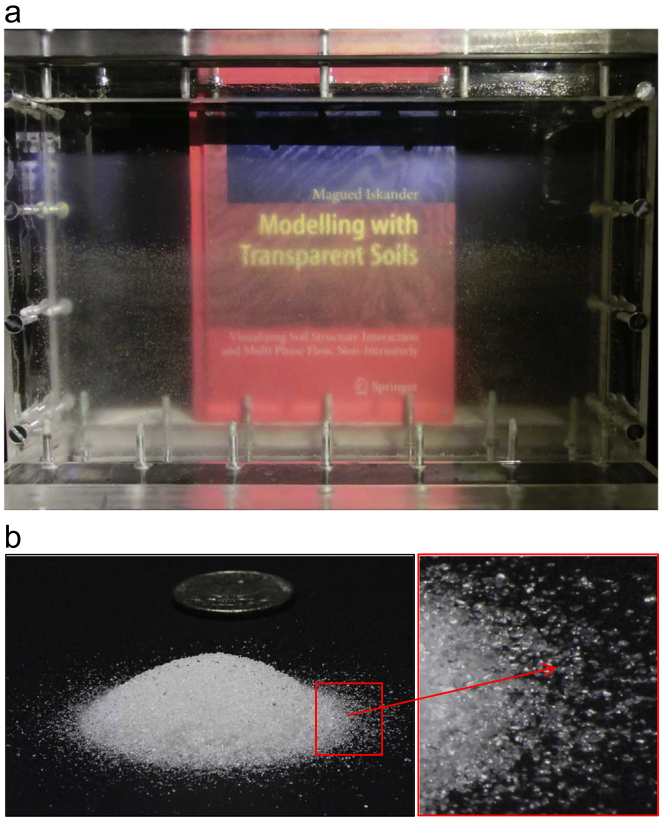

Fig. 1. (a) Reference viewed behind a 5 cm thick model made of transparent soil, and (b) fused quartz grains (Kashuk et al., 2014).

This study presents a mathematical approach to iteratively reconstruct the 3D NAPL zone by using three 2D images obtained at orthogonal projections of the zone. Direct tomographic 3D mapping of the contamination plume is possible using the 2D concentration data obtained at orthogonal projections. Tomography is the acquisition of information using penetrating waves, in this case visible light, within a given cross-section of the scene. This process involves gathering the projection data from multiple directions and serving the data into a tomographic reconstruction algorithm. There are many different reconstruction algorithms that can be employed depending on the signal acquisition system (Kak and Slaney, 1988). These algorithms make use of computational software to process the reconstruction of the scene, typically with iterative and/or inversion methods. In general, there is a trade-off between the time required and the accuracy of the computation. Therefore, certain assumptions are employed to speed up computations and prevent some unrealistic scenarios from being reconstructed (Herman, 2009).

A novel algorithm is developed to approximately reconstruct binary three dimensional arrays from its three orthogonal projections. The problem of contaminant transport is simplified by using clear transparent cubes to represent transparent soils, and yellow transparent cubes to represent the contamination NAPL. Images of the yellow cubes (“contamination”) are captured at the boundaries through the clear cubes (“transparent soil”). This offers the advantage of easily validating the developed tomographic routines by checking that the number of cubes determined in the calibration was captured correctly. The study employs two assumptions. First, that the contamination plume is contiguous. Second is that the contamination concentration is constant, which implies binary resolution of each measurement voxel as either uncontaminated (clear), or contaminated (yellow). The latter assumption simplifies the algorithm considerably, but it does not trivialize the problem because most NAPL plumes do not partition significantly into soils, and their concentration remain constant. Finally, a known volume of NAPL was injected into a transparent soil model in order to validate the algorithm under realistic test conditions. A Known volume of NAPL was also recovered and the model in order to determine the significance of various assumptions on the efficacy of model reconstruction.

2. Background

2.1. Color space

A color space is a three-dimensional space that can be used to geometrically represent any specific color. RGB is the most widely used color space in digital imaging and is often used in consumer photography and commercial digital cameras. RGB space was standardized in 1931 by the *International Commission on Illumination* (CIE), which defines red, green, and blue colors as monochromatic lights of wavelength 700.0 nm, 546.1 nm, and 435.8 nm, respectively. Generally, in digital RGB color format, at least 8-bits of memory is allocated to each component to enable each color to have a assigned value from zero to 255 in digital space. In analog RGB space, each component of RGB ranges from zero to one. Therefore, the coordinate, (R,G,B)=(0,0,0), corresponds to black, and the coordinate, (R,G,B)=(1,1,1), corresponds to the reference white.

Another standard RGB color space is sRGB created by HP and Microsoft in 1996 for monitor and printer applications. This space adds a fourth parameter known as gamma correction which is a nonlinear operator for encoding signals to compensate for the relationship between voltage and the resulting brightness in a display device. sRGB is typically employed in digital photography to encode color images. Gamma correction from linear RGB scale ranging from 0 to 1 can be converted to sRGB as follows:

$$C_{sRGB} = \begin{cases} 12.92\, C_{linear} & C_{linear} \le 0.0031308 \\ (1+0.055)C_{linear}^{1/2.4} - 0.055 & C_{linear} > 0.0031308 \end{cases} \tag{1}$$

where C_{sRGB} is the color component value in sRGB space and C_{linear} is the color component value in linear RGB space.

Although RGB space is commonly used in photography, it is not necessarily the most informative space for analysis of images of NAPL zones. There is a variety of different color spaces with properties based on their applications, supported by unique physical, physiological, or mathematical properties (Sharma and Trussell, 1997). These spaces may be derived from color electromagnetic wavelength characteristics, color properties based on the perceptions of the human eye, or luminance–chrominance colorimetric properties. Luminance is the intensity of light emitted from a surface per unit area in a given direction; chrominance is an objective specification of a color regardless of its luminance (Hunt and Pointer, 2011). Most color spaces are standardized by CIE (1986). Kashuk et al. (2013, 2014) previously defined a set of criteria to choose the ideal color space for calibration of pixel information and the depth of contamination for eight color spaces, including RGB, XYZ, Lab, YC_BC_R, YIQ, HSI, rgb and xyz color spaces.

For this study rgb chromatic color space is chosen because it better captures the yellow color of the contamination cubes. In comparison with RGB, rgb space preserves only chromatic information irrespective of the luminance properties of color. Therefore, sRGB pixel data is mathematically transformed into rgb chromaticity color space using the following transformations: