Computers & Geosciences 50 (2013) 44–51

Contents lists available at SciVerse ScienceDirect

Computers & Geosciences

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

Benchmark hydrogeophysical data from a physical seismic model

Juan M. Lorenzo [a,*], David E. Smolkin [a], Christopher White [b], Shannon R. Chollett [b], Ting Sun [b]

[a] Department of Geology and Geophysics, Louisiana State University, Baton Rouge, LA 70803-4101, USA
[b] Department of Petroleum Engineering, Louisiana State University, Baton Rouge, LA 70803-4101, USA

ARTICLE INFO

Article history:
Received 14 May 2012
Received in revised form
19 July 2012
Accepted 23 July 2012
Available online 19 August 2012

Keywords:
Saturation
Soil
Sensors
Hertz–Mindlin
Gassmann

ABSTRACT

Theoretical fluid flow models are used regularly to predict and analyze porous media flow but require verification against natural systems. Seismic monitoring in a controlled laboratory setting at a nominal scale of 1:1000 in the acoustic frequency range can help improve fluid flow models as well as elasto-granular models for uncompacted saturated–unsaturated soils. A mid-scale sand tank allows for many highly repeatable, yet flexible, experimental configurations with different material compositions and pump rates while still capturing phenomena such as patchy saturation, flow fingering, or layering.

The tank ($\sim 6\times 9\times 0.44$ m) contains a heterogeneous sand pack (1.52–1.7 phi). In a set of eight benchmark experiments the water table is raised inside the sand body at increments of $\sim$0.05 m. Seismic events (vertical component) are recorded by a pseudowalkaway 64-channel accelerometer array (20 Hz–20 kHz), at 78 kS/s, in 100- scan stacks so as to optimize signal-to-noise ratio. Three screened well sites monitor water depth ($+/-3$ mm) inside the sand body. Seismic data sets in SEG Y format are publicly downloadable from the internet (http://github.com/cageo/Lorenzo-2012), in order to allow comparisons of different seismic and fluid flow analyses.

The capillary fringe does not appear to completely saturate, as expected, because the interpreted compressional-wave velocity values remain so low (<210 m/s). Even at the highest water levels there is no large seismic impedance contrast across the top of the water table to generate a clear reflector.

Preliminary results indicate an immediate need for several additional experiments whose data sets will be added to the online database. Future benchmark data sets will grow with a control data set to show conditions in the sand body before water levels rise, and a surface 3D data set. In later experiments, buried sensors will help reduce seismic attenuation effects and in-situ saturation sensors will provide calibration values.

1. Introduction

Theoretical fluid flow models are commonly used to predict and analyze porous media flow but require verification against natural systems. Modeling approaches include pore network, lattice gas and lattice Boltzmann methods, Monte Carlo and particle methods (molecular dynamics, dissipative particle dynamics, and smoothed particle hydrodynamics), and conventional grid-based computational fluid dynamics coupled with interface tracking and a contact angle (Meakin and Tartakovsky, 2009). Although these methods are well-accepted and can achieve correct results if used with care, even the best fluid-flow simulators require assumptions and have limitations. These models remain prone to error, especially if the problems under consideration are nonlinear or have spatial heterogeneity. One way to check model accuracy is by comparison to observed natural responses.

Classically, the water table is a saturated surface at atmospheric pressure (Deming, 2002) (Fig. 1). Another saturated surface, such as the top of the capillary fringe, can exist at lower pressures. A water-saturated medium implies 100% of the pore fluid is water, but in the near-surface and under dynamic conditions, some amount of soil gas may be retained or generated in situ. For example, some organic-rich soils can have more than 80% of their volume constituted by fluids (Nyman et al., 1990) of which at least 5% is free gas (Parsekian et al., 2012). The capillary fringe is broadly defined as being fully saturated (Lu and Likos, 2004), and the thickness of the fringe is related to the air-entry pressure (Lu and Likos, 2004) or the point at which air can enter the largest pores in the soil. For medium sand, the capillary fringe is a little less than half the height of total capillary rise (Malik et al., 1989). Capillary forces create a zone above the water table (Fig. 1) occupied by fluid moving from the water table up to a height primarily dependent on the radius of the pore throats. A system containing various pore throat sizes will likely induce "fingers" of high fluid-saturation, creating heterogeneities.

* Corresponding author. Tel.: +1 225 578 4249; fax: +1 225 578 2302.
E-mail address: gllore@lsu.edu (J.M. Lorenzo).

0098-3004/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.cageo.2012.07.034

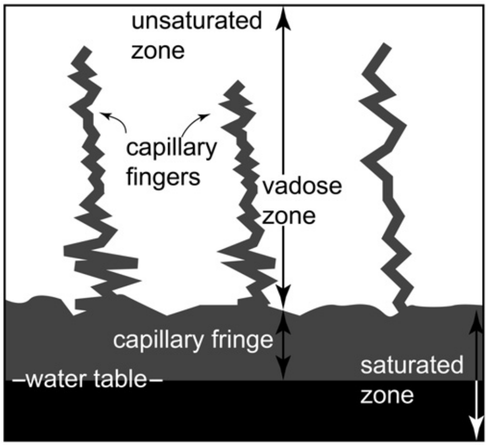

Fig. 1. Soil saturation zones. At least three different saturation levels between water table and surface (adapted from Lu and Likos, 2004 and Deming, 2002) are expected for shallow loose soils. A fully saturated zone lies below the water table (black). Pore pressure at water table is atmospheric. Above the water table lies a second saturated zone (gray zone) where pore pressure is less than atmospheric. Unsaturated conditions (white zone) prevail where air can enter pore spaces. Irregular unconnected capillary fingers are able to reach the top of the capillary fringe.

Additionally, whenever water levels drop, whether due to natural causes or pumping, some water remains trapped in the pores due to capillary forces. The trapped water creates a residual saturation and forms the vadose zone between the surface and the water table.

Large-scale field projects and reference sites (e.g., Koch et al., 2009) are capable of providing data with which to test constitutive flow models, but they can be costly, in time and money. Resultant data can be sparse and may require careful geostatistical characterization especially in heterogeneous sediment (Barrash and Clemo, 2002). Even homogeneous field sites can be constrained by weather and tides (Bachrach and Nur, 1998a). Moreover, because models of large natural systems can be limited (Oreskes et al., 2007) a lab-scale experiment may help complement our understanding of these models.

Fully described experimental data sets, publicly available on the internet, provide benchmark cases to which flow simulations and soil physics models can be compared. Mid-size experiments can be controlled and modified while maintaining complexity in the physical characteristics of the media. Herein, we focus on a seismic laboratory experiment and present eight data sets plus the details of their collection. Preliminary analyses of these initial results imply additional experiments are needed; their data will also be made public. We refer to this work collectively as the sand tank experiment. The sand tank serves as an unconfined model reservoir or aquifer, and because seismology can be used to image features on multiple scales, it lends itself to physical modeling.

Such open-source data can provide a readily available, common-reference and inexpensive body of observations that multiple researchers can use to test granular soil and fluid flow models. We envision future expansions of these data sets to include useful parameters such as water-level pressure, temperature and in-situ measured saturation that can help calibrate models. Additional sand tank experiments can incorporate lowering as well as raising of water levels in order to capture hysteretic effects, which have been observed seismically (Knight and Nolen-Hoeksema, 1990).

Seismic detection of subsurface water saturation remains a challenge to near-surface seismology. Seismic experiments conducted during pumping tests generally are able to detect amplitude changes in reflection events attributed to an increase of the zone of heterogeneous partial saturation (Birkelo et al., 1987; Sloan et al., 2007) and an increase in complexity. Yet, the ability to measure the changes in the height of the water table from the surface, or its proxy, can provide information on aquifer properties (Birkelo et al., 1987), soil conditions in agriculture, and contaminant flow and removal. While electromagnetic methods have been in common use for many years (e.g., Neill, 1990; Zhody et al., 1974) and are considered essential in groundwater investigations (Santamarina et al., 2005), in their absence seismic parameters such as V_P/V_S (compressional wave velocity/shear wave velocity) ratios can be used as good indicators of variations in fluid saturation (Grelle and Guadagno, 2009).

The strongest seismic reflections are expected to emanate across the largest changes in acoustic impedance (seismic velocity times density), possibly corresponding to the top of the saturated capillary fringe (Fig. 1). However, even in the case of a nominally homogeneous medium, heterogeneity in the acoustic impedance can also be affected by factors such as matric suction (Hicher and Chang, 2008), or patchy saturation (Knight et al., 1998; Konyai et al., 2009). The capillary electro-attractive force between the water and solid grain surfaces and the origin of matric suction is strongly dependent on the size of the pore throats and the angle of the wetting fluid (Deming, 2002). Patchy saturation can have a significant impact on seismic velocities. The size of the patches relative to the wavelengths used (Knight et al., 1998) can provide an inaccurate image of the subsurface. Relatively controlled geological homogeneity, as in our sand tank, can minimize the effects of patchy saturation and can create a system that is more easily imaged by seismological methods.

Often, predictions of seismic velocities in saturated–unsaturated unconsolidated sediments require an estimate of the effective values of the wet bulk (K_{wet}), wet shear moduli (G_{wet}) and wet bulk density (ρ_{wet}) of the medium where

$$V_P = \sqrt{\frac{K_{wet} + \frac{4}{3}G_{wet}}{\rho_{wet}}} \text{ and } V_S = \sqrt{\frac{G_{wet}}{\rho_{wet}}}$$

At the low-frequency limit in Gassman–Biot theory (Gassmann, 1951; Biot, 1956) K_{wet} is relatable to the reference bulk modulus of the framework of mineral grains (K_{ref}) whose porosity is ϕ, the bulk modulus of the minerals comprising the sediment ($K_{\min}$), and the bulk modulus average of the pore fluid (K_{fl}), as follows (Mavko et al., 1998, p. 168):

$$\frac{K_{wet}}{K_{\min}-K_{wet}} = \frac{K_{ref}}{K_{\min}-K_{ref}} + \frac{K_{fl}}{\phi(K_{\min}-K_{fl})}$$

and where the shear modulus (G_{ref}) is unchanged by the pore fluids. In addition, K_{ref} and G_{ref} can be provided by a generalized Hertz–Mindlin (Mindlin, 1949) contact theory extended to a randomly disordered, stack of spheres as:

$$K_{ref} = \sqrt[3]{\frac{C^2(1-\phi)^2 G_{\min}{}^2}{18\pi^2(1-\upsilon)^2} P_{eff}}$$

$$G_{ref} = \left(\frac{5-4\upsilon}{5(2-\upsilon)}\right) \sqrt[3]{\frac{3C^2(1-\phi)^2 G_{\min}{}^2 P_{eff}}{2\pi^2(1-\upsilon)^2}} \quad \text{(Mavko et al., 1998)}$$

where C (coordination number) is the average number of contacts between grains, $G_{\min}$ is the shear modulus and ν is Poisson's ratio of the mineral grain, and P_{eff}, the effective confining stress between grains. An increase in saturation in the sand body increases the overall bulk density and through hydrostatic buoyancy, may also decrease the effective confining stress – $P_{eff} = (\rho_{\min} - \rho_{water})(1-\phi)g\,z$, (Velea et al., 2000) – both processes act to decrease the overall V_P. Modifications to the basic assumptions such as the actual smoothness of grains and direct grain contact interaction may limit the accuracy of these velocity predictions (Bachrach et al., 2000; Velea et al., 2000). Intrinsic