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Review

A review of experimental studies on double-porosity soils

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Double-porosity is an important characteristic in soil that is found to influence the migration of fluids within the soil. Of late, a number of laboratory experiment studies have been carried out on the flow of water through soil media with double-porosity characteristics as well as on the mechanical aspects of the double-porosity structure of the soil. This paper first introduces the double-porosity concept as apposite to soil and then presents a review of the experimental studies mentioned. It is concluded that there is still a significant gap in the literature with regards to laboratory experiments conducted in double-porosity soil using liquids that are immiscible with water.

Key words: Aggregated soil, dual-porosity, fluid flow, porous media.

INTRODUCTION

In most subsurface fluid flow problems, a very intricate environment in the form of the unsaturated zone will be encountered. It is the zone where transport of water and nutrients for plants occur and it also forms the first line of defence for groundwater sources against contaminants introduced from the surface of the ground (Li et al., 2000). In the case of multiphase immiscible flow in the unsaturated zone, fluid transport is already complex as different phases are involved, namely water, non-aqueous phase liquids (NAPL), air and the soil matrix. On top of the multiple phases concerned, the structure of the soil matrix itself adds to the complexity of the fluid flows within the soil. When the structure of the soil is such that two separate pore systems occur concomitantly, double-porosity is said to be present.

Double-porosity is a naturally occurring phenomenon that can be found in many subsurface media such as agricultural top-soils (El-Zein et al., 2006), rock aquifers (Pao and Lewis, 2002), and compacted soils (Romero et al., 1999). These types of media are usually described as having two discrete but overlapping continuums, where the different characteristic pore size of each continuum results in hydraulic properties divergent from the other.

Fluid flow in double-porosity media has been studied extensively in the past using computational methods, albeit mainly with fractured rock as the media. Actual physical experiments on fractured rocks were understandably scarce as the medium was not easy to reproduce in the laboratory. Moreover, actual testing of fractured rock requires significant amount of money as well as sophisticated equipment to locate and acquire which few laboratories around the world have the capacity to do. On the other hand, soil is much easier to work with and this shows in the number of physical experiments on double-porosity soil that has been conducted in recent years.

This paper aims to provide a current review on physical laboratory experiments on double-porosity soil media. In this paper, a brief description of the double-porosity concept is given, followed by a literature review of all the experimental studies on double-porosity soil that the authors knew about. A summary of the reviews wraps up the review section and a conclusion is then drawn at the

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end of this paper.

DOUBLE-POROSITY IN SOIL

History

The history of the concept of double-porosity can be traced back to the initial years right after the boom of the petroleum industry which started with the drilling of the first commercial oil well in the year 1859, dubbed the Drake discovery well in northwestern Pennsylvannia, North America (Black, 1998). Andrews (1861) first introduced the notion of double-porosity by postulating in his paper that there is a direct relation between the number of fissures in the rock and the amount of oil extracted from it. This was followed by the work of Barenblatt et al. (1960) nearly a century later who enunciated the double-porosity concept based on an overlapping continuum technique. This concept was adopted soon after by Warren and Root (1963) who applied it in the field of petroleum engineering.

Since the publication of the works of Barenblatt et al. (1960) and Warren and Root (1963), many researchers have advanced the concept of double-porosity and developed various double-porosity models for simulating production and recovery of oil in fractured reservoirs. Table 1 shows a list of the documented modelling works on fractured rock systems known to the authors of this article. These studies are all different in their formulation and solution procedure but the one thing they have in common is having rock as the double-porosity medium and the use of numerical or analytical modelling, usually performed via computer codes, as opposed to physical experiments.

Due to the nature of oil-bearing formations, the large amount of attention given to double-porosity in petroleum reservoir engineering is fathomable. However, double-porosity also occurs in soil. Ghezzehei and Or (2003) stated that tillage of soil will result in soil aggregates separated by inter-aggregate pores. Double-porosity in soil may also be due to soil fauna, plant roots, natural soil pipes and cracks as well as fissures (Beven and Germann, 1982). These features mentioned by Ghezzehei and Or (2003) as well as Beven and Germann (1982) are the soil equivalent of the fractures and other elements making up the fracture porosity in rocks since the presence of such features will cause double-porosity in soil and rock, respectively. Gerke (2006) can be referred to for an extensive review on different modelling approaches to water flow and solute transport in structured, double-porosity soils.

The double-porosity concept

In petroleum reservoir engineering, the fractured reservoir rocks consist of two types of porosity systems: Primary porosity, also known as matrix porosity, that are made up of intergranular pore spaces, and the secondary porosity, also known as fracture porosity, that are formed by fractured voids or, less commonly, vugs. The fracture porosity is usually the result of rock fracturing, fissures, jointing and dissolution by water (Warren and Root, 1963). The summation of the primary and secondary porosities will be equivalent to the total void space as shown in Equation 1.

$$\phi_1 + \phi_2 = \phi_T \tag{1}$$

Where ϕ_1 is the primary or matrix porosity, ϕ_2 is the secondary or fracture porosity and ϕ_T is the total porosity. Previous studies (Table 1) have established that the secondary porosity is substantially smaller than the primary porosity while the opposite is true with regards to fluid permeability. In cases of fluid flow such as oil, this means that the advective transport will occur primarily in the fracture network with the porosity of the rock matrix serving as stagnant zones connected to the advective flow paths via molecular diffusion (USEPA, 2003). The porous matrix will act as a long-term diffusion source or sink for the fluid.

It was found during discussions with people from the geotechnical field that in geotechnics, the term ‘primary porosity’ would most likely be associated with higher permeability compared to secondary porosity due to the word ‘primary’. It is stressed here that in this paper, primary porosity is associated with low permeability whereas secondary porosity is associated with high permeability.

Using aggregated soil as an example of a double-porosity soil, the double-porosity constituents are disassembled and discussed as follows. The makeup of an aggregated soil is shown in Figure 1. For the sake of simplicity, the soil aggregates in the soil sample in Figure 1 are shown as monodispersed, though in actuality this type of aggregate arrangement is extremely rare even for laboratory-created aggregated samples. If the aggregates were to totally collapse, Figure 1(a) will become Figure 1(b) where the soil will be in its unaggregated form with the space above it originating from the inter-aggregate pores. Figure 1(b) also shows that the intra-aggregate pores are in fact the same as the pores of the unaggregated soil. Thus, the inter-aggregate pores are also known as the secondary porosity in aggregated soils. If the intra-aggregate pores in Figure 1(b) can somehow be sequestered from the solid soil particles, this would result in Figure 1(c) where each physical composition of the aggregated soil is separately displayed. Determination of the inter-aggregate and intra-aggregate porosities of an aggregated soil has been presented by Ngien et al. (2012a) whereas a clear depiction of the structure of aggregates in clay soils can be found in Baker and Frydman (2009).

Cutting-edge technology has given rise to many

Table 1. Published fractured rock models.

Rigid/Deformable	Fluid Phase	Scheme	Dimension	Reference
Rigid	Single (l)	A	1-D	Barenblatt et al. (1960)
Rigid	Single (l)	A	1-D	Warren and Root (1963)
-	Dual (w, n)	FD	3-D	Kazemi et al. (1976)
Rigid	-	A	3-D	Aifantis and Hill (1980)
-	Single (wm)	FE	1-D	Bibby (1981)
Deformable	Single	A	1-D, RPC	Wilson and Aifantis (1982)
Deformable	Single	FE	2-D	Khaled et al. (1984)
Deformable	Single	FE	-	Valliappan and Khalili-Naghadeh (1990)
-	Single	H	-	Arbogast et al. (1990)
Deformable	Single	FE	-	Khalili-Naghadeh and Valliappan (1991)
Deformable	Single	FE	2-D	Elsworth and Bai (1992)
Deformable	Single	H	-	Auriault and Boutin (1992, 1993)
Deformable	Single	FE	2-D	Bai et al. (1993)
Rigid	Single (wm)	FE	1-D	Gerke and van Genuchten (1993)
-	Single	A	-	Bai et al. (1994)
-	Single	S	2-D	Rubin (1995)
Deformable	Single	-	-	Berryman and Wang (1995)
Rigid	Single (w)	FE	1-D	Tseng et al. (1995)
Deformable	Single	-	-	Wang and Berryman (1996)
Deformable	Single (wm)	A	1-D, RPC	Bai et al. (1996)
-	Dual (w, n)	H	-	Bourgeat et al. (1996)
Deformable	Single	FE	1-D	Ghafouri and Lewis (1996)
Deformable	Multi (w, n, a)	FE	3-D	Lewis and Ghafouri (1997)
-	Single (wm)	FE	2-D	Valliappan et al. (1998)
Deformable	Single	FE	2-D	Bai et al. (1999a)
Deformable	Single	FE	3-D, RPC	Bai et al. (1999b)
-	Dual (w, n)	FE	2-D	Kim and Deo (2000)
-	Single (wm)	FV	2-D	Moutsopoulos et al. (2001)
Deformable	Multi (w, n, a)	FE	3-D	Lewis and Pao (2002)
-	Single (wm)	FE	-	Alboin et al. (2002)
-	Single (wm)	H	-	Royer et al. (2002)
Deformable	Single	FE	3-D, RPC	Zhang et al. (2003)
Deformable	Single	FE	2-D	Nair et al. (2004)
Deformable	Single	FD	1-D	Zhang et al. (2004)
Deformable	Single	-	1-D	Zhao and Chen (2006)
-	Dual (w, n)	A	1-D	Ryzhik (2007)
-	Single (g)	FE	1-D	Hattingh and Reddy (2009)
-	Single	A	2-D	Coronado et al. (2011)
-	Single	Varied	Varied	Bodin et al. (2012)

*Note: (l) – liquid, either water or NAPL; (w) – water; (n) – NAPL or oil; (wm) – water with miscible contaminants; (a) – air or gas; FE – finite element; FD – finite difference; FV – finite volume; A – analytical; H – Homogenization; S – stochastic; RPC – radial polar coordinates.

modern techniques and advanced methods that are used to investigate the microstructures present in soils. Environmental scanning electron microscopy and mercury intrusion porosimetry are examples of the current techniques available for qualitative and quantitative testing of unsaturated soil microstructures, respectively. Both methods have been applied in a number of the experimental studies on double-porosity soil reviewed further on in this paper. Romero and Simms (2008) have presented an in-depth study of the background, advantages and limitations of the two said testing techniques.

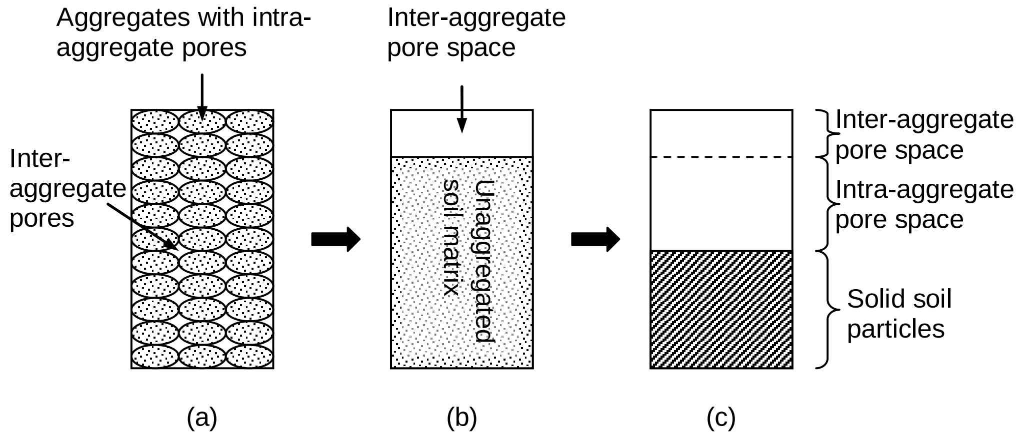

Figure 1. Physical composition of aggregated soil.

PAST AND PRESENT EXPERIMENTAL STUDIES

Actual site sample studies

Coppola (2000) tested field samples of an aggregated clay for water retention data and examined the capacities of several approaches to predict the water retention curves. The aggregated field samples were fully saturated before being tested for the hydraulic conductivity and unsaturated hydraulic conductivity using the falling head test and the crust method, respectively. Suction head was monitored through the use of tensiometers with the aggregated samples placed on a column of medium-textured sand. A layer of mixture with high hydraulic resistance was applied to the surface of the samples and a Mariotte feeding column was used to regulate the water supply at the inlet. For the water retention function, a silt-kaolin box apparatus was used to gravimetrically obtain the relationship. Suction was obtained using either natural drainage or vacuum system for varying levels of suction head. Coppola (2000) found that in soils consisting of two pore systems, a bimodal approach that allowed for partitioning of the porous medium into inter-aggregate and intra-aggregate pores gave a much better description of the retention data compared to the unimodal approaches investigated.

Simunek et al. (2001) carried out infiltration and evaporation experiments on undisturbed, aggregated soil samples to demonstrate the presence of non-equilibrium water flow. In the infiltration experiments, tensiometers were placed at predetermined depths of the aggregated soil samples. A porous membrane placed at the bottom of the aggregated samples acted as a suction plate. Throughout the experiments, the soil samples as well as the water taken in by the soil were weighed. Weighing of the aggregated field sample were also done in the evaporation experiments. The setup of the evaporation experiments were the same as for the infiltration experiments with tensiometers installed at certain intervals. Through the results obtained, they surmised that redistribution of water occurred, where the water slowly moved from the larger inter-aggregate pores to the smaller intra-aggregate pores during the experiments.

Alaoui et al. (2003) assessed the degree of preferential flow in a group of water and bromide solution infiltration tests on an unsaturated, structured sandy soil sample that contained macropores characterized by earthworm and root channels. Infiltration tests of increasing intensity were performed on the column of double-porosity soil obtained. A constant head permeameter was used to obtain the saturated hydraulic conductivity of the double-porosity soil sample. A metallic disc with perforated holes acted as a rainfall simulator to the samples where outflow was collected using a funnel. Water content, matric potential and drainage flow were measured. Results from two numerical models based on different approaches to flow in structured soils were compared with the experimental results and it was found that there was an absence of pure preferential flow due to the efficient lateral mass exchange in the sandy soil.

Carminati et al. (2008) studied the flow of water through two uncompacted clay-loam forest soil aggregates that were in contact with each other through their rough surface asperities. Using x-ray tomography as well as a morphological pore network model, they measured the water-filled contact area of the aggregates at different water potential and related it to the hydraulic conductivity when the aggregates are in series.

Fluid flow studies

More researches studying double-porosity soil emerged after the discovery by Lewandowska et al. (2005) that the double-porosity characteristics in soil can be created in the laboratory. Lewandowska et al. (2005) presented a series of one-dimensional infiltration experiments in an initially dry double-porosity medium under constant pressure head. The columns used were made from acrylic and a tension disc infiltrometer was placed on the column surface. One-dimensional flow was obtained by ensuring that the disc connecting the infiltrometer to the column was the same size as the column opening. The amount of water infiltrated was recorded as a function of time. At the bottom of each sample, a porous membrane was fixed to allow outflow of which the mass were measured. Lewandowska et al. (2005) produced their samples by mixing spheres made of sintered clay material, that had minute pore sizes, with uniformly distributed sand, which had much larger pore sizes, to produce marked differences in pore sizes, hence the double-porosity trait. The mixing was done by placing a layer of the sintered clayey spheres and then completely covering the spheres with sand before using a small hammer to mechanically compact the mixture. This process was repeated until the sample height was achieved for each double-porosity experiment. It was found that the microporosity in the sintered clay spheres contributed to water retention as well as flux retardation in the soil.

This was followed by Lewandowska et al*.* (2008) who performed a set of drainage experiments using the same double-porosity materials but based on gamma ray attenuation to get the water content. They compared the results to a set of similar tests using only homogeneous sand and arrived at the same conclusion as Lewandowska et al. (2005).

Szymkiewicz et al. (2008) extended the works by Lewandowska et al. (2005, 2008) by looking at the same double-porosity materials through a two-dimensional perspective. An acrylic box was used in place of the columns and the infiltrometer with a quarter-circle porous disc was installed at one corner of the box. The experimental procedure was similar to that described by Lewandowska et al. (2005). The wetting front of the infiltrating water was observed on the surface of the soil sample as well as on the walls of the acrylic box. The main aim of this experiment was to validate a numerical model produced by the same authors and good agreement was obtained between the numerically-predicted infiltration data and the observed ones.

The latest addition to experimental fluid flow investigations in double-porosity soils was presented by Ngoc et al. (2011) who modelled salt solution dispersion in double-porosity media similar to that used in the three previous works. The laboratory setup was also identical to the water infiltration experimental setup reported by Lewandowska et al. (2005, 2008). The difference is that in Ngoc et al. (2011), the column experiments were divided into two steps. The first step was to establish unsaturated water flow by imposing a constant flow from the bottom of the columns until a steady state condition was achieved. Cumulative water outflow was recorded using a balance and water content was measured by gamma ray attenuation. The second step involved displacement of the water by the salt solution. The changes in salt concentration measured in the effluent outflow were recorded every six minutes. The data from the series of one-dimensional experiments were used to calibrate and validate a theoretical double-porosity model also developed by Ngoc et al. (2011).

Mechanistic studies

Koliji et al*.* (2008) used a combination of oedometric compression tests and neutron tomography to evaluate the evolution of both field and reproduced aggregated soil samples where the results were used to propose a new state parameter to quantify the aggregated soil structure. The oedometric compression tests were carried out on dry aggregated soil samples where the dry field aggregates were placed freely and then compressed slightly to produce macropores in the samples whereas the reconstituted samples were prepared in the oedometric cell directly without any compression involved.

In the work of Bagherieh et al*.* (2009), a series of one-dimensional consolidation and drying experiments on laboratory-prepared, aggregated kaolin samples were conducted. In the drying experiments, a modified oedometer capable of measuring and controlling the various pressures, stresses, deformation and water volume changes was used. The aggregated sample was subjected to an initial net stress before being soaked by water percolating through the base of the sample. The net stress was then increased to the different target value for each drying experiment and the various pressures brought to equilibrium. Suction was then increased in stages by keeping the air pressure constant while decreasing the water pressure at the sample base. The consolidation experiments on the other hand made use of conventional oedometers and non-aggregated soil was also tested for comparison. From the results, Bagherieh et al. (2009) found that above a certain applied vertical effective stress, the response of the aggregated soil will approach that of a non-aggregated soil in terms of compressibility and water retention. It was shown that the effective stress principle can be used to predict quantitative volume changes in aggregated materials. Another observation by the authors was that suction hardening may not be present in all unsaturated soils.

Li and Zhang (2009) investigated the formation of double-porosity in compacted, decomposed granitic soil samples and also the evolution of the microporosity structure in the samples during the wetting-drying process. Unsaturated soil samples with different void ratios were used to study microporosity structure formation as a result of sample compaction. Saturated soil samples were used to study the microporosity structure variation after sample saturation and during the drying process. SEM tests were also performed on soil samples with different degrees of saturation to obtain qualitative results of the microporosity structure. Inter-aggregate and intra-aggregate pores formed when the samples underwent compaction and the inter-aggregate pores were found to be very compressible under applied stress. On the other hand, changes to the intra-aggregate pores dominated during soil saturation and drying. From the experimental data obtained, Li and Zhang (2009) then developed a mathematical model relating the pore-size distributions to the void ratio.

Koliji et al. (2010) performed structural characterization of aggregated Abist and Bioley soils. They used imaging techniques as well as porosimetry to examine various combinations of saturation, vertical loading and aggregation state of the samples. Mercury intrusion porosimetry and environmental scanning electron microscopy were used to investigate the fabric of the soil at pore scale as well as to obtain the distribution of the pore sizes whereas neutron tomography was used to evaluate macropores between the aggregates in the soil samples. It was found that aggregated samples after soaking along with single aggregates have textures similar to reconstituted soil and that sufficient mechanical loading will destroy the aggregated structure of the samples through closure of existing macropores.

Summary

The list of experimental studies reviewed in this paper provided good insight on double-porosity in soil but the common denominator in all of them is that the fluid applied was limited to water. Using both numerical modelling and laboratory experiments, Ngien et al. (2012a, b) found that the presence of double-porosity features also has significant influence on the migration of immiscible fluids within double-porosity soils. Prior to that, Nambi and Powers (2000) have carried out experiments on NAPL dissolution where the medium used, contained in a flow cell with glass walls, was a rectangular coarse sand lens enclosed by finer sand. The heterogeneous system used gave a resultant effect similar to double-porosity but the effect was limited to the boundary between the coarse sand lens and the finer sand only and did not extend to the whole domain of the medium. The study by Ngien et al. (2012a) was limited to qualitative observations of NAPL behaviour in aggregated soil experiments. There is still a considerable gap in the open literature currently with respect to experimental investigations on immiscible fluids migration in double-porosity soils.

CONCLUSION

Double-porosity features are natural occurrences that can be found in a variety of soils. The concept of double-porosity stemmed from the oil and gas industry and has been adopted to study flow and transport in porous media, which includes soil. Soils that have double-porosity characteristics were found to have significant influence on the migration of fluids, especially with regards to multiphase immiscible flows. In the last decade, experimental research using soil as the double-porosity medium has begun to flourish. Nevertheless, most of the experimental studies were focused on water flow and solute transport in the double-porosity samples as well as studying the mechanistic characteristics of double-porosity soils. The flow of immiscible fluids, specifically NAPL, in double-porosity soils is still a relatively uncharted territory. This provides the proper grounds for more experimental studies on NAPL or immiscible fluid flows in double-porosity soils to be conducted. NAPL contamination in the subsurface is a widespread problem and good data of NAPL behaviour, particularly in the presence of double-porosity features, that are obtained from physical experiments will go a long way in the effort to understand and solve such problems.

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