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Characterization of transition from Darcy to non-Darcy flow with 3D pore-level simulations

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Abstract

We characterize seepage flow in porous media via a series of three-dimensional (3D) direct numerical simulations (DNSs) of Navier-Stokes flows in representative volume elements (RVEs) at the pore level. The immersed boundary method with a fixed staggered grid is employed for calculations based on the finite difference method in the pore domain formed with spatially arranged rigid particles in RVEs. The numerical results of the DNSs with different particle sizes and different seepage flow velocities are volume-averaged over the RVEs to evaluate the permeability coefficients of the seepage flows and are ordered according to the Reynolds numbers for porous media. After the numerical scheme is validated with a simple RVE model, the transition from Darcy to non-Darcy flow, for which experimental results have reported in the literature, is demonstrated in terms of the calculated permeability coefficients and examined based on the pore-level flow characteristics to clarify the mechanism of the permeability change, i.e. the macroscopic behaviour of RVEs related to the Reynolds number.

Keywords: Permeability; Immersed boundary method; Micro-scale; Non-Darcy flow **IGC: E07**

1. Introduction

Interactions between fluids and solid particles occur in various engineering fields. Thus, the precise kinematics with concrete of many such dynamic phenomena is waiting to be clarified, such as erosion, liquefaction, and landslides in geomechanics. Because of the difficulties in establishing fully theoretical fluid dynamics descriptions of these systems, numerical approaches have been utilized not only to express those problems but also to aid us in further understanding these phenomena. Thanks to increases in computing power in recent decades, there have been many studies that have focused on numerically expressing the interactions between fluids and particles.

Here, we briefly introduce previous studies in this field of research and some applications. In general, porous media consisting of solid particles have been studied using several numerical approaches. For example, Hasert et al. (2011) conducted simulations of the high Reynolds number flow of air through 3D porous media using the Lattice Boltzmann Method (LBM) (Chen and Doolen, 1998), and compared the results with those of other calculation schemes. In another approach, Robinson et al. (2014)

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u	velocity	f	external force on an Eulerian point
t	time	F	external force on a Lagrangian point
Δt	time interval between consequent steps	U	velocity evaluated on a Lagrangian point
ρ	density	X	location of the Lagrangian point
p	pressure	u	velocity evaluated on an Eulerian point
μ	viscosity	h	grid size
g	field force (e.g. Gravity)		

proposed a 3D mesh-free scheme based on the two-way coupling method of the discrete element method (DEM) (Cundall, 1971) with the smoothed particle hydrodynamics (SPH) (Gingold and Monaghan, 1977), which considers the dynamic displacement of particles.

To list some example of applications, several studies in the field of geomechanics utilized DEM to express soil particles, as DEM is one of the most common simulation methods used to solve problems involving solid contact. Further, employing fixed grids for water flow expressions is a practical way to study the interactions between soil and water; the fineness of the grid systems can indicate how strict the interaction expression is. For example, Nakase et al. (1999) proposed a 2D simulation technique for soaked soil that establishes the relationship between the dynamics of the soil particles and the nearby water pressure by using a sparse grid system to enclose the soil particles. In that paper, pores were expressed as enclosed regions amongst the particles, and a pressure gradient was calculated from volume ratio change of the fluid. Fluid calculations were performed using a uniformed Eulerian mesh system. Therefore, fluid motion could be expressed as water transportation between neighbouring cells according to Darcy's law. Additionally, Shafipour and Soroush (2008) conducted a study on biaxial shearing of granular materials using a 2D fluid-coupled DEM, which is based on a similar principle, to numerically evaluate the stress-strain responses and pore pressures.

Different numerical approaches can yield much higher resolutions. For example, a study with a resolution around the scale of a single soil particle was conducted by Tarumi and Hakuno (1988). Their 2D liquefaction simulation used DEM to detect every single region amongst the particles to take pore water into account. Apart from the Eulerian fixed-grid system, Lagrangian treatments to express the pore region of nearby particles can be found in Okada (2011), where each DEM elements have its own nearby region to deal with pressure changes from interactions with other elements. In that paper, the difference between loose and dense soil was quantitatively reproduced by numerical undrained triaxial compression tests.

Even more precise simulations, using grid systems smaller than a particle, have recently been gaining in popularity. These approaches are based on Direct Numerical Simulations (DNSs) (Alfonsi, 2011; Moin and Mahesh, 1998), which do not employ any specific calculation models, but instead draw on equations from fluid principals for pore fluids' motion; thus, they perform very strict expressions. For example, Ohtsuki and Matsuoka (2010) demonstrated an application of LBM to particle transport problems driven by porous fluid motion in soil. Further, Ahrenholz et al. (2008) conducted a simulation using LBM to reproduce experimentally obtained hysteresis curves of a drainage and imbibition system of a soil sample as well as the microscopic behaviour of fluid in soils. Additionally, Fujina et al. (2015) conducted 2D numerical hole erosion tests using LBM-DEM coupled simulations to study the relationship between several erosion parameters. Although DNS have been gaining in popularity in geomechanics, those kind of detailed high-definition approaches are still difficult to deal with because of the complexity of geomaterials and the high calculation costs. Thus, further analyses and trials are required.

With regards to fluid-solid coupling techniques, the immersed boundary method (IBM) (Peskin, 1972) is commonly employed to express the solid-fluid boundaries. The IBM was originally proposed as a numerical scheme to solve 2D blood flow problems around elastic heart valves. Over the years, many variations have been developed to allow it to be applied to fluid-solid interaction problems in other fields. Notably, with regards to IBM-DEM coupling for fluid simulations, Uhlmann (2005) presented an integration to finite difference method, while Noble and Torczynski (1998) presented works using the LBM. The common idea of both those methods is to define a formula that can translate between Eulerian and Lagrangian frameworks, by either using interpolations (Peskin, 2002) or extrapolations (Fadlun et al., 2000).

In this paper, we characterize seepage flow in porous media using a series of 3D simulations of Navier-Stokes flows in representative volume elements (RVEs). The IBM with a fixed staggered grid is employed for calculations based on the finite difference method in the pore domain formed with spatially arranged rigid particles in the RVEs. The Reynolds number for porous media defined by Chilton and Colburn (1931) was calculated for each numerical result with different particle sizes. The transition of the flow from Darcy to non-Darcy (experimental data reported by Fancher and Lewis (1933)) is reproduced in the simulations. Studying the microscopic flow characteristics, we investigate the mechanism of the permeability change by relating the microscopic behaviour of RVEs to the Reynolds number.