PhD Proposal : Flow kinematic in 3D porous media

The research unit RECOVER from INRAE is pleased to invite applications for a PhD (3 years) dedicated to the experimental characterisation of flow within complex three-dimensional porous media. This PhD proposal is fully funded by the AQUA department from INRAE.

Research thematic : Experimental investigation in fluid dynamics and geomechanics

Workplace : UMR RECOVER, INRAE Aix-en-Provence, 3275 route de Cézanne, Le Tholonet (France)

Doctoral school : ED 353 Aix-Marseille Université, Engineer Science : Mechanics, Physics, Micro and Nano Electronics doctoral school of Aix-Marseille University

Supervised by : Mathieu Souzy (researcher, INRAE RECOVER), Pierre Philippe (research director, INRAE RECOVER)

Contract period : From October 2026 to September 2029

Keywords : 3D porous media, experiments, direct visualization, transport processes, flow kinematic, pore scale

Context and problematic

Geomaterial are complex porous material presenting a wide diversity of structures that set the flow kinematic of any fluids through it. When rainwater flows through rocks, or when expansive resin is injected to stabilize a soil and reinforce its mechanical properties to prevent crack [1], the way the injected solute is dispersed and homogenized in the surrounding media is directly driven by the local microstructure and the pore network. The presence of local heterogeneities such as a crack, the progressive development of an erosion channel [2], or the clogging of pores, will strongly affect the dispersion and mixing processes. These transport processes are characterized by investigating the velocity fields and relating the local pore scale processes to the macroscale behaviour of the porous material. The understanding of the small scale mechanisms thus allows to predict and control the macroscale dispersion and mixing process. This is of crucial importance for a broad range of applications, such as contaminant transport in soils and aquifers, drug delivery and nutrient transport in brain or plant tissues, heat exchangers, filters and catalytic processes in chemical or energy industry, biocalcification and soil reinforcement of hydraulic structures such as dam and dikes.

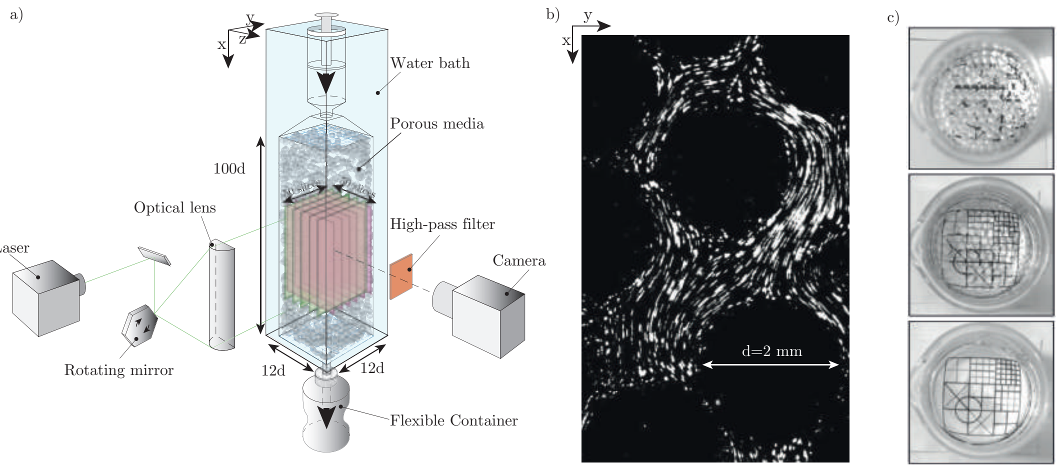

FIGURE 1 – **Experimental setup** a) The porous medium consists of a 3D random stack of PMMA grains tightly packed in a long transparent container. The fluid is forced through the porous medium with a syringe placed at the top of the set-up and collected at the bottom in a stretch container. The interstitial flow is imaged in a 2D plane formed by a planar vertical laser sheet, formed by reflecting a laser beam on a rotating mirror. The laser sheet is displaced across the porous medium to reconstruct the 3D fields, see Figure 2a. Scattered light is discarded with the help of a high-pass filter located before the camera lens to ensures that only the light emitted by fluorescent tracers is collected by the camera. b) Typical long-time exposure image of a sectional view of the porous medium (from Souzy *et al.* [3]). c) From top to bottom : illustration of poor to good refractive index matching between grains and the suspending fluid (from Voermans *et al.* [4]).

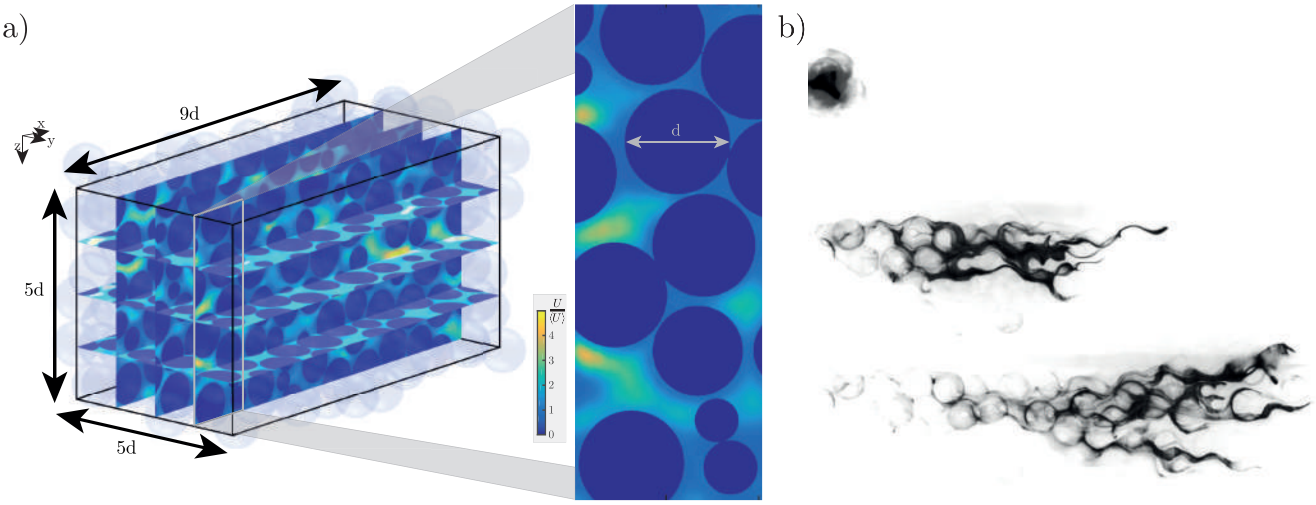

FIGURE 2 – a) Microstructure and velocity field measured experimentally in a 3D porous media composed of randomly packed solid monodisperse beads of diameter d. Colors stand for the velocity amplitude. b) Successive images of a blob of dye injected through a 3D porous media. The dye is progressively dispersed (as it is exploring the surrounding media) and mixed (as the dye concentration homogenize). Adapted from Souzy *et al.* [3].

Because of the opaque nature of porous media, the characterization of the velocity fields within a porous media is particularly challenging in three-dimensional (3-D) porous media. However, recent development of experimental techniques including index matching [5], allow to use transparent porous media (fluid and grains with the same optical refractive index) to perform direct visualization of the flow in artificial porous media [6]. These promising techniques allow to provide highly resolved experimental reconstruction of the 3-D Eulerian fluid velocity field. Such approach have already been successfully implemented to study porous media composed of randomly packed solid monodisperse spheres, and to investigate how a blob of injected dye stretches and get mixed [3].

This experimental thesis project aims to characterize the flow kinematic in 3-D porous media by developing these direct visualization techniques in artificial porous media with a progressively increased level of structure complexity to investigate how local heterogenities affect the transport processes. This will be addressed through careful laboratory experiments. The main questions that will be investigated are :

-How do the pore distribution affect the velocity distribution ? In other words, for a porous media composed of a random pack of particles, what is the role of polydispersity on the flow kinematic ?

-How does the presence of local heterogeneity like a crack affects the transport processes ? For instance when injecting a resin for soil reinforcement through a porous media with a crack, would all the solute flow through the crack as a preferential path, or would it also disperse and mix in the surrounding ?

-When a flowing solute transports fine particles – a widespread phenomenon during erosion and suffusion processes – how does the clogging of pores affect the flow kinematic by progressively closing flow paths ?

Experimental methodology

This thesis project plans to characterize the effect of the microstructure over the flow kinematic within porous media, by developping experimental techniques to perform direct visualization in 3D artificial porous media. The porous media will be made transparent by use of iso-optical index matching techniques, with a progressively increasing microstructure complexity. The porous media will be composed of a solid matrix made of randomly packed beads of transparent material, see Figure 1a. A fluid of corresponding optical refractive index will then be injected within the interstitial pores. Using velocimetry techniques (PIV/PTV), successive scans of the velocity field will be measured and used to reconstruct the 3D velocity field in the bulk of the porous media.

Starting with investigating the effect of polydispersity over the flow kinematic, the complexity of the artificial porous media will be progressively increased, and several configurations will be explored such as porous media presenting cracks, or within which some pores could get eroded, transporting fine particles which may eventually clog downstream pores.

In particular, we will focus on investigating how the velocity distribution of the interstitial fluid can be related to the microstructure, and on the effect of local heterogeneities over the macroscale transport processes. Furthermore, with the ongoing development of numerical methods to simulate the flow within complex 3D porous media, there is nowadays a strong need for benchmark datas set for testing and validation. Providing reliable three-dimensional high resolution experimental velocity fields datas sets therefore represents a very innovative work lacking to this day from the scientific bibliography, and the datas sets will be used for scientific collaborations with local colleague researchers to feed DEM (Direct Element Method) simulations.

Framework

The doctoral student will be registered at the doctoral school of Aix-Marseille University (ED 353, Engineer Science : Mechanics, Physics, Micro and Nano Electronics) and will be based in the RECOVER unit of INRAE PACA. This research unit is equipped with experimental benches and technical means for the characterization and study of porous material and their mechanical properties. RECOVER is an active research team composed of more than 75 permanent staff (researchers, engineers, and professors) and about 40 non-permanent scholars (PhD students, post-docs and technical support staff). The lab is located in Le Tholonet, few kilometers from Aix-en-Provence and close to Marseille (south of France).

The PhD is scheduled to start in October 2026 (with some flexibility) for a period of 36 months. Depending on the work progress, a master student may be recruited and supervised by the PhD candidate during the course of the PhD. The PhD will also benefit from a good quality of life, enriching interactions in an international environment, with a working site in an outstanding natural setting and a quality company restaurant.

Expected profile and requirements for the position

We are looking for a candidate with a master of research or graduate in mechanics – fluid mechanics – geotechnical engineering. The candidate is expected to have a potent inclination for experiments and strong knowledge in fluid mechanics. A training course in mixing, transport processes or a past experience in laboratory work will be profitable. The PhD student will be involved at all stages of the project : experimental setup design, sample preparation, and numerical image analysis (PIV, particle tracking, 3D reconstruction).

Expected skills : motivation for research work, faculty for working independently and in a team, capability to formulate concepts, curiosity, constructive criticism, perseverance and scientific rigour.
A good level in English is mandatory.

Application

Applicants should submit i) a CV, ii) a cover letter (in English or French) describing interests ans qualifications related to the position. Inquiries and applications should be sent by email to :

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Références

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