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Mohamed El Shamieh, Ngoc-Son Nguyen, François Bignonnet, Rachel Gelet, Didier Marot. Numerical investigation of a permeability-microstructure relationship in the context of internal erosion. IS-Grenoble 2024, Sep 2024, Grenoble, France. hal-04920824

HAL Id: hal-04920824

<https://hal.science/hal-04920824v1>

Submitted on 30 Jan 2025

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NUMERICAL INVESTIGATION OF A PERMEABILITY-MICROSTRUCTURE RELATIONSHIP IN THE CONTEXT OF INTERNAL EROSION

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Abstract

Internal erosion, characterized by the migration of soil particles within hydraulic earth structures due to seepage, is a significant global concern for risk management and maintenance. Among various mechanisms contributing to internal erosion, suffusion emerges as a prominent process. It involves the simultaneous detachment, transport, and potential self-filtration of fine particles through the pore network, leading potentially to a change in permeability and shear strength. Thus, investigating the link between permeability and microstructure is a key to achieve a better understanding of suffusion and to predict its consequences on the soil's permeability. The proposed methodology involves generating discrete element method-based samples, characterizing their constriction size distribution, and computing permeability using fast Fourier transform. While the Kozeny-Carman model was initially developed for stable microstructures, it may not apply to suffusion due to microstructural evolution. Thus, a modified approach is introduced, incorporating a characteristic constriction diameter computed from the constriction size distribution. This modified model is being compared against the original Kozeny-Carman one on fourteen gap-graded specimens. Encouraging results are herein being obtained so that the modified approach will be later used on flow modified specimens.

Keywords: Permeability, suffusion, granular soils, discrete element method, fast Fourier transformation, Delaunay triangulation, constriction size distribution, Kozeny-Carman.

1. Introduction

Earthfill hydraulic structures have several essential functions for our society which include irrigation, hydropower, water supply and flood control. These structures are built with soil materials that can easily be reused and are in good harmony with the environment in comparison with concrete gravity dams. Nevertheless, numerous earth structures display heterogeneities, large linear lengths, age and sometimes disorders leaving them susceptible to geotechnical instabilities. One of the major concerns affecting the integrity of these structures is internal erosion. This phenomenon is characterized by the migration of soil's particles within hydraulic earth structures due to seepage. Among the four mechanisms of internal erosion, we focus on suffusion also called volumetric erosion. It involves the simultaneous detachment, transport and partial self-filtration of fine particles through interconnected pore spaces within the soil matrix. Suffusion is a strongly coupled mechanism that induces significant changes in permeability, porosity, flow velocity, microstructure and strength of granular soils. The modelling of suffusion requires a relationship that links permeability with the evolving microstructure. Recall that permeability strongly influences the flow evolution, favoring or preventing the kinetics of suffusion. We aim to investigate the link between the permeability and the microstructure of eroded granular soils. To achieve this micro-macro investigation, a work methodology is proposed. Initially, numerical samples with different gradings of spherical particles are generated with discrete element method DEM. Subsequently, each microstructure undergoes a characterization of its constriction size distribution CSD using a method based on Delaunay triangulation [6]. Then, the macroscopic permeability is numerically homogenized by a method based on Fast Fourier Transform [1]. Specifically, this method solves Stokes equations within the pore space, which are a linearized form of Navier-Stokes equations appropriate for low Reynolds number flows typical of porous media. The no-slip boundary condition is imposed at the solid-fluid interface.

In literature, several empirical relationships have been proposed to link the permeability to some microstructural parameters such as Kozeny-Carman relationship [3] and the one proposed by Indraratna in 2012 [2]. However, it is crucial to note that this empirical relationship has been developed for stable homogeneous microstructures only. This means that it may not be applicable to a suffusion context that involves a significant evolution of the pore size distribution and the CSD due to grain rearrangements at the pore scale. In this work, we first study the Kozeny-Carman relationship and then we introduce a modified version of the Kozeny-Carman approach by using a characteristic constriction diameter obtained from the CSD, named the controlling constriction size D_c^* . This diameter represents the constriction size that is dominant within the specimen [7].

2. Methodology and microstructure characterization

The project utilizes the DEM, implemented in YADE open-source software to generate numerical samples subjected to isotropic compression. This research focuses on the analysis of gap graded samples due to their susceptibility to internal erosion (Figure 1.a). Loose and dense samples are generated with the respective compaction index of 10% and 90%. To respect the concept of representative volume element RVE, a minimum number of particles is needed. The number of particles used ranges from 4000 to 16000 depending on the grading. In our work, the RVE error on the variability of permeability estimated from the filtration method [5] is less than 8%. In total, 14 gap graded configurations are studied.

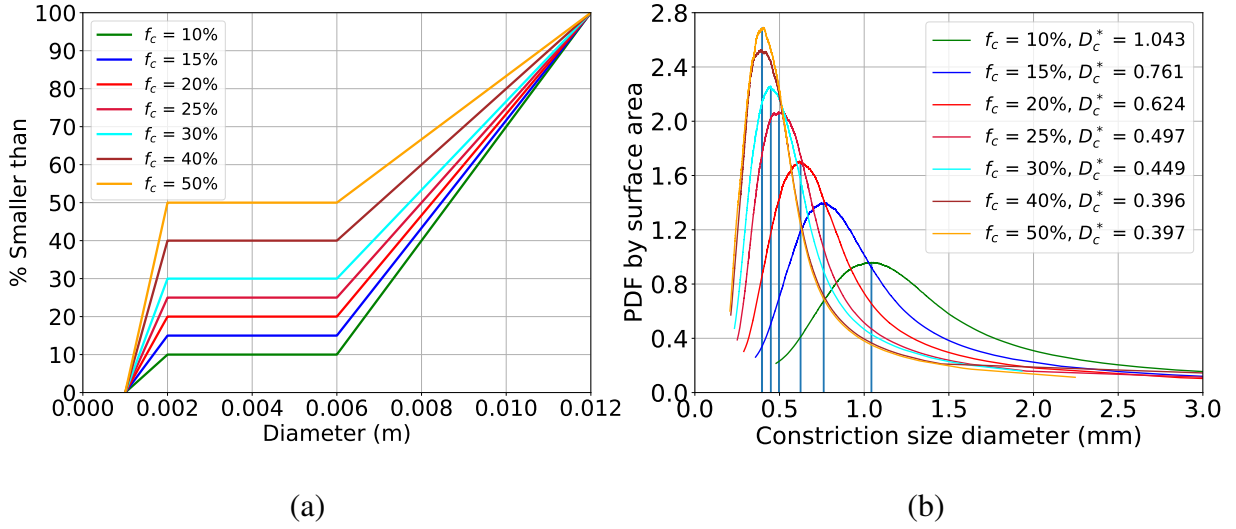


Figure 1. GSDs for gap graded specimens having different fine contents (a). Probability density function of the CSD for seven gap graded samples (b). Vertical blue lines represent the controlling constriction diameter D_c^* (mm) defined by each curve's peak (b).

The method based on Delaunay triangulation proposed in [6] is used to extract characteristics of the pore space of each sample. In this study, the constriction size distribution CSD is defined in terms of surface area. Figure 1.b shows several constriction size distributions represented by the probability density function PDF for the dense gap graded samples. For each CSD, the controlling constriction size D_c^* is defined as the diameter at the peak of the PDF curve. It is shown that the controlling constriction diameter D_c^* decreases when the fine content increases. This reduction is due to the reduction of void spaces, as the fine particles gradually fill the inter-coarse void space. Logically, we observe smaller constrictions for denser states than for looser ones. Then, the macroscopic permeability is numerically homogenized by the method based on FFT [1]. A physical relationship between permeability and the microstructure is then investigated at the scale of RVE.

3. Results and discussion

In this work, the first step is to study Kozeny-Carman model [3] for different homogeneous samples. This relationship is shown in eqn. 1 in which it links the permeability K to the porosity Φ and a specific length called the hydraulic radius R_H . This radius is the ratio of the pore volume to the area of the solid-fluid interface. One of the scientific challenges in this model involves numerically computing R_H , which is based on the assumption of spherical particle shapes. However, in the specific context of suffusion, the microstructure evolves significantly upon seepage. During this action, although the porosity and the hydraulic radius may remain constant upon the flow, the permeability may vary [4]. As a result, the later model may not apply to a suffusion context that involves a significant evolution of the pore network due to rearrangements of the grains at the pore scale. This remark reveals the presence of additional factors that influence the permeability of granular samples, highlighting the need for an alternative model. Hence, a modified version of the Kozeny-Carman approach is introduced by incorporating a characteristic constriction diameter obtained from the CSD, i.e. the controlling constriction size D_c^* (eqn. 2). Both parameters R_H and D_c^* characterize the opening size of the pore space. Figure 2.a shows R_H versus D_c^* for all the samples. It can be seen that R_H is quite well correlated to the D_c^* except for some dense samples with high fine contents. Indeed, a closer investigation shows that the ratio $D_c^*/(2*R_H)$ tends to decrease with the porosity (Figure 2.b).

$$K = \frac{R_H^2 \Phi}{k} \quad (1)$$

$$K = \frac{D_c^{*2} \Phi}{k^*(\Phi)} \quad (2)$$

Figure 3 shows the dimensionless constants k and k^* of the original and modified Kozeny-Carman models applied to homogeneous gap-graded samples. It is shown that the Kozeny-Carman coefficient k varies between 4.5 and 5.5 with a mean value of 5.0 (Figure 3.a), while the coefficient k^* in the modified model shows a decreasing trend with porosity, the dependency of k^* on porosity can be correlated by a decreasing power law function as shown in Figure 3.b.

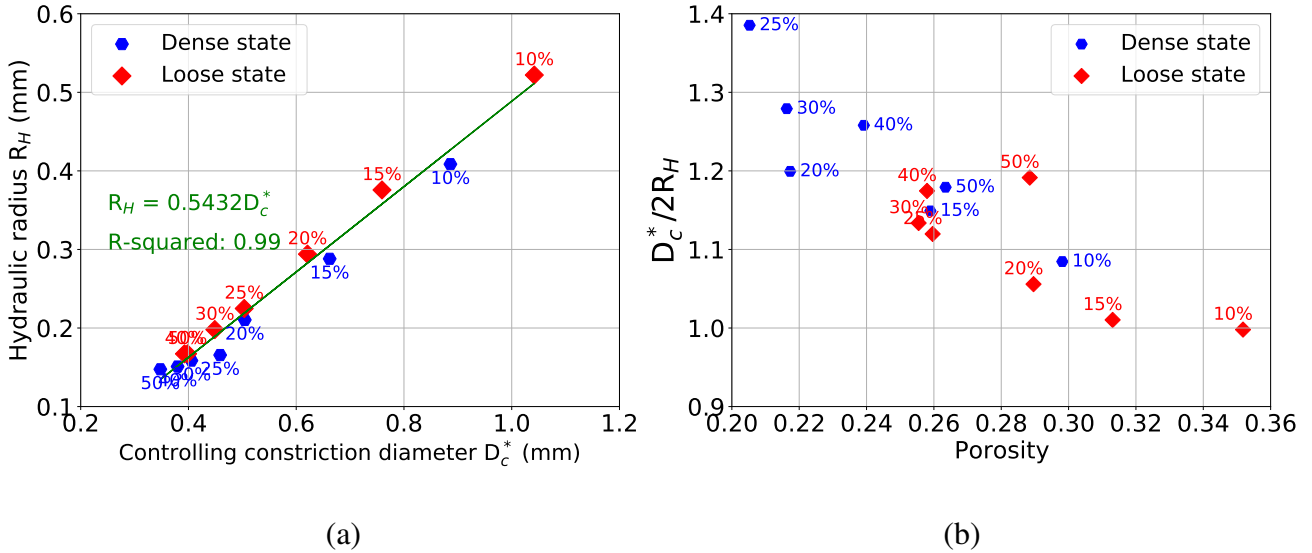


Figure 2. Correlation between hydraulic radius R_H and controlling constriction diameter D_c^* for fourteen gap graded specimens. A linear regression is estimated with a Pearson coefficient $R^2 = 0.99$ (a). A dimensionless $D_c^*/2R_H$ ratio evolution with respect to porosity (b).

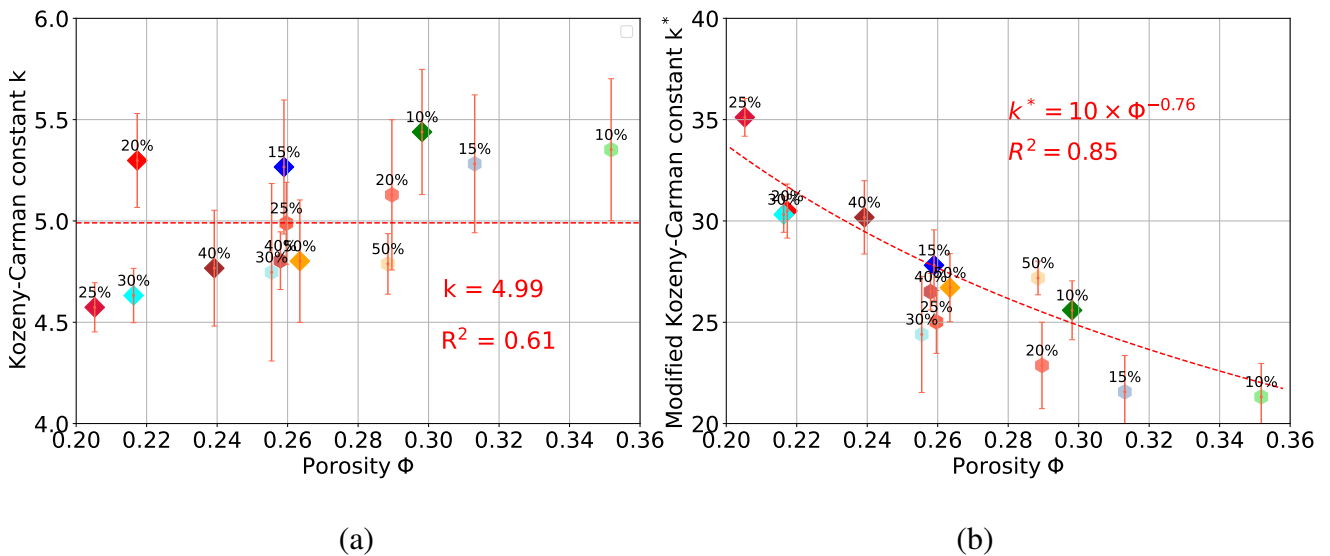


Figure 3. Kozeny-Carman constant k (a) and modified Kozeny-Carman constant k^* (b) for the fourteen dense and loose gap-graded specimens. The vertical error bars represent RVE error on permeability of 95% confidence interval by filtration method.

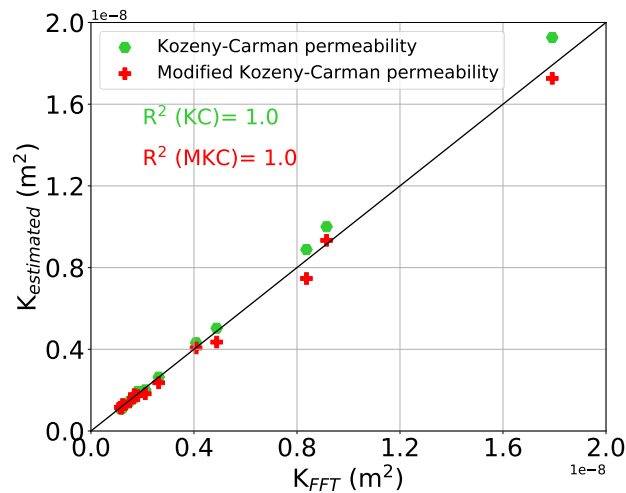


Figure 4. Comparison between numerical computed permeability K_{FFT} and estimated permeabilities using Kozeny-Carman model and modified Kozeny-Carman model.

For the fourteen homogeneous gap graded specimens, both the classic and modified Kozeny-Carman models work fine. This result is demonstrated in Figure 4, where permeabilities are estimated using the two later explained models and compared with respect to extrapolated permeabilities upscaled using fast Fourier transformation method. The modified Kozeny-Carman model shows that an alternative length can be used instead of hydraulic radius. This is an advantage because this study conveniently assumes spherical particles, making hydraulic radius' computation easier, but that is not the case for real soils that possess real particles shape and angularity. Furthermore, recall that in flow modified microstructures R_H will not be the best candidate anymore due to the strong evolution of microstructure by seepage.

4. Conclusions and perspectives

The above results show that the Kozeny-Carman model works quite well for homogeneous samples as well as the modified Kozeny-Carman model. However, for flow-modified specimens, the Kozeny-Carman model will not work anymore since the porosity and the hydraulic radius may remain constant upon seepage, while the permeability may change significantly due to the reorganization of grains induced by flow. For such samples, the modified Kozeny-Carman model becomes of interest as the CSD would allow us to capture the microstructure evolution. Hence, this work will be extended later to non-homogeneous specimens by applying drag forces to fine particles and thus simulating suffusion or flow modified microstructures. Such perspectives will enhance our comprehension of intricate porous media behaviors under dynamic flows.

Acknowledgements

This research was funded, in whole or in part, by l'Agence Nationale de la Recherche (ANR), project ANR-21-CE22-0005-01. For the purpose of open access, the author has applied a CC-BY public copyright licence to any Author Accepted Manuscript (AAM) version arising from this submission.

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