Permeability of structured porous media: numerical simulations and microfluidic models

Key words:

Permeability; Microfluidic model; Porosity; Tortuosity; Anisotropy

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Introduction

- Permeability characterizes the difficulty of flow through porous media, and represents the pore interconnectivity for fluid conductivity (Collins, 1961).
- Microfluidics is a system that processes or manipulates small fluids through microchannels, with sizes ranging from a few micrometers to several hundred micrometers. There is no doubt that using a microfluidic model to study permeability of porous media shows great potential
- Studies of permeability that are relevant to the geotechnical engineering community and are carried out at the microscale level with a micro-fluidic model in porous structures are limited
- The existing theoretical models fail to predict the permeability of the microfluidic model accurately (Serrenho and Miguel, 2009; Gunda et al., 2013; Wagner, et al., 2021).

Materials

- The hydrophilic borosilicate glass micro-channels, consisting of micropillars, were fabri-cated using the deep reactive ion etching (DRIE) microfabrication technique.
- Microchannels with dimensions of 1 cm (width)×2 cm (length)×50 μm (depth) were built into the microfluidic chip
- We investigated square and triangular arrangements of microchannels with micropillar diameters of 500, 1000, and 2000 μm, and porosities of 0.3 and 0.9

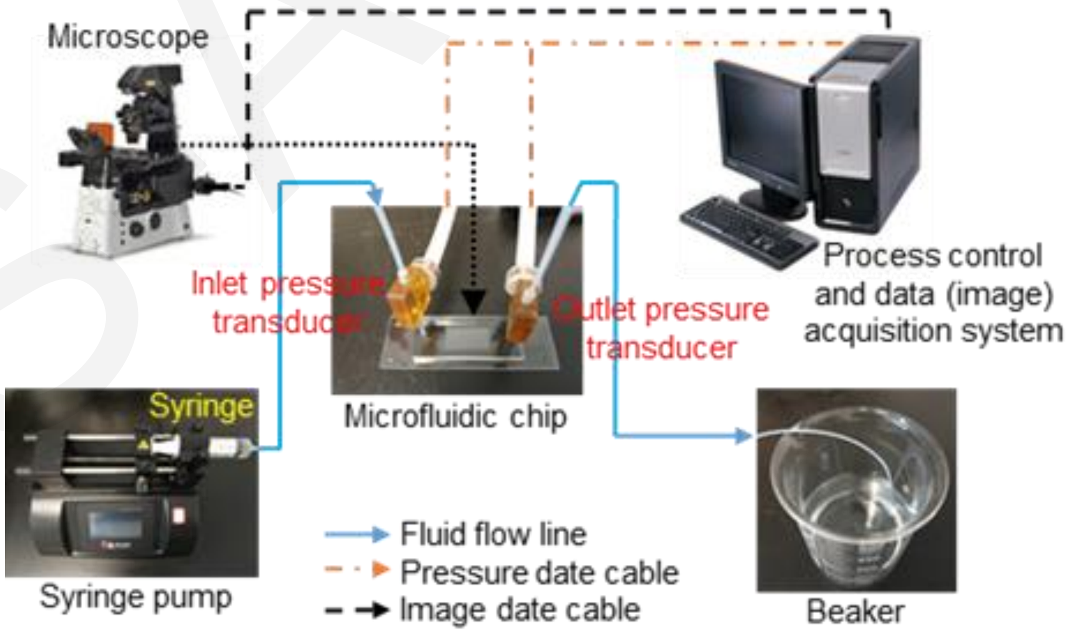

Fig. 3 Schematic of the experimental system used for pressure drop measurement

Effects of porosity on tortuosity

- With the same porosity, models with triangular arrangement always yielded higher tortuosity than those with square arrangement
- We proposed a mathematical model for calculating 2D circular-based soil tortuosity for different particle arrangements:

$$\tau = \frac{1}{\cos\left[(1-\varepsilon)^{\frac{1}{3}}\alpha\right]} + \left(\frac{\pi}{4} - \frac{1}{2}\right)\frac{4(1-\varepsilon)}{\pi}$$

where α is the horizontal angle between two particles, which arranges from 0 to $\arctan(B/(2C))$.

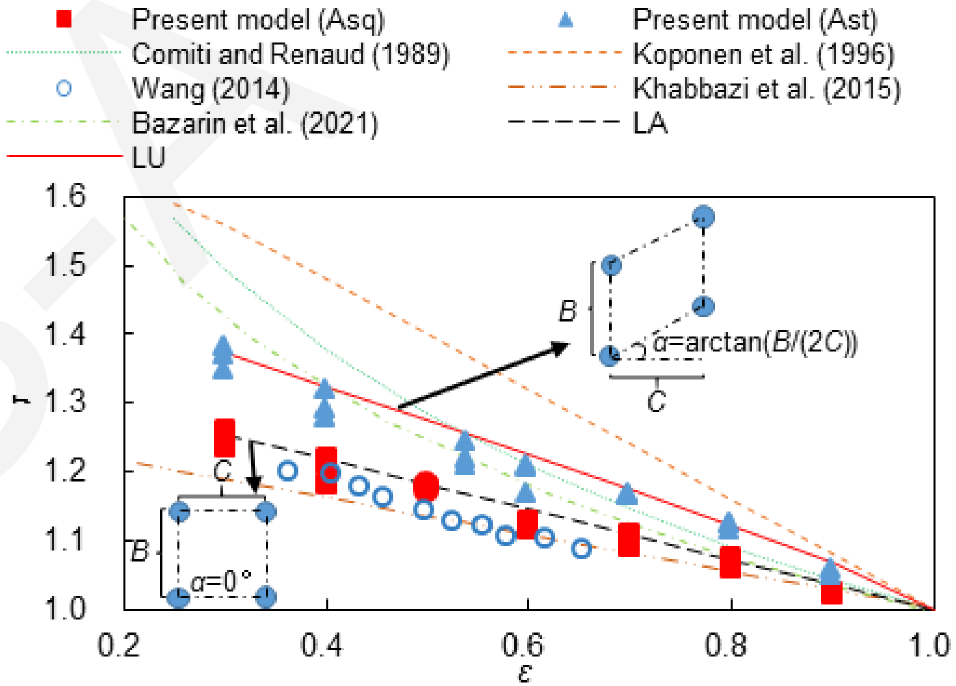

Fig. 7 Comparison of tortuosity between nu-merical simulations and models in the literatureLA represents the line of lower-limit arrangement, and LU represents the line of upper-limit arrangement

Effects of Reynolds number on permeability

- It is observed that the threshold of the Reynolds number is 1. When Re is below the threshold, the permeability is independent of the Reynolds number. When Re is over this threshold, the viscous force plays a dominant role and the permeability decreases with the Reynolds number increment.

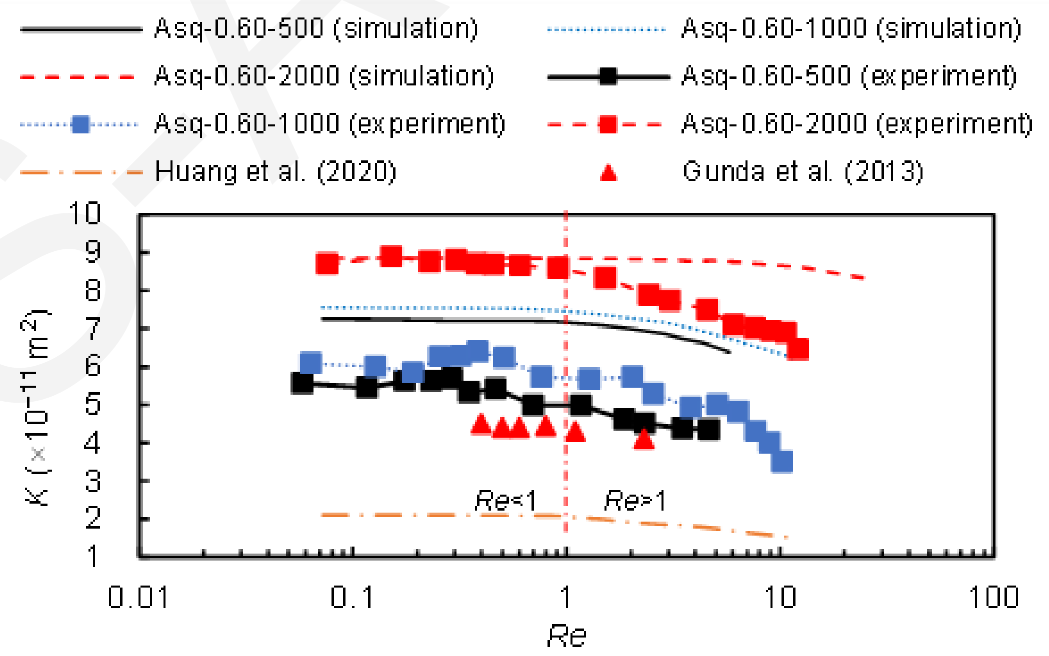

Fig. 8 Effects of Reynolds number on permeability of square-arrangement microfluidic chips with a porosity of 0.60

Effects of anisotropy on permeability

- With the same tilt angle, the tortuosity of the triangular-arrangement model was higher than that of the square-arrangement model
- we proposed an analytical model based on 2D rectangular particles:

$$\tau = 1 + \frac{r^2\cos^2\theta}{\left(\frac{3\varepsilon}{1-\varepsilon}+2\right)(r\cos\theta+\sin\theta)}$$

where r is the aspect ratio

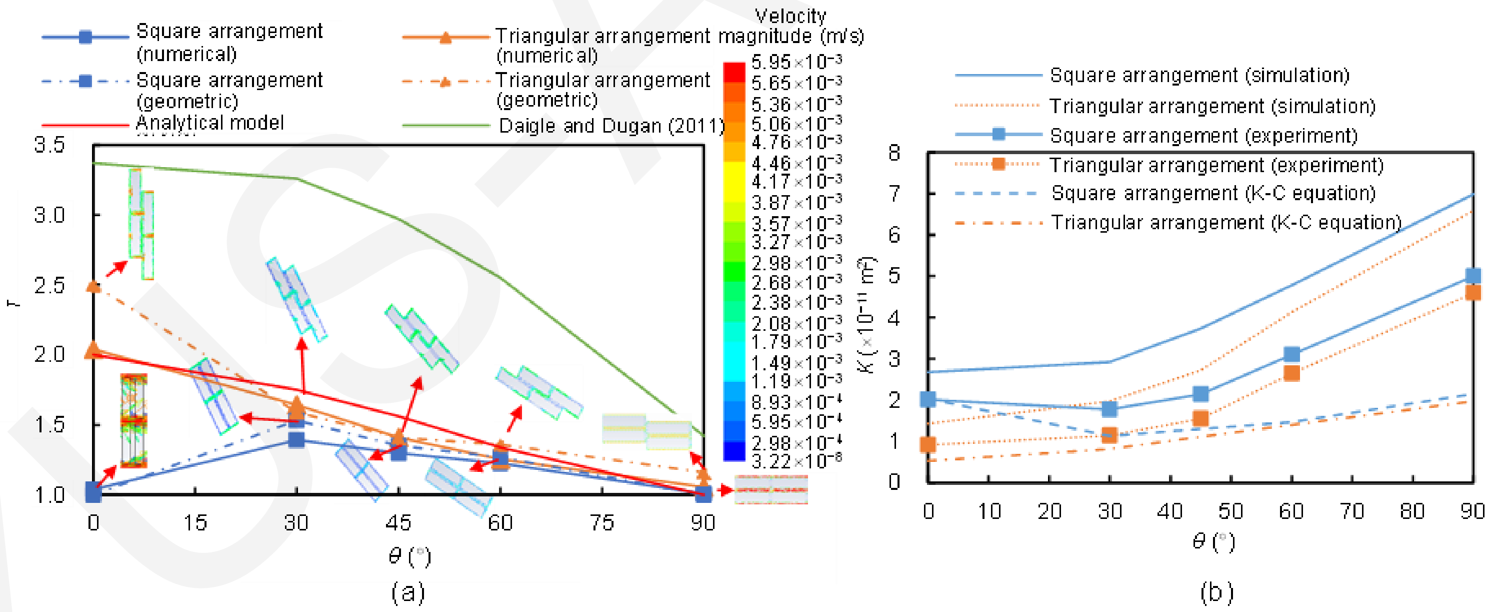

Fig. 11 Effects of tilt angle on tortuosity (a) and permeability (b).

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Effects of tortuosity on permeability

- there was an inverse relationship between permeability and tortuosity
- Compared to tortuosity, permeability is more sensitive to porosity.

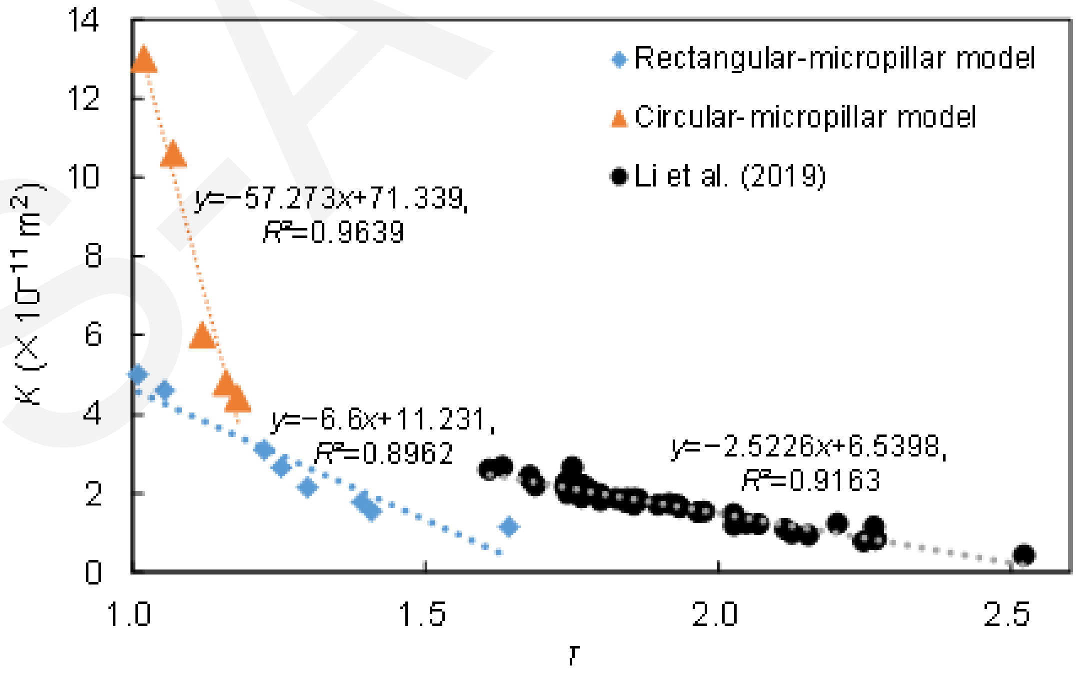

Fig. 12 Variation of permeability with tortuosity

Effects of porosity on permeability

- Permeability generated by numerical simulation was consistent with that obtained from experiments, and the error was 9.78%– 28.43%
- a predicted model for the permeability of a mi-crofluidic model was proposed:

$$K = \frac{1}{c\tau}\varepsilon^2 r_{cr}^2$$

where r_{cr} is the pore radius, and c is a shape parameter.

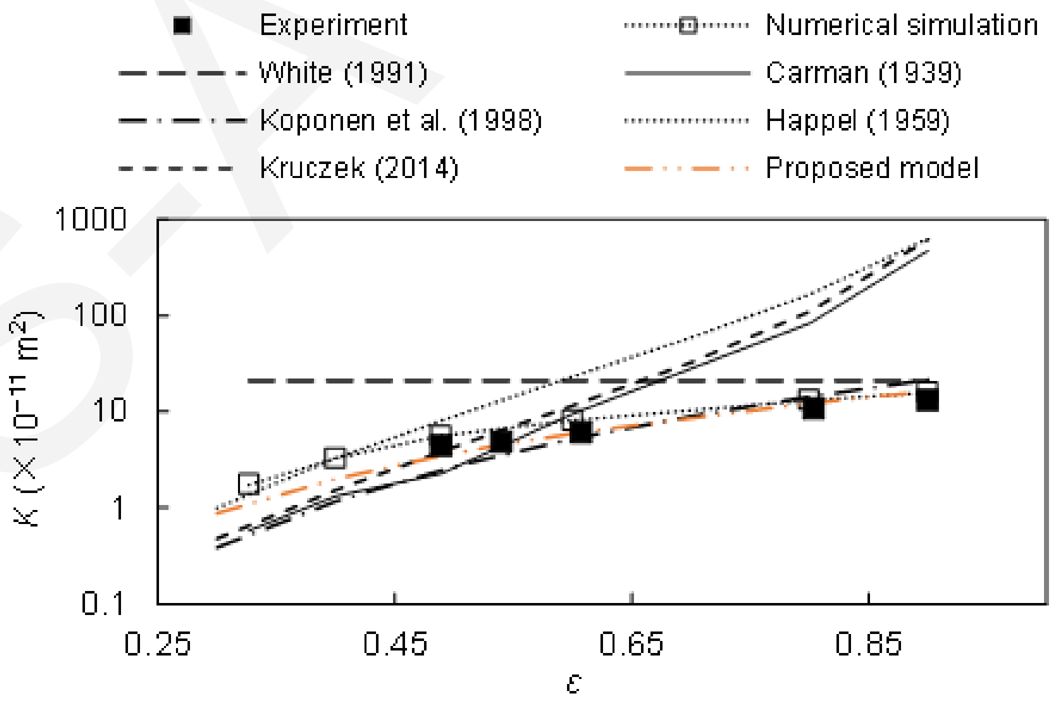

Fig. 13 Comparison of permeabilities obtained from experiment and numerical simulation with those ob-tained from formulas available in the literature for Asq-500

Conclusions

- Anisotropy induced by the tilt angle (0°–90°) of rectangular micropillars formed preferential flow and decreased the effective porosity
- The threshold of the Reynolds number was 1
- The permeability of the microfluidic chip models is influenced by the diameter, arrangement, and shape of the micropillars
- It was proved that the predicted model is suitable for estimating the experimental permeability of microfluidic models