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Can varying velocity conditions be one possible explanation for differences between laboratory and field observations of bacterial transport in porous media?

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ABSTRACT

Laboratory column experimental results are frequently used to estimate field-scale, fecal bacterial transport distances. However, it is not uncommon for fecal bacteria to be observed at greater distances than predicted by up-scaling laboratory results. Fluctuating or varying velocity conditions is one complex in-situ condition that might account for such inaccurate prediction, yet it is often neglected in laboratory column experiments. In this study, one-dimensional, laboratory column experiments were performed under both constant and varying velocity conditions using 2 μm microspheres and 100 μm glass beads to simulate bacterial transport in saturated porous media. Particle breakthrough curves and particle concentrations retained in the column at the end of an experiment were obtained for five constant and three varying velocity conditions. The range of constant velocities investigated was between 3.17 m/day and 27.65 m/day. For varying velocity conditions, the velocity was steadily increased and/or decreased over the period of the experiment within the same range. Results from the constant velocity experiments were successfully modeled using first order, irreversible particle attachment kinetics. The irreversible attachment coefficients obtained from the constant velocity experiments were used to derive a power function relationship between a dimensionless irreversible attachment coefficient, K_i^* and velocity, v. This relationship was then used to model the varying velocity experiments, with limited success (NRMSE > 10% for all model fits). A comparison of K_i^* values obtained from direct fitting of the varying velocity tests, with the K_i^* values derived from the results of the constant velocity experiments, revealed a potential dependence of K_i^* on the rate of change of velocity. Observed particle breakthrough curves (BTCs) for the varying velocity experiments were also modeled using a constant value of K_i^* based on the average velocity of each experiment. The results of this modeling under-estimated observed maximum breakthrough concentrations for the column experiments where velocity increased, and especially under conditions where velocity increased then decreased. Overall, the results of this study point to the need for better understanding of how varying velocity conditions impact bacterial transport in the field.

1. Introduction

Diarrheal diseases cause illness and death globally, killing an estimated 1.8 million people every year [1]. Fecal bacteria, a major source of diarrheal disease [2], are widespread in shallow aquifers and detected even when fate and transport predictions would indicate otherwise [3,4]. Laboratory column tests and field scale investigations are the two main experimental approaches for investigating subsurface bacterial fate and transport and advancing predictive theory.

Bacteria are micron-sized particles, often classified as colloid particles, whose attachment and detachment to the solid phase of a porous medium are controlled by physical, chemical, and biological interactions between a particle and the grains of the medium. Over the past several decades, a large number of laboratory column experiments have been used to investigate the effects of flow velocity magnitude, flow direction, particle size, grain size, grain surface roughness, liquid temperature, liquid pH, liquid ionic strength (IS), and bacterial characteristics on particle column breakthrough concentrations and retained concentration profiles [5]. For example, *Hendry et al.,* [6] investigated *Klebsiella oxytoca* and *Burkholderia cepacia* transport in laboratory columns at four different, constant flow velocities and observed that the peak breakthrough concentrations of bacteria increased as the velocity increased. Through modeling,

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Hendry et al., [6] also demonstrated that particle attachment and detachment behavior are bacteria specific and related to surface chemistry. Based on their results, these researchers recommended that the relationship between velocity and particle behavior be determined before using column results to predict field behavior. *Keller et al.,* [7] conducted laboratory column experiments under constant velocity conditions with bacteriophage MS2 and two different size microspheres to quantify the effect of velocity magnitude and particle size on the early breakthrough of particles. They found that both particle size and velocity magnitude influence early breakthrough behavior, and thus, potentially, rapid transport phenomena in aquifer systems. *Vasiliadou and Chrysikopoulos* [8] conducted laboratory column experiments with *Pseudomonas Putida* bacteria and kaolinite clay particles, both separately and together, in order to examine their co-transport effects on particle behavior. For tests examining the individual transport characteristics of the bacterial and kaolinite, these authors reported a decrease in mass recovery for both particle types with decreasing velocity. More recently, *Shang et al.,* [9] halted flow for different time intervals during laboratory column experiments in order to examine how dynamic groundwater conditions might impact the transport of engineered nano-porous particles in saturated porous media. Although *Shang et al.,* [9] found that nanoparticle detachment was influenced by the duration of the no-flow period, they were able to model observed particle transport using theory developed for constant flow conditions. Nonetheless, despite the fact that dynamic groundwater conditions are the norm in aquifer systems contaminated with fecal bacteria, very few column studies have systematically investigated how varying velocity conditions impact colloid transportation in saturated media.

Complementing column experiments, numerous field scale experiments have also been undertaken to study bacteria transport in shallow aquifers [10–13]. Compared with laboratory testing, field scale experiments occur in a more complex environment and are subject to many uncontrollable factors, including subsurface physical and chemical heterogeneity, as well as often ill-defined three dimensional flow conditions. Previous research reported that up-scaling column experiment results to predict bacterial transport at the field scale always fall short of observed transport distances in the field [14–16]. *Knappett et al.,* [17] speculated that one reason for this at their Bangladeshi experimental field sites, might be the rapidly increasing and decreasing advective transport velocities observed during the monsoon season, which are not accounted for in laboratory experiments conducted at constant flow velocity. *Anders and Chrysikopoulos* [18] conducted field tests with bacterial viruses in order to specifically examine recharge source effects. Their results showed time-dependence of particle collision efficiencies, which they concluded was mainly due to fluctuations of the interstitial fluid velocity.

This study investigated the effects of varying velocity on particle transport in saturated porous media by modifying traditional column test protocols to enable simulation of increasing and decreasing flow velocities during an experiment. Results from varying velocity experiments were compared with results from experiments conducted under constant velocity conditions. In addition, models derived from the constant velocity experiments were used to predict the varying velocity experiments, in order to explore whether relationships derived under constant conditions could predict transport in transient systems.

2. Material and methods

2.1. Particles

Spherical, mono-dispersed, fluorescent, carboxylate-modified, polystyrene latex microspheres were used as the micron sized particles in the experiments (Molecular Probes, Inc., Eugene, OR). The microsphere diameter was 2µm, and the excitation and emission wavelengths of the particles were 365 nm and 415 nm, respectively. The solids concentration of the manufacturer-supplied stock solution was 0.02 g/mL. The experimental solutions were prepared by diluting the stock solution using artificial groundwater (AGW) at the desired ionic strength (IS) and pH value.

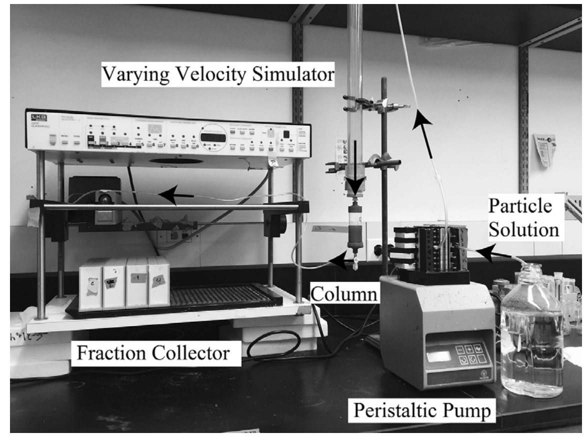

Fig. 1. Set-up of column experiments for varying velocity conditions. The particle solution was introduced into the Varying Velocity Simulator (VVS) via a peristaltic pump. The flow velocity into the top of the column at any one point in time was determined by the height of the particle solution in the VVS, which changed over the course of each experiment. The solution exiting the base of the column was collected in aliquots using a fraction collector. For the constant velocity experiments, the Varying Velocity Simulator was removed and the peristaltic pump introduced the particle solution into the top of the column at a constant, predetermined rate.

2.2. Porous media

Glass beads of 100µm diameter (USA Scientific, Inc., Ocala, FL) were used to simulate sediment in the experiments. The glass beads were washed with deionized water and dried in an oven at 60 °C prior to the preparation of each column experiment.

2.3. Solution chemistry

The AGW was made with KCl at an IS of 100 mM. The solution pH value was adjusted to 6.8 +/– 0.05 by using 0.1M NaOH and 3% HCl solution. Column inlet solutions contained the 2µm diameter microspheres at a concentration of 2.67×10^{-3} mg/L, referred to as C_0. Inlet solutions were stirred throughout each experiment to help ensure a uniform particle inlet concentration.

2.4. Experimental set-up and protocol

In order to simulate both constant and fluctuating velocity conditions, the experimental protocol designed of *Feighery et al.,* [19] was modified (Fig. 1). Eight flex columns (Kimble Chase Life Science and Research Products LLC, Rockwood, TN) of 2.5 cm inner diameter and 8 cm length were used in the experimental series. The columns were equipped with stainless steel screens on both the top and bottom to retain the glass beads. The glass beads were wet-packed into the columns at an average porosity of 0.33. Columns were alphabetically labeled from A to H, with each letter referring to a different velocity condition. Prior to an experiment, each column was attached to a ring stand and each column inlet was leveled to the same elevation. Before particle injection, clean AGW was upwardly injected for 10 pore volumes at the base of each column to saturate the glass beads and flush out impurities.

To simulate different velocity conditions, eight velocity protocols were designed. A multi-channel peristaltic pump (Minipuls 3, Gilson, Inc., Middleton, WI) was used to introduce test solutions directly into