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Experimental investigation of acoustically enhanced colloid transport in water-saturated packed columns

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Abstract

The effects of acoustic wave propagation on the transport of colloids in saturated porous media were investigated by injecting Uranine (conservative tracer) as well as blue and red polystyrene microspheres (colloids of different diameters; 0.10 and 0.028 μm, respectively) into a column packed with glass beads. Experiments were conducted by maintaining the acoustic pressure at the influent at 23.0 kPa with acoustic frequencies ranging from 30 to 150 Hz. The experimental results suggested that colloid size did not affect the forward and reverse attachment rate coefficients. The acoustic pressure caused an increase in the effective interstitial velocity at all frequencies for the conservative tracer and colloids of both sizes, with maximum increase at 30 Hz. Furthermore, acoustics enhanced the dispersion process at all frequencies, with a maximum at 30 Hz.

Keywords: Colloid transport; Acoustic waves; Enhanced transport; Subsurface transport; Polystyrene microspheres

1. Introduction

Groundwater aquifers are often contaminated by an assortment of pollutants that derive from various sources. One common class of groundwater contaminants is dissolved molecular solutes. Examples include pesticides and fertilizers from agricultural runoff, nitrate and nitrite from wastewater release, and radionuclides that can leach into groundwater from deep geological disposal sites. Another common class of groundwater pollutants is colloidal particles such as viruses and bacteria (biocolloids) from domestic or industrial wastewater spills. A third common class of pollutant is dissolved light or dense non-aqueous phase liquids (DNAPLs) such as TCE, PCE, and gasoline by-products from leaking storage tanks, leaking pipelines, or accidental spills [1–4]. In addition, natural colloidal particles (very fine particles that have some linear dimension between 0.001 and 10 μm [5]) are ubiquitous in groundwater aquifers, and may significantly affect the subsurface fate and transport of these contaminants.

Typical colloids present in groundwater include clay minerals, oxides or hydroxides of Fe and Al, colloidal silica, and organic matter such as humic macromolecules [6–10]. The large specific surface areas of these colloids cause relatively weak forces such as van der Waals forces, electric double layer forces, and electrostatic forces to have a profound effect on their transport and deposition. Experimental evidence has shown that colloids can have a faster breakthrough compared to solute tracers in packed columns (e.g., [9,11–14]). This effect is attributed to size exclusion and electrostatic repulsive forces [15]. It is also widely accepted that colloids migrate faster than nonsorbing conservative tracers in natural fractures [16–18]. Enhanced mobility of colloids in porous media depends on the size of the pore spaces and on the nature of the colloid–matrix interactions (surface chemistry). Unfavorable deposition interactions result in enhanced mobility [17].

There is also substantial evidence from both laboratory and field experiments that colloids are efficient sorbents for contaminants such as heavy metals, nonpolar organic compounds, and radionuclides [15,19,20]. Tatalovich et al. [10] showed that applying humic substances to groundwater contaminated with a DNAPL pool enhanced the mass transfer of DNAPL to the

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aqueous phase. Parametric investigations have also shown that liquid-phase contaminant concentration of DNAPL is sensitive to the partition coefficient for contaminant sorption onto suspended colloids [16]. The ability of contaminants to adsorb onto colloids and of colloids to experience enhanced mobility (colloid-associated transport) may contribute to faster contaminant migration and dispersion, which exacerbates the contamination problem.

In many parts of the world, including the United States, groundwater is often pumped and distributed directly into homes for consumption without any processing. Consequently, the prevalence, toxicity, and mobility of contaminants has facilitated interest in groundwater remediation techniques. There are a number of available technologies for treatment of contaminated groundwater that have been utilized with varying degrees of success: filtration through granular activated carbon (GAC), soil removal and/or washing, air stripping, and biological contact or trickle filtration. These remediation technologies rely heavily on pump-and-treat methodologies such that the amount of contaminant mass removed is proportional to the amount of water pumped from the subsurface and to the concentration of dissolved or suspended contaminant in that water. Therefore, groundwater remediation is limited by the aqueous solubility of the particular contaminant. Unfortunately, several of the contaminants present in groundwater have low aqueous solubilities (e.g., DNAPLs [21]), or high affinities for adsorption onto the subsurface formation creating a long persisting source of contamination. Various methods have been explored in recent years to enhance contaminant transport and dissolution to address this issue. Some methods involve introduction of nonindigenous colloids or humic substances, specialized biocolloids, surfactants, or cosolvents. These methods could be problematic as all of the added substances are considered to be either contaminants themselves or undesirable in the drinking water supply.

A desired groundwater remediation approach is a 'clean' technology that will increase contaminant mass transport and dissolution in porous media with conventional pump-and-treat methods, thereby facilitating enhanced remediation without adding further contaminants to the subsurface. An example of such a technology is the introduction of acoustic (sound) waves in saturated porous media to increase contaminant mass transport. Building on the fundamental work of Biot [22,23], the theory of acoustic propagation in porous media has been studied extensively in soil mechanics, seismology, earthquake engineering, geophysics, and petroleum engineering [24]. However, only recently has the concept of using waves for aquifer remediation been given attention and several preliminary studies have been conducted. For example, acoustic waves were found to enhance transport of a conservative tracer in packed column experiments with the effective velocity of the solute being approximately inversely proportional to the frequency of the acoustic wave [25]. Other theoretical and experimental results have shown that significant displacement of solutes in saturated porous media results from the propagation of different types of compression waves (e.g., compaction waves and short and long shock waves), even in the absence of background flow [1]. Experimental evidence also shows that acoustic waves can increase both mobilization and dissolution in multi-phase systems (i.e., NAPL/water) [24,26–28]. Thomas and Narayanan [29] showed that solute mass transfer is enhanced by several orders of magnitude when the fluid medium is subject to oscillatory motion, even if there is no net total flow over a cycle of oscillation. Experimental evidence has shown that effluent aqueous DNAPL concentration increased with the application of acoustic pressure waves with the greatest dissolution enhancement occurring at lower frequencies [26]. Furthermore, ganglia that were immobile under steady background flow were mobilized when acoustic pressure was added [27,28]. Gross et al. [1] have suggested that the unique significance and economic potential of introducing pressure waves into an aquifer is in the ability to focus on cleaning groundwater at localized sites, mobilize trapped contaminants, and guide the motion of a contaminant plume by controlling the intensity and direction of the applied pressure. However, the effects of acoustic waves on colloid transport in saturated porous media have not been investigated, and they are the focus of the present work.

Whether colloids present in groundwater are contaminants themselves, natural colloids that facilitate contaminant transport, or nonindigenous colloids used for remediation, understanding the effects of acoustic wave application on the transport of colloids in saturated porous media is necessary before acoustics can be applied for aquifer remediation.

2. Mathematical model development

The one-dimensional advection–dispersion equation for colloidal particles in homogeneous saturated porous media accounting for adsorption (or filtration) and inactivation under a constant hydraulic gradient is given by the following linear second-order partial differential equation:

$$\frac{\partial C(t,x)}{\partial t} + \frac{\rho}{\theta}\frac{\partial C^*(t,x)}{\partial t} = D_e\frac{\partial^2 C(t,x)}{\partial x^2} - U_e\frac{\partial C(t,x)}{\partial x} - \lambda C(t,x) - \lambda^*\frac{\rho}{\theta}C^*(t,x), \quad (1)$$

where C is the concentration of colloids in suspension [M/L^3], C^* is the mass of colloids adsorbed on the porous medium [M/M], D_e is the effective hydrodynamic dispersion coefficient [L^2/t], U_e is the effective interstitial fluid velocity [L/t], ρ is the bulk density of the porous medium [M/L^3], λ is the inactivation constant of suspended colloids [t^{-1}], λ^* is the inactivation constant of adsorbed colloids [t^{-1}], θ is the porosity of the porous medium [–], and t is time [t]. Inactivation was included in the governing transport equation so that the solution can be applied to biocolloids and radiocolloids, though they were not studied in the present work. The effective interstitial fluid velocity is defined as [25]

$$U_e = U + U^*, \quad (2)$$

where U is the steady-state background interstitial fluid velocity [L/t], and U^* is the additional velocity component attributed to acoustic pressure [L/t]. Similarly, the effective dispersion coefficient is defined as

$$D_e = D + D^* = (U + U^*)\alpha_L + \mathcal{D}_e = U_e\alpha_L + \mathcal{D}_e, \quad (3)$$