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The impact of methanogenesis on flow and transport in coarse sand

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ABSTRACT

The effects of biofilm growth and methane gas generation on water flow in porous media were investigated in an anaerobic two-dimensional sand-filled cell. Inoculation of the lower portion of the cell with a methanogenic culture and addition of methanol to the bottom of the cell led to biomass growth and formation of a gas phase. Biomass distributions in the water and on the sand in the cell were measured by protein analysis. The biofilm distribution on sand was observed by confocal laser scanning microscopy. The formation, migration, distribution and saturation of gases in the cell were visualized by the charge-coupled device (CCD) camera. The effects of biofilm and gas generation on water flow were separated by performing one tracer test in the presence of both biofilm and a gas phase and a second tracer test after removal of the gas phase through water flushing. The results of tracer tests demonstrated that flow and transport in the two-dimensional cell were significantly affected by both gas generation and biofilm growth. Gas generated at the bottom of the cell in the biologically active zone moved upwards in discrete fingers, so that gas phase saturations (gas-filled fraction of void space) in the biologically active zone at the bottom of the cell did not exceed 40–50%, while gas accumulation at the top of the cell produced gas phase saturations as high as 80%. The greatest reductions in water phase permeability, based on measurements of reductions in water phase saturations, occurred near the top of the box as a result of the gas accumulation. In contrast the greatest reductions in permeability due to biofilm growth, based on measurements of biofilm thickness, occurred in the most biologically active zone at the bottom of the cell, where gas phase saturations were approximately 40–50%, but permeability reductions due to biofilm growth were estimated to be 80–95%.

1. Introduction

Stimulation of anaerobic biological activity through addition of electron donors and bioaugmentation of the subsurface with anaerobic cultures with demonstrated reductive dehalogenating capability is becoming widely accepted for remediation of groundwater contamination by chlorinated solvents (Major et al., 2002). One of the major challenges in field implementation of anaerobic bioremediation of chlorinated solvents is delivery of electron donor to the treatment zone. The addition of electron donors can lead to significant biomass growth and potentially significant gas generation (Sleep et al., 2006). The resulting occlusion of pore spaces due to bioclogging and gas generation can lead to significant reductions in hydraulic conductivity (Baveye et al., 1998), making it difficult to continue to deliver electron donor to the treatment zone.

There have been many studies of the impact of biomass growth under aerobic conditions on the hydraulic conductivity of soils (Taylor and Jaffe, 1990; Taylor et al., 1990; Wu et al., 1997; Yarwood et al., 2006), but very few have investigated biomass growth impacts on flow and transport under anaerobic conditions relevant to in situ bioremediation of chlorinated solvents. There have been several investigations of anaerobic biogenic effects on hydraulic conductivity

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reductions in peat soils (Reynolds et al., 1992; Beckwith and Baird, 2001; Kellner et al., 2005). These studies indicated that methane gas generation had a significant impact on peat hydraulic conductivity. DeLozada et al. (1994) reached similar conclusions from column studies of methane generation in sand columns inoculated with *Methanosarcina Barkeri* 227 and fed methanol. While Reynolds et al. (1992) and Beckwith and Baird (2001) did not determine the potential effect of biomass growth on soil properties, DeLozada et al. (1994) conducted biomass assays to show that biomass growth was limited and therefore did not likely have a major impact on hydraulic conductivity relative to gas pore blockage effects. In contrast, Seki et al. (1998) studied glucose degradation in Andisols and concluded that reductions in hydraulic conductivity were due to a combination of bioclogging and gas pore blockage.

Most of the studies of the impact of anaerobic biological activity on soil properties were done with small one-dimensional columns (DeLozada et al., 1994; Seki et al., 1998). The results of these experiments presented only the bulk changes in hydraulic conductivity of the porous media, but not the spatial changes in hydraulic conductivity of the porous media. Istok et al. (2007) investigated nitrogen gas produced during denitrification in a two-dimensional cell. In their experiments the effect of gas production on hydraulic conductivity was relatively minor, because most gas produced in the system migrated to the top of their cell and flowed out of the cell resulting in low gas phase saturations (fraction of void space occupied by gas phase) throughout the experiments. Although this may occur in the field, in many cases, capillary barriers will restrict the buoyancy driven upward movement of biogenic gases. This could lead to larger gas phase saturations and significant reductions in hydraulic conductivity.

The objective of this study was to quantify the effects of biofilm and gas bubble on flow and transport in an anaerobic two-dimensional confined aquifer system. The system was inoculated with a known methanogenic dechlorinating microbial consortium and fed methanol to stimulate methanogenesis. The impacts of microbial growth and gas generation on gas phase saturations, biomass levels, hydraulic conductivities, and tracer transport patterns were monitored to determine the extent to which biomass growth and gas generation could impede the delivery of electron donors to treatment zones during anaerobic bioremediation of chlorinated solvent contamination of groundwater.

2. Materials and methods

2.1. Construction of two-dimensional sandbox system

A glass and aluminum cell (55 cm wide × 45 cm high × 1.28 cm thick) was constructed for this study (Fig. 1). A rectangular 1.28 cm thick aluminum frame (interior frame) with interior length of 55 cm and interior height of 45 cm was constructed to serve as a spacer between the two glass sides of the cell. One glass side was a 19.1 mm thick glass plate and the other glass side was a 15.9 mm thick tempered glass plate. The glass plates were placed on either side of the interior frame and then two additional aluminum frames were placed on the exterior side of each of the glass plates and connected to each other using 15.9 mm bolts. Viton strips were placed between the glass and aluminum frames (strips measured approximately 2 cm wide × 1.6 mm thick × length of aluminum frame). In addition to the Viton strips the sandbox was sealed with GE Silicone I caulking (Mississauga, ON). The sandbox was designed with an adjustable sealed lid to enable confined aquifer experiments. The sandbox was fitted with inlet and outlet wells. These inlet and outlet wells were screened with stainless steel mesh (mesh size 100) and each well had a volume of 2.8 cm^3. Eighteen ports, spaced as shown in Fig. 1, were built around the sand box. Three of the ports served as inlets, three of them served as outlets and others served as sampling ports. The top eight sampling ports were fitted with Whitey valves attached to 3 mm O.D. stainless steel tubes, which reached different depths in the cell (Fig. 1). The steel tubes were open at the end attached to the valves and closed at the bottom end in the cell but had 3 rows of 4 holes equally spaced around the tube and spaced vertically 5 mm apart, starting 5 mm above the closed end. The sampling tubes were inserted into the cell after packing

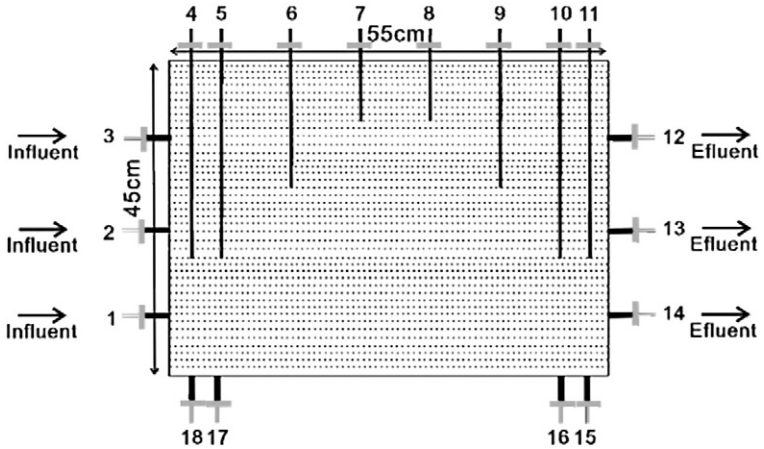

Fig. 1. Configuration of the cell.