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Hydraulic performance of a permeable reactive barrier at Casey Station, Antarctica

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HIGHLIGHTS

- A permeable reactive barrier to intercept and degrade fuel installed in Antarctica.
- Permeable reactive barrier permeability assessed through use of tracer tests.
- Particle disintegration and fine wash through promoted barrier freezing.

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ABSTRACT

A permeable bio-reactive barrier (PRB) was installed at Casey Station, Antarctica in 2005/06 to intercept, capture and degrade petroleum hydrocarbons from a decade old fuel spill. A funnel and gate configuration was selected and implemented. The reactive gate was split into five separate cells to enable the testing of five different treatment combinations. Although different treatment materials were used in each cell, each treatment combination contained the following reactive zones: a zone for the controlled release of nutrients to enhance degradation, a zone for hydrocarbon capture and enhanced degradation, and a zone to capture excess nutrients. The materials selected for each of these zones had other requirements, these included; not having any adverse impact on the environment, being permeable enough to capture the entire catchment flow, and having sufficient residence time to fully capture migrating hydrocarbons.

Over a five year period the performance of the PRB was extensively monitored and evaluated for nutrient concentration, fuel retention and permeability. At the end of the five year test period the material located within the reactive gate was excavated, total petroleum hydrocarbon concentrations present on the material determined and particle size analysis conducted. This work found that although maintaining media reactivity is obviously important, the most critical aspect of PRB performance is preserving the permeability of the barrier itself, in this case by maintaining appropriate particle size distribution. This is particularly important when PRBs are installed in regions that are subject to freeze thaw processes that may result in particle disintegration over time.

1. Introduction

Fuel spills and past poor waste management practices have resulted in numerous contaminated sites in polar-regions. While a wide range of technologies exist for remediation of sites located in temperate regions, translation of these to cold climates has proved challenging. Very few remediation systems have been constructed, and are generally limited to land-farming processes (Paudyn et al., 2008; Sanscartier et al., 2009a,b), traditional "dig and haul" techniques (Northcott et al., 2003) and permeable reactive barriers (PRBs) (Lai et al., 2006; Kalinovich et al., 2008, 2012).

Numerous field investigations have shown that for a PRB to remain effective not only is it essential that the materials remain reactive, but also critical is the maintenance of appropriate hydraulic conductivities throughout the system over the entire remediation timeframe (Moraci and Calabro, 2010; Liu et al., 2011). Of particular importance is ensuring; all flow is intercepted, that is flow is funneled towards the reactive gate and no short circuiting of the gate occurs. This must hold even as precipitates are formed (Parbs et al., 2007), gas is evolved (Henderson and Demond, 2011), hydrocarbons captured (Mumford et al., 2013) or biofilms grown (Seki et al., 2006).

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A number of approaches can be used to evaluate the hydraulic performance of PRB installations including hydraulic gradient measurements combined with hydraulic conductivity data (Gavaskar et al., 2002), in situ flow measurements (Gavaskar et al., 2002), tracer tests and geochemical changes measured up- and down-gradient of the PRB coupled with mass balance calculations (Wilkin et al., 2003). However, on occasion these methods vary in their conclusions or have limits on their accuracy. For instance, generally in the field it is difficult to measure water level differences across the relatively short width of a PRB, which is further complicated by the gradients in highly permeable PRB media being low (Gavaskar et al., 2002; Wilkin et al., 2014). Therefore, tracer tests are most often used to evaluate the hydraulic characteristics of PRB systems, especially when the reactive material does not contain zero valent iron (ZVI).

Schipper used a bromide tracer to show diversion of flow beneath a nitrate reducing PRB as the bulk hydraulic conductivity of the PRB was more than a factor of 100 times less than the surrounding material (Schipper et al., 2004). Wanner conducted Cr isotope measurements and multi-tracer experiments to confirm that most of a Cr(VI) load was bypassing a sequence of PRBs due to a limited PRB permeability, resulting in a treatment efficiency of only 0–23% (Wanner et al., 2013).

Tracer tests are also useful to capture changes in hydraulic performance that may be a result of mineral precipitation or biofilm formation over the entire remediation timescale. Johnson found through use of a bromine tracer that a portion of water contaminated with explosives was increasingly being diverted beneath the ZVI reactive gate. This was attributed to secondary mineral precipitation reducing the permeability of the gate and promoting flow by-pass. Importantly the PRB was not keyed into an underlying aquitard in this instance (Johnson et al., 2008).

Another important component of PRB design is to ensure that the residence time within the barrier is sufficient for the required reactive processes so contaminant breakthrough does not occur (Passeport et al., 2013). Gibert used a combination of organic substrate and ZVI for in-situ remediation of an acid mine drainage site using PRBs. They found the residence time within one of their test cells was too short to enable complete sulphate reduction. It was concluded that the reason for this was clogging and heterogeneities in the reactive material creating preferential flowpaths through the system (Gibert et al., 2013). Mushovic developed a PRB that successfully reduced high concentrations of radioactive and other target metal contaminants to non-detectable levels during the first four years of operation. However, precipitation resulted in a reduction of hydraulic conductivity of 3 orders of magnitude and reduced system performance after this time (Mushovic et al., 2006).

This paper follows an original journal article presenting the installation of a test barrier at Casey Station Antarctica that was installed to prevent further migration of a decade old fuel spill during summer melt periods by intercepting, capturing and degrading hydrocarbon contaminant down-gradient of the spill (Mumford et al., 2013). This PRB was a funnel and gate design with the gate comprising five test cells, each containing different reactive material combinations. A diagram of the funnel and gate barrier, based on dGPS co-ordinates, is presented in Fig. 1. In this diagram the barrier wings (used to funnel to the contaminated water to the reactive gate), the five test cells of the reactive gate, the fuel spill origin and piezometers located around the site are shown. Importantly, the ratio of wing to gate length is relatively high in this system. This is due to the relatively low solubility of the Bergen distillate and Aviation Turbine Kerosene (ATK) contaminant mixture at this site ($\sim$7 ppm) allowing for a lower amount of reactive material per unit flux. Further information regarding the site history can be found in our previous publication (Mumford et al., 2013).

As described, the reactive gate comprised five test cells, each comprising different treatment combinations. A schematic of the reactive gate is presented in Figs. 2 and 3. As shown, the reactive gate was 5.55 m long (1.11 m for each of the five treatment cells), 0.76 m deep and had a width of 1.8 m. Eight multi-ports (labelled from MP1 to MP40) were placed at even and set intervals within each cell to draw water samples, temperature sensor strings were located on MP4, 10, 17, 19, 21, 23, 26 and 36 as well as underneath at 0.9, 1.0 and 1.2 m below ground surface (b.g.s). To ensure that the reactive gate thawed before the surrounding area, heat trace (Deviflex DTIE-10) was woven on the underside of a square support mesh (50 mm) and placed, as three independently controlled layers, at 0.2, 0.4 and 0.6 m b.g.s. To prevent the permafrost beneath the treatment zone from thawing, as well as preventing flow bypass, 0.1 m and 0.24 m of insulation was placed at both ends and underneath the reactive gate respectively. A concrete layer, 0.20 m, was also placed underneath the insulation to ensure the gate was level and bedded into the permafrost. Temperatures within and below the insulation were monitored constantly via the temperature sensors located at 0.9, 1 and 1.2 m b.g.s.

Each of the five cells were split into three zones, each zone was designed to carry out specific tasks; (1) deliver nutrients into solution to bio-stimulate indigenous micro-organisms (zone 1); (2) prevent the further migration of petroleum hydrocarbons (zone 2); (3) provide a suitable substrate for micro-organism growth (zones 1 and 2); and, (4) capture excess nutrients (zone 3). From these requirements a number of materials were selected and utilized in the PRB reactive gate as shown in Fig. 3.

The objective of the first zone was to deliver nutrients in a controlled fashion. To achieve this, three fertilizers were selected: Maxbac, Zeopro and ammonium loaded zeolite. Maxbac is a commercially available slow release fertilizer based on the slow dissolution of soluble nutrients encapsulated in a vegetable oil coating. Zeopro is a commercially available ammonium and potassium loaded zeolite that is coated with a synthetic calcium phosphate. In this system, the calcium phosphate dissolves releasing calcium and phosphorous; the calcium then exchanges with the ammonium and potassium located in the pores of the zeolite. The ammonium loaded zeolite was manufactured by the authors so that only ammonium was in the pores of the zeolite. The second zone was for hydrocarbon capture and enhanced degradation. For this, granulated activated carbon (GAC) in combination with zeolite or Zeopro was used. GAC has been shown effective in the treatment of contaminated ground water and is widely used (Hornig et al., 2008). The third zone was designed to capture excess nutrient cations and for this purpose sodium loaded zeolite was installed. The grain size selected for each material was relatively uniform and large enough (0.4–3.5 mm) to keep the water holding capacity to a minimum at the end of the melt period, thereby maximizing permeability at the onset of the next season's melt. Further information regarding the materials used can be found in our previous publication (Mumford et al., 2013).

The objectives of this work were to demonstrate the use of tracers at a contaminated Antarctic site to determine the ongoing hydraulic characteristics of the site and treatment system and potential impacts on treatment efficiencies. In this case a series of conservative, aqueous tracers were used. Due to the proximity of the field site to the ocean, abundance and largely benign properties (in certain concentrations), sodium chloride (salt) was selected as the most appropriate conservative tracer. In total three conservative tracer tests were conducted and salt progression monitored by electrical conductivity (EC) measurements. The results of the tracer tests were used to determine the proportion of flow captured, distribution of flow between cells, freezing of cells and flow interruption. Some of these characteristics were confirmed by temperature measurements and particle size analysis. The overall