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Analytical solutions for flow fields near continuous wall reactive barriers

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ABSTRACT

Permeable reactive barriers (PRBs) are widely applied for in-situ remediation of contaminant plumes transported by groundwater. Besides the goal of a sufficient contaminant remediation inside the reactive cell (residence time) the width of plume intercepted by a PRB is of critical concern. A 2-dimensional analytical approach is applied to determine the flow fields towards rectangular PRBs of the continuous wall (CW) configuration with and without impermeable side walls (but yet no funnel). The approach is based on the conformal mapping technique and assumes a homogeneous aquifer with a uniform ambient flow field. The hydraulic conductivity of the reactive material is furthermore assumed to exceed the conductivity of the aquifer by at least one order of magnitude as to neglect the hydraulic gradient across the reactor. The flow fields are analyzed regarding the widths and shapes of the respective capture zones as functions of the dimensions (aspect ratio) of the reactive cell and the ambient groundwater flow direction. Presented are an improved characterization of the advantages of impermeable side walls, a convenient approach to improved hydraulic design (including basic cost-optimization) and new concepts for monitoring CW PRBs. Water level data from a CW PRB at the Seneca Army Depot site, NY, are used for field demonstration.

1. Introduction

The presence and transport of contaminant plumes in the groundwater is a more than widely recognized threat to the human health and environment. Permeable reactive barriers (PRBs) represent a passive and in-situ alternative to pump-and-treat systems that require a continuous energy supply and commonly include extraction of contaminated groundwater to the surface for treatment (Cunningham and Reinhard, 2002). The working principle of PRBs is based on the installation of a reactive medium in the flow path of a contaminant plume, which is thus forced under a natural groundwater gradient to migrate through the reactive medium in the subsurface. Physical, chemical and/or biological processes between the reactive medium and the contaminants lead to the desired degradation and/or deposition of the contaminants as they cross the reactive cell, thus performing the actual remediation process before the groundwater reenters the natural aquifer (Environmental Protection Agency, 2003). For a given reactor cell, the treated portion of the groundwater flow can be increased by deploying impermeable cutoff walls extending from the reactor sides into the aquifer, which is referred to as the funnel-and-gate (F&G) system (Starr and Cherry, 1994). Alternatively, draining trenches can be used in the drain-and-gate (D&G) configuration (Bundesministerium für Bildung und Forschung, 2006), which act as collectors of contaminated groundwater up-gradient of the reactor and as distributors of clean water on the down-gradient side. Relatively high installation costs and a limited predictability of the long-term performance are identified as two of the major drawbacks of PRBs (Cunningham and Reinhard, 2002).

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A fundamental issue for the design and operation of a PRB is the hydraulics of the groundwater flow, since it provides the answers to the following two questions: (1) what portion of the groundwater flow is actually captured by the PRB and does it contain the contaminant plume? (2) What is the residence time of a contaminant inside the reactive cell and is it sufficient for the desired degree of remediation? The goal of the present study is to provide an improved understanding of the flow field towards so-called continuous wall (CW) PRBs with no funnel or drainage systems. Two cases are distinguished according to Fig. 1: (1) a "simple" CW PRB with permeable side walls; (2) a CW PRB with impermeable side walls (e.g., sheet piles to eliminate flow entering and leaving the reactor through the sides), but yet no funnel. Previous work on the hydraulics of CW but mainly F&G PRBs were initiated through numerical flow field simulations in combination with particle tracking algorithms in homogeneous 2-dimensional aquifers (e.g., Starr and Cherry, 1994; Teutsch et al., 1997; Gavaskar et al., 1998; Sedivy et al., 1999; Hudak 2004). Besides available extensions of these approaches to heterogeneous aquifers (e.g., Gupta and Fox, 1999, Bilbrey and Shafer, 2001) and 3-dimensional flow (e.g., Smyth et al., 1997; Gupta and Fox, 1999; Painter, 2004), Cirpka et al. (2004) present a probabilistic approach (on numerical bases in two dimensions) to quantify uncertainty in plume caption as a function of aquifer heterogeneity and PRB geometry. In contrast, efforts for analytical solutions of PRB hydraulics are by far not as abundant and include approximate approaches in one (Christensen and Hatfield, 1996) and two dimensions (Rabideau et al., 2005; Craig et al., 2006). The latter use the analytic element method (AEM) with elliptic approximations to PRB shapes or high order analytic line element approximations for exact PRB shapes, both limited to the simple CW type. It follows, and is also observed by Craig et al. (2006), that analytic expressions for rectangular PRBs of any type are not currently available. These analytic expressions are expected to grant insight into PRB hydraulic behavior, which is superior to analytical approximations and typically not available from numerical studies. Respective solutions may become an essential part of tools for (preliminary) PRB design and monitoring optimization.

The present work presents solutions of aquifer flow fields for the boundary conditions of the PRB configurations in question by using (1) the method of conformal mapping and (2) the superposition principle of solutions. According to the theory of potential flow, the distribution of the complex hydraulic potential Ω [L^3/T] is governed by Laplace's equation

$$\frac{\delta^2\Omega}{\delta x^2}+\frac{\delta^2\Omega}{\delta y^2}=0 \tag{1}$$

where

$$\Omega=\Phi+i\Psi \tag{2}$$

The real part Φ [L^3/T] of Ω is known as the hydraulic potential and the imaginary part Ψ [L^3/T] represents the stream function; both Φ and Ψ satisfy Laplace's equation. The obtained solutions for flow fields are analyzed regarding the widths and shapes of the capture zones under the following scenarios: (1) different dimensions (aspect ratio) of the reactive cell; (2) presence or not of impermeable side walls; (3) deviation of the actual ambient groundwater flow direction from the PRB design direction. Furthermore, results are represented graphically in a form to allow for convenient CW PRB (preliminary) design and cost-optimization given plume and aquifer parameters, such as plume width, ambient groundwater flux and required minimum contaminant residence time inside the reactor. Finally, a new concept is proposed that takes advantage of the inferred relationships for monitoring the magnitude and direction of the ambient groundwater flow field and the hydraulic performance of a PRB in an efficient manner. Water level data from the simple CW PRB at the Seneca Army Depot site, NY, are used for a field demonstration of the developed concepts.

2. Solutions of the flow fields

In a non-rigorous way, conformal mapping is a technique based on the theory of functions of complex variables, which allows a given solution of Eq. (1) (i.e., a known flow field in terms of the complex potential) for a prescribed set and geometry of boundary conditions to be transformed (mapped) into the respective solution for the same set of boundary conditions on a different geometry (e.g., Betz, 1964; Bear, 1972; Strack, 1989). More intuitively, it may be compared to the geometric distortion of a flow domain and the flow field it contains such that the orthogonality of potential and stream lines as dictated by Laplace's equation is maintained throughout the distorted flow domain. The method is limited to two dimensions and the use of analytic functions for flow field transformations. In order to be able to account for an arbitrary ambient groundwater flow direction conformal mapping is used for the design flow direction indicated in Fig. 1 (hereafter referred to as "across" the PRB) as well as the flow direction perpendicular to it (hereafter referred to as "along" the PRB). The resulting flow fields are then weighted according to their contributions to the ambient groundwater flow of a certain direction and superposed. Moreover, the nomenclature adopted uses the term "length" of a reactive cell for its typically larger extent perpendicular to the direction of groundwater flow (i.e., "along" the PRB and being parallel to the "width" of a plume), and the term "width" of a reactive cell refers to the typically smaller extent in the direction parallel to groundwater flow (i.e., "across" the PRB). The inherent assumptions in the present approach are that (1) the aquifer can be regarded as homogeneous subject to uniform ambient groundwater flow in a theoretically infinite flow domain, (2) the flow problem can be

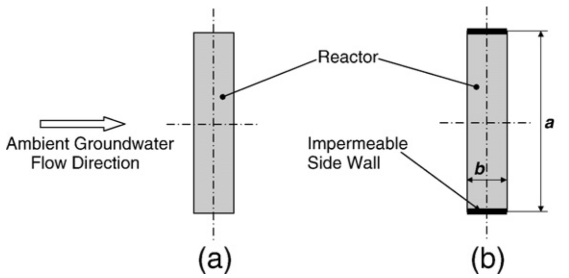

Fig. 1. Horizontal cross sections of CW PRBs. (a) "simple" configuration without impermeable side walls; (b) configuration with impermeable side walls.