GROUNDWATER MODELING OF A PERMEABLE REACTIVE BARRIER TO ENHANCE SYSTEM PERFORMANCE

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ABSTRACT

Experience has shown that one of the most common reasons permeable reactive barriers (PRBs) fail to meet performance criteria is inadequate understanding of the groundwater flow system. For example, contaminated water may flow around the ends of the barrier or funnelling slurry walls, under the barrier walls, or through the slurry walls. An analysis of the groundwater flow regime resulting from the installation of a PRB can lead to an effective design that significantly reduces the escape of untreated water through associated slurry walls and/or around the ends of the PRB system. A three-dimensional groundwater flow model using Modflow was developed to evaluate the effectiveness of groundwater capture and treatment resulting from the installation of a funnel-and-gate PRB. The results of the model analysis provided for a design that incorporated several barrier and gate segments at varying orientations to groundwater flow for optimization groundwater capture. The model indicated the ideal location for gates to minimize head increases along the upgradient portion of the slurry wall, which resulted (as compared to a more simplistic design) in reduced seepage of untreated groundwater through the wall and reduced flow around the end points of the barrier by an estimated 100 per cent. The length of the gates were also optimized to provide sufficient resident time of groundwater in the PRB to accomplish treatment. The model results were also used to locate optimum sites for downgradient monitor wells to assess performance of the system.

Key words: *barrier, reactive, modeling, PRB*

INTRODUCTION

Many permeable reactive barriers (PRBs) fail to meet performance standards because of an inadequate understanding of the groundwater flow system that will exist after the PRB is installed. Deficient designs may lead to groundwater flowing around and through the containing slurry wall, over-topping of the barrier or gate, or a groundwater residency time in the reactive gate which is too short for complete treatment. McMahon (1999), for example, indicates that the results of a post-construction evaluation of a PRB installed at the Federal Center in Denver, Colo., revealed that the hydraulic impacts from the installation of the PRB were substantial and resulted in some of the contaminated groundwater bypassing the system.

Numeric modeling of various PRB design scenarios and evaluation of the resulting groundwater flow systems can aid in determining the appropriateness of the PRB for specific site conditions and finalization of the preconstruction design. Understanding the groundwater travel paths and flow volumes, through modeling, can provide for an optimum design that can meet performance criteria and provide for a margin of safety while preventing costly over-design of gates that are too long, thick, or high, or not placed in optimum locations. Additionally, an understanding of the resulting PRB flow system is necessary for locating monitoring points to assess performance criteria after the system becomes operational.

A PRB system was one remedial option being considered for containment and treatment of a groundwater chlorinated-solvent plume at a former manufacturing site. Off-site property ownership, adjacent to the site, is residential,

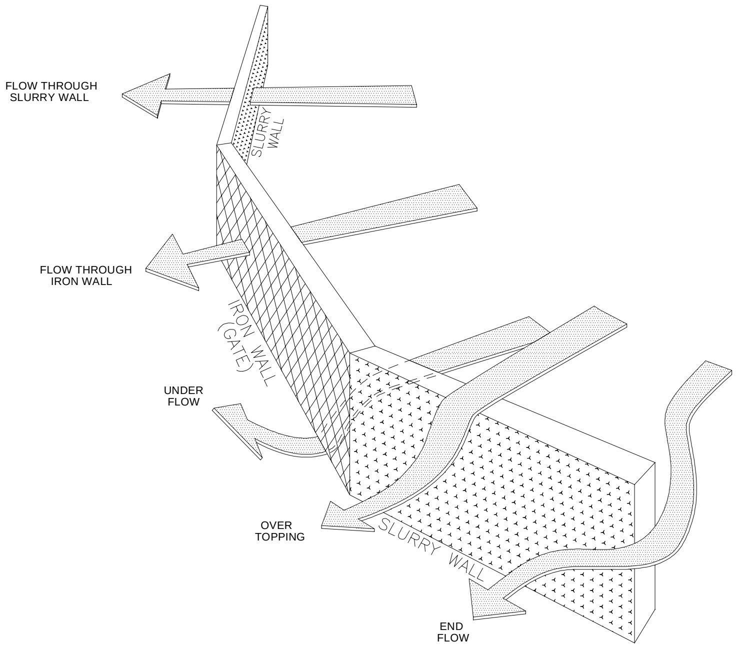

Figure 1. Reactive barrier modeled flow paths.

which necessitated that the PRB be constructed entirely on site; however, because of the size of the plume, a simple linear PRB design with one gate could not be constructed entirely on the property and still provide for complete capture of groundwater plume. A site-specific numeric groundwater flow model was used to test various PRB design configurations that could be built entirely within the boundaries of the site. The model was also used to measure the performance of each system design based on the groundwater flow path and gradients through the gate(s) and slurry wall. The possible flow paths produced from the installation of permeable reactive barriers are illustrated on Figure 1 and comprise the following:

- end flow around the slurry walls
- flow through the slurry wall
- flow through the gate
- overtopping of the gate(s) or slurry wall
- under flow at the base of the slurry wall or gate

Under flow at the base of the slurry walls or reactive gates was not modeled , as this flow path is mainly controlled by geotechnical considerations and the success in keying the PRB into a low-permeablity zone. The results of selected PRB design simulations are presented in this paper and illustrate the effectiveness of numeric modeling analysis in evaluating various site-specific PRB designs.

SITE CONDITIONS AND HYDROGEOLOGY

The site is located in Denver, Colo., within the region of the Denver Basin. Site-specific stratigraphy and hydrogeologic parameters were

Figure 2. 1,1 DCE plume in groundwater.

evaluated from over 76 boreholes and monitor wells drilled on and off site. The site is underlain by interbedded sands, clays and silts, and weathered and unweathered deposits of the Denver Formation. The weathered Denver Formation is comprised of poorly consolidated sandstone, siltstone, and claystone deposits. The unweathered Denver Formation occurs at a depth of approximately 17 meters and consists mainly of claystone and sandstone, which are massive and moderately well lithofied.

Groundwater in the shallow aquifer occurs at a depth of about 7 meters, providing for about 10 meters of saturated section above the top of the unweathered Denver Formation. Groundwater flows in a northeast direction with a horizontal gradient of about 0.02. The hydraulic conductivity of the shallow aquifer falls in the approximate range of 1×10^{-5} centimeters per second (cm/sec) to 1×10^{-3} cm/sec, as assessed from an aquifer pump test and slug tests conducted in over 33 wells on and off site.

Historic releases of chlorinated solvents from the on-site manufacturing facility and upgradient sources came into contact with and dissolved into groundwater, resulting in a groundwater solvent plume approximately 230 meters wide that has migrated in a northeast direction off site into a residential area. Groundwater analytical results indicate that the plume is confined to the shallow aquifer and does not extend below the top of the unweathered Denver Formation at a depth of approximately 17 meters. The plume has concentrations of 1,1- dichloroethene (1,1 DCE) ranging up to 3,000 ug/l near the fenceline, resulting from the degradation of 1,1,1-trichloroethane (1,1,1 TCA) and trichloroethene (TCE). The location of the plume in relation to the site is shown on Figure 2.

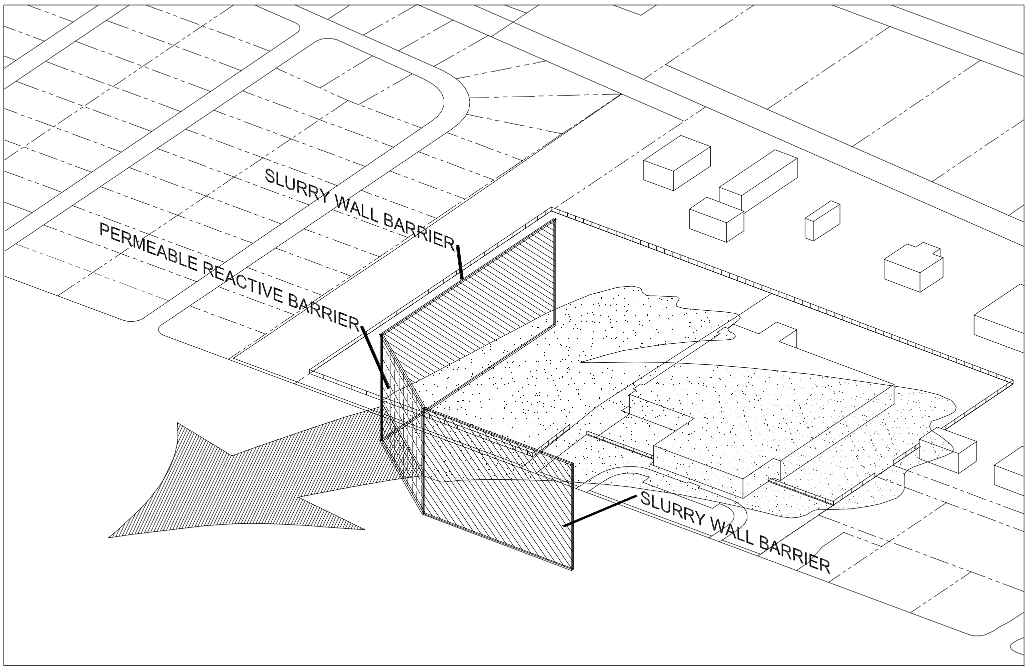

Figure 3. Cut-a-way view of the permeable reactive barrier.

Containment and treatment of the groundwater plume by installing a PRB in the northeast portion of the site was evaluated along with other remedies, including pump and treat, *in situ* chemical oxidation, and *in situ* biodegradation. A conceptual diagram of a simplistic PRB with two funnelling slurry walls and one reactive gate in relation to groundwater plume is shown on Figure 3.

GROUNDWATER MODEL DESIGN AND SIMULATED PARAMETERS

The U.S.G.S. MODFLOW computer code (McDonald and Harbaugh, 1988) was used to quantitatively estimate aquifer response and the artificial flow field (specifically the flow paths identified above) developed from the simulation of various PRB designs under steady-state conditions. Plume capture capabilities of the system were evaluated using the head distribution from the groundwater model with the PATH3D particle-tracking program (Popadopulos, 1991).

Model layer and cell configuration

The model was designed with one layer and approximated 10 meters of saturated section above the top of the unweathered Denver Formation. The model grid incorporates 38,784 variable dimension cells with the central portion of the model (177 by 186 meters), incorporating 14,152 1.5 square meters (m^2) grid cells. The total dimensions of the model were 1525 meters by 1540 meters. The small-dimension cells in the central portion of the model were used to provide the detailed head distribution necessary to assess the theoretical groundwater capture zone and resulting flow field generated by the slurry wall(s) and gate(s), using the particle-tracking program.

Horizontal gradient and hydraulic conductivity

Groundwater was modeled to flow in a northeasterly direction with a horizontal gradient of 0.02 to approximate observed on-site conditions. Model simulations were conducted using an aquifer hydraulic conductivity (K) of 1 X 10^{-3} cm/sec, which was at the high end of the range observed from aquifer tests at the site. The hydraulic conductivity of the barriers or funneling slurry walls were estimated at 1 X 10^{-6} cm/sec and the reactive gates at 1 X 10^{-3} cm/sec. The higher value of aquifer K was used in the model to provide a conservative or high estimate of the anticipated groundwater flow rates through the gates (lowest retention time in the reactive iron) and slurry walls and greatest head increases upgradient of the PRB system.

EVALUATION OF SIMULATED DESIGNS

PRB design scenarios were modeled incorporating variable slurry wall and gate lengths, and the number and position of gates. Model results for each design condition were evaluated considering:

- end flow around the gates and slurry wall
- flow through the slurry wall
- overtopping of the gate(s) or slurry wall due to upgradient head increases
- residence time within the reactive barrier
- probable location of compliance monitoring points

Flow volumes

The model cell-by-cell flow terms and zone budget modules were used to assess the amount of water flowing through the slurry wall and gates and around the ends of the PRB system.

Particle tracking

Particles were introduced to the head distribution simulated by the groundwater flow model for each simulated PRB design. The particle-tracking program produces flow paths that approximates the path a particle of water would follow by advective transport in the simulated flow field. Particles were introduced upgradient of the PRB in each 1.5 m^2 model grid cell and produced a flow line simulating its potential path. The fate of the particle(s) (i.e., whether they were captured or not) was used to assess the effectiveness of a particular PRB design in capturing and treating the groundwater plume.

MODEL SIMULATIONS

The initial PRB design simulations consisted of a slurry wall or funnel system installed in a 90-degree orientation as illustrated on Figure 3. Reactive gates of varying lengths were simulated at the apex of the funnel system. The length of the slurry wall was increased to reduce end flow. Additional gates were placed in areas of increased head upgradient of the PRB to reduce the gradient and flow through the slurry wall. Variable length gates were simulated at one end of the slurry wall to provide for treatment of water flowing around the end of the barrier system.

RESULTS AND DISCUSSION

One-gate system

The results of four design scenarios are illustrated in Figures 4 and 5. A comparison of the particle flow paths for each design can

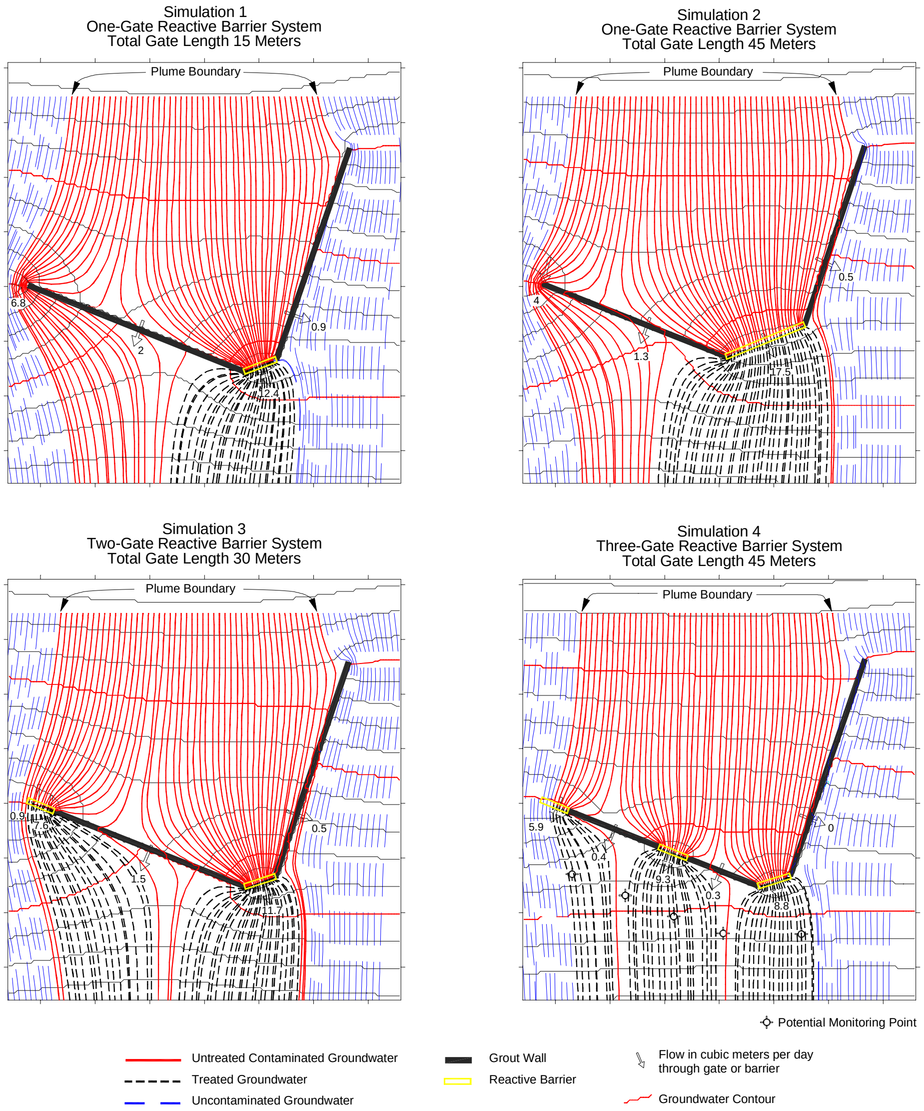

Figure 4. Flow paths for selected simulations.

demonstrate the utility of the model in assisting in the design of a PRB system. The flow paths shown on Simulation 1, Figure 5 are produced from a system with one, 15-meter gate located at the apex of the funneling slurry walls. End flow of 6.8 cubic meters per day (m^3/day) or 31% of total plume flow of untreated water occurs on the east (left) side of the system. Additional flow of 2.9 m^3/day bypasses the gate by flowing through the confining slurry walls from increased head and gradient, upgradient of the system. Increasing the gate to 45 meters in length (Simulation 2) still results in end flow of 4 m^3/day and flow through the slurry walls of 1.8 m^3/day.

Two-gate system

A second 15-meter gate was simulated at the end of the east slurry wall, in addition to the 15-meter gate at the apex of the system, Simu-

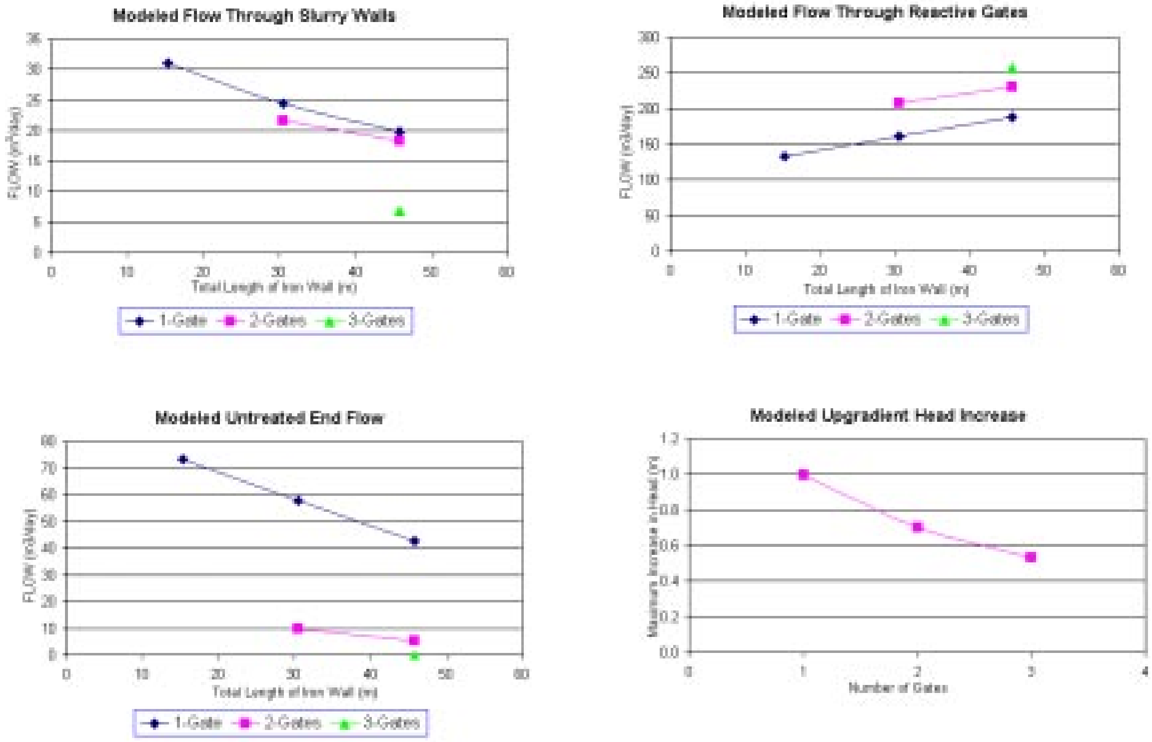

Figure 5. Modeled flow rates and increases.

lation 3. The additional gate at the end of the slurry wall significantly reduced the end flow of untreated water, but still allowed 0.9 m^3/day to flow around the ends of the system and 2 m^3/day to flow through the slurry walls.

Three-gate system

An additional PRB design, Simulation 4, included three gates each of 15 meters in length located along the north slurry wall. One gate was located at the apex of the funnelling slurry walls, and one gate each at the middle and end of the north slurry wall. The third gate in the middle of the slurry wall reduced the upgradient head by allowing more water to flow through the central portion of the slurry wall. The decreased head in turn reduced end flow, allowing all the end flow water to pass through the end gate and reduced flow through the slurry wall to 0.65 m^3/day. Additionally, the reduced head provided for a groundwater flow velocity through the reactive gates that would furnish a long enough resident time for the plume to be oxidized by the reactive wall (gate).

Potential locations for compliance monitoring points are indicated on the flow path diagram for Simulation 4. The monitoring points are located, based on the results of the particle tracking program, to more reliably assess the system performance by placing them in downgradient areas to assess the impacts of potential barrier leakage and system end flow, and to evaluate the extent of groundwater treatment by the reactive gate.

Quantitative comparisons of additional PRB design simulations are shown in Figure 5. The first three graphs depict untreated end flow,

flow through the reactive gate(s), and flow through the slurry walls for three cases. The first case is a one-gate system with a variable length gate of 15 meters to 45 meters. The second case is a two-gate system which is varied in length from 30 meters to 45 meters. The last case is a three-gate system with 45 meters of total gate. These graphs demonstrate that the three-gate system with 45 meters of total reactive gate will out perform a one- or two-gate system with the same length of reactive gate. The three-gate system has the least amount of untreated end flow water and flow through the slurry wall, and the greatest flow through the reactive gates. The forth graph shows that the upgradient head increases, resulting from the installation of the PRB, are the least with the three-gate system providing for the minimum potential to force water under the PRB or around the ends of the system. Additionally, the lower head increase also provides for the least vertical height required to capture the groundwater plume and prevent overtopping.

Numeric modeling of the groundwater flow field produced from the installation of a PRB should be considered as a prerequisite prior to developing the final design and installation of a PRB system. The results of model analysis can provide for a design that will optimize groundwater capture by incorporating multiple gates located along portions of the low K barrier. The model results can also identify the locations for gates to minimize head increases along the upgradient portion of the low K barrier, resulting in reduced seepage of untreated groundwater through the funnelling slurry wall and flow of untreated groundwater around the end points or under the barrier. The length of the gates can also be optimized to provide for minimal gradients and sufficient resident time of groundwater in the reactive barrier to accomplish treatment. Results from the particle-tracking model are essential in locating critical areas where monitor wells could be placed to assess performance of the system.

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