DOI: 10.4408/IJEGE.2007-01.S-05

CONSTRUCTION AND MONITORING OF A PERMEABLE REACTIVE BARRIER NEAR THE CITY OF TORINO IN ITALY

Rajandrea SETHI, Valerio ZOLLA & Antonio DI MOLFETTA(*)

(*) Politecnico di Torino, Dipartimento di Ingegneria del Territorio dell'Ambiente e delle Geotecnologie, C.so Duca degli Abruzzi 24, - 10129 Torino, Italy

INTRODUCTION

The concept of PRBs is relatively simple: reactive material is placed in the subsurface to intercept a contaminated plume which moves through it under natural gradient. Physical and chemical processes that occur inside the barrier transform contaminants to less harmful or immobile species (Orth & Gillham 1996, Gillham & O'Hannesin 1994, Orth *et alii,* 1998, Di Molfetta & Sethi, 2005). Permeable reactive barriers are generally backfilled with high permeability coarse grained materials containing zero-valent iron, organic carbon, modified bentonite, calcium carbonate, microrganisms (biobarriers). The choice of reactive media depends on the type of contaminant to be treated and ambient geochemistry. Emplacement of PRBs is performed, for shallow depths, using conventional excavation techniques (i.e. open and shored trenching) and for average and high depths using construction techniques adapted from geotechnical field (Day *et alii,* 1999, Di Molfetta & Sethi 2006, Di Molfetta *et alii*, 2006).

The aim of this study is to describe the first full scale application of a zerovalent iron permeable reactive barrier in Italy and illustrate the preliminary results of the monitoring plan. The PRB was designed and emplaced to remediate a chlorinated hydrocarbons plume at an old industrial landfill site, in Avigliana, near the city of Torino, in the Piemonte Region. The installation of the 120 m long, 13 m deep and 0.6 m long barrier was accomplished using a clamshell for the excavation of the trench and a guar-gum slurry to support the walls. After a description of the intervention, preliminary results of the monitoring plan are presented.

Key-words: *permeable reactive barrier (PRB), clamshell, zerovalent iron (ZVI), biopolymer slurry, guar gum*

SITE DESCRIPTION

The studied area is located between Avigliana and Buttigliera Alta, near the city of Torino, in the North of Italy. This site was used in the past as an industrial landfill for the disposal of wastes coming from metal working factories.

The area is characterized by alluvial sequences deposited by Late Pleistocene glacial events and Ancient Holocene. Middle, recent and present alluvial drifts relate to the evolution of the course of the Dora Riparia River. Deposits are sandy-gravely materials that are medium fine to coarse grained with sparse occurrence of fine muddy and clayey-muddy materials.

The most superficial part of the lithostratigraphic sequence contains an unconfined aquifer whose impermeable bottom layer consists of muddy clayey drifts found 11-20 m below the ground surface. The saturated thickness of this aquifer ranges from 9 to 11 m showing a progressive reduction towards the Dora River, thus representing the drainage axis of the groundwater. The average flow direction in the area is SSW-NNE, the hydraulic gradient is 1.1% and the average effective velocity is $9.9 \cdot 10^{-6}$ m/s. The hydrodynamic characterization of the aquifer was based on constant rate multiwell pumping tests and slug tests (Table 1).

Parameter	**Symbol**	**Value**
Saturated thickness	b	10 m
Horizontal hydraulic conductivity	k	$1.8 \cdot 10^{-4}$ m/s
Effective porosity	n_c	0.2
Hydraulic gradient	i	0.011

Table 1 - Average hydrogeological and hydrodynamic parameters of the superficial aquifer

A detailed horizontal and vertical, soil and groundwater, characterization was performed by means of rotary drillings and direct push system (Geoprobe) borings. Chemical analyses of site groundwater revealed the presence of two contaminated plumes with a concentration of PCE, TCE and daughter products higher than Italian maximum concentration levels (Figure 1 and Table 2).

The most suitable technologies to remediate the contaminated plumes were found to be a zerovalent iron permeable reactive barrier (ZVI PRB) for the first plume and a capping and MNA for second and less contaminated plume. A detailed risk assessment analysis (tier 3) was performed leading to a remediation goal of 30 µg/l of total carcinogenic chlorinated aliphatic compounds.

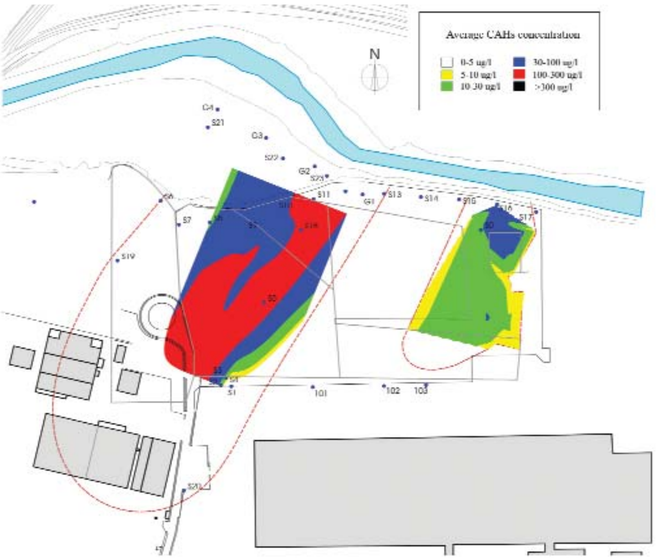

Fig. 1 - Delineation of the contaminated areas.

Groundwater concentration	Area 1 µg/l	Area 2 µg/l	MCLs µg/l
PCE	0.46	**56**	1.1
TCE	**130**	**36**	1.5
cDCE	135	0.3	60
VC	-	0.1	0.5

Tab. 2 - Groundwater contaminant concentrations and Italian maximum concentration levels (MCLs)

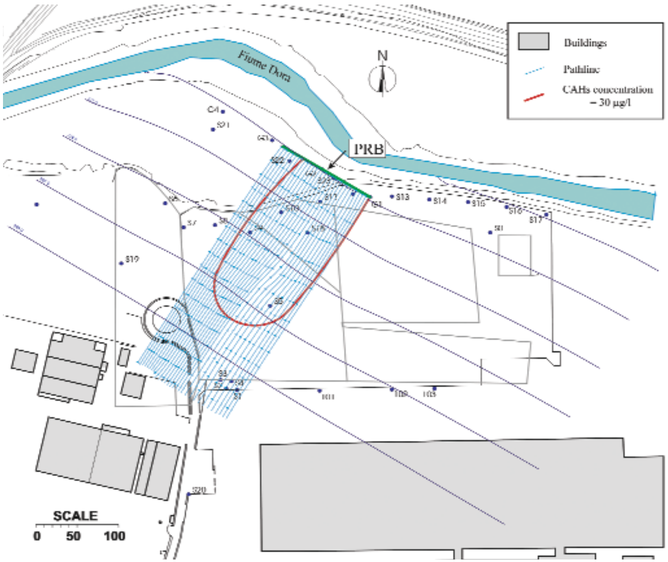

Fig. 2 - Final position, orientation and capture area of the permeable reactive barrier

	$t_{1/2}$ lab (h)	$t_{1/2}$ lab (h)
TCE	0.74	2.2
cDCE	8.4	25.2
1,1-DCE	1.5	4.5
VC	8.2	24.6

Tab. 3 - Laboratory and field half lives determined for the uncoupled multispecies contaminant model from lab test results

DESIGN OF THE PRB

The dimensioning phase required definition of the configuration, position, orientation, capture area, geometry (height, length, width) of the PRB in order to assess the amount of ZVI needed to achieve treatment. The design phase was supported by numerical flow, particle tracking and multispecies contaminant transport simulations implemented using Visual Modflow Pro v.3.1.

The site assessment, the flow and particle tracking simulations lead to the choice of a 120 m long continuous reactive barrier configuration (Fig. 2). This solution was the least expensive and easiest to implement alternative and is predicted to have the least impact on the groundwater flow. The reactive barrier was designed to penetrate 0.6 m into the loamy-clayey bottom, thus the average depth of the excavation is 13 m, whereas the average reactive height of the barrier is 10.5 m (i.e. approximately 2.5 m of unsaturated zone exists above the PRB).

The calculation of the width of the barrier was performed by means of a 3D multispecies uncoupled and coupled (network) contaminant transport model. The CAHs degradation kinetics were derived from a column test performed by University of Tubingen (I.M.E.S., unpublished data) on contaminated water sampled from the site. The half-lives calculated during laboratory tests were corrected by a factor of three to account of the temperature differences among laboratory and field conditions (Table 3). Both the uncoupled and coupled multispecies simulation, performed by implementing an RT3D (CLEMENT, 1997) user defined module, lead to similar results (SETHI, 2004) and to width of 0.5 m of ZVI.

The final width of the barrier was chosen as 0.6 m, due to the standard dimensions of commercial excavation grabs. The trench was planned to be filled with a mixture of 5 parts of and Gotthart Maier Metallpulver iron and 1 part sand.

CONSTRUCTION OF THE PRB

The construction of the PRB began with several site preparation activities including the flatting of the area and the construction of a concrete wall to guide the digger.

Excavation of the trench was performed in November 2004 and lasted just 8 days. The excavation was performed using a crawler crane equipped with an hydraulic grab (clamshell). During excavation the trench was supported by guar gum slurry until the backfill with ZVI.

The construction of the 120 m long and 13 m deep permeable reactive barrier (Table 4) was performed by means of 17 panels whose average length was 7 m. The choice of proceeding by panels was a safety measure in the case biopolymers degraded prematurely thus compromising the trench stability.

Parameter	Symbol	Symbol
Lenght	L	120.37 m
Width	W	0.6 m
Height	H	11.90-13.80 m
Volume	V	928 m^3
Reactive height	RH	9.70-11.80 m

Tab. 4 - Dimensions of the PRB

The phases undertaken during excavation can be roughly summarized as follows (Figure 3):

- installation of grab guide wall;
- excavation of a panel supporting the trench with biopolymers;
- positioning of a steel separating tube (ST) in order to avoid fluid exchange between neighbouring panels;
- positioning of a screened PVC tube (ET) in the middle of the panel for enzymes recirculation;
- displacement of the slurry with zerovalent iron and sand mix;
- breaking down of the bioslurry by enzymes;
- filling the top of the barrier with sand and three layers of compacted clay of 20 cm each.

The zerovalent iron used for the backfill was supplied by the Gotthart Maier Metallpulver GmbH (Rheinfelden, Germany) in the quantity of 1700 t. The material, free from oils and other impurities was characterized by an iron content higher than 90% by weight and a carbon content lower than 4%. The 85% of the iron had a particle size in the range 0.25-3 mm and all the material was below 5 mm. The biopolymer slurry was prepared in a batch mixing plant made up of an hopper for the solids and a dispenser for the liquids. Each batch was prepared using 3.5 m^3 of tap water, 22.5 kg of guar gum and preserved with 2.5 kg of soda ash and 0.2 kg of biocide.

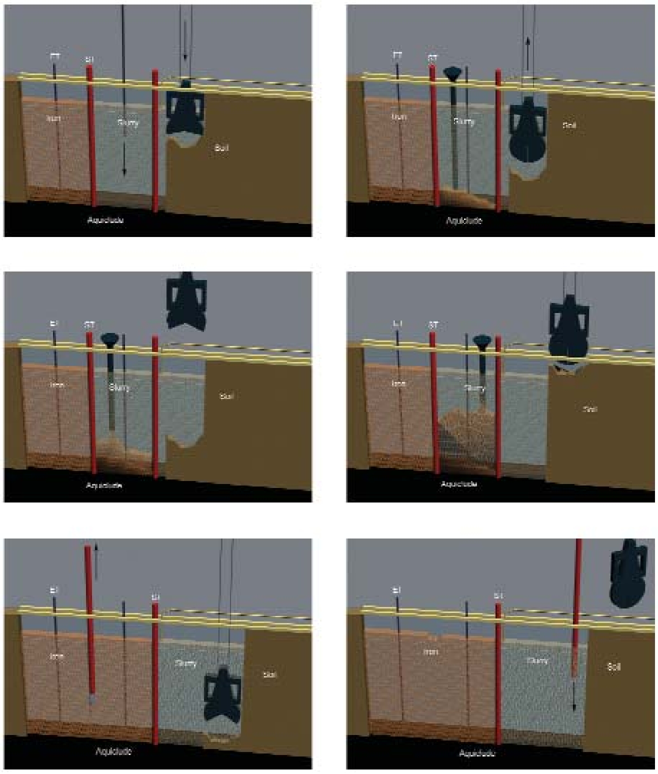

Fig. 3 - PRB construction's phases

The trench excavation was executed by Rodio Division, Trevi S.p.A., by means of a Link Belt LS338 crawler crane equipped with a Casagrande K4000 hydraulic grab (Fig. 4). The grab was 0.6 m wide, 4 m long and with a volumetric load capacity of 1 m^3.

Due to the length of each of the 17 panels, the excavation of each section was performed in two or three operations. At the beginning the lateral portion of the panels were excavated and then the central part was removed. The excavation of each panel was extended 1 meter into the neighbouring panel in order to leave enough room for the insertion of the separation tube (ST) and to avoid scraping with the grab. The hydraulic separation of the panels was achieved by

Fig. 4 - Crawler crane equipped and hydraulic grab

inserting steel cylindrical separation tubes, between the guide wall and into the subsoil and till aquiclude. The separation tubes were 15 m long and 0.6 m in diameter and built with two later ribs. After the excavation of the panel and before filling it with iron-sand, a slotted PVC tube for enzyme recirculation (ET) was inserted.

Excavation of the barrier using crane digger equipped with hydraulic grab was fast enough to allow construction of 3 panels in just 12 hours. The average productivity of the excavation and filling operations was around 18 m^2/h. After excavation, the breakdown of guar gum was initiated by injecting into the recirculation tubes (ET) 2 PV of water solution containing 60 l of LGB-10 Apex enzymes. Air lifting was used to pump the enzymes solution from the barrier. At the end of this operation Marsh Funnel viscosity was less than 30 s relative to 50–60 s of virgin slurry.

A sand layer overlain by an impermeable three layered clayey cap was placed on the top of the permeable reactive barrier to prevent oxidation of the iron.

CONTAMINANT MONITORING

The monitoring plan of the PRB started in November 2005 with the aim to verify the attainment of the cleanup goals and to evaluate the efficiency of the PRB (ZOLLA *et alii*., 2006). The primary objective of the monitoring effort is to assure that the plume is being adequately captured and treated, and that downgradient concentrations of the target contaminants (and any byproduct) are below the cleanup levels.

The configuration of the monitoring network is shown in Figure 5. A row of four long-screened wells is used to monitor the downgradient aquifer, aligned to the upgradient wells. Two additional small diameter monitoring wells are placed inside the reactive medium, and another couple of wells is placed at the two ends of the barrier to monitor for contaminant bypass that could result from inadequate flow capture. Eight monitoring well have been provided with submersible bladder pumps for groundwater sampling, whereas the other ones are sampled with submersible centrifugal pumps.

Monitoring activity includes:

- quarterly measurement of water levels, in order to indicate any seasonal changes in groundwater flow;
- chemical monitoring with the determination of groundwater field parameters (Eh, pH, dissolved oxygen, temperature and conductivity), inorganic chemicals and chlorinated organic compounds. Samples collection is conducted on a quarterly basis to indicate any seasonal changes in contaminant distribution or geochemistry;
- “Low flow purging” and “low flow sampling” methods are adopted to minimize chemical and hydrological disturbances in and around the well, in order to yield representative water samples (PULS & BARCELONA 1996). Appropriate quality control procedures are followed to ensure that valid data are collected and analyzed.

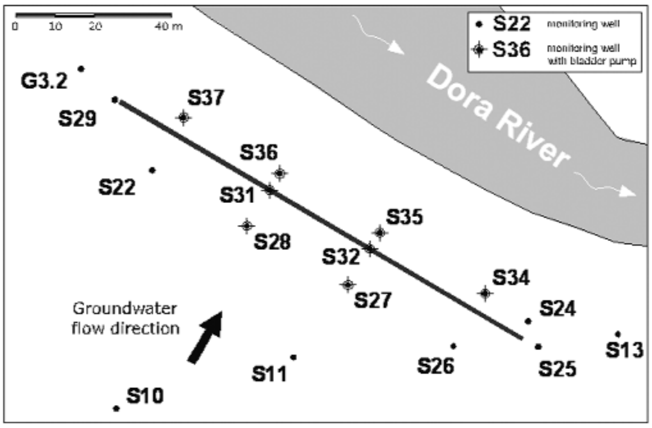

Fig. 5 - Monitoring wells configuration

Measured values of groundwater contaminant concentrations after PRB installation are shown in Table 5. Laboratory results show that the residence time of groundwater inside the reactive cell is enough to decrease CAHs’ concentration below clean-up goals, maintaining a good safety margin.

Output concentrations are largely below the limit of 30 µg/l of total carcinogenic compounds, indeed carcinogenic CAHs are below detection levels in almost every water sample taken from downgradient wells. Reaction byproducts (VC, 1,1-DCE, 1,2-DCE) are nearly absent both inside and downgradient the PRB and this proves that the barrier is able to perform a complete dehalogenation process.

CONCLUSIONS

The construction of the first PRB in Italy by means of a crawler crane equipped with grab (clamshell) proved to be an effective and affordable construction method. In 8 days it was possible to excavate a 120 m long and 13 m deep PRB and fill it with 1700 t of iron, achieving an average productivity of 18 m^2/h. Fast excavation rates coupled to use of a concrete guide wall and of short panels, lead to contain the amount of used guar gum slurry to 50% of the volume of the trench. Moreover, the monitoring results show that the PRB is able to intercept and treat the contaminated plume attaining the remediation goals. The output concentrations of the original contaminants and of their potential by-products are frequently below detection levels, to indicate the complete degradation of chlorinated organic compounds.

ACKNOWLEDGEMENTS

The authors would like to acknowledge Stephanie O’Hannesin, Andrzej Przepiora, Jennifer Son from E.T.I., Hermann Schad from I.M.E.S. and Steve Day from Geosolutions Inc. who provided technical guidance during the different phases of the project. Lorenzo Buonomo and Studio Buonomo Veglia who participated, with Studio Bortolami e Di Molfetta, to the design of the remediation

		upgradient aquifer	upgradient aquifer	upgradient aquifer	upgradient aquifer	PRB	PRB	downgradient aquifer	downgradient aquifer	downgradient aquifer	downgradient aquifer
	Monitoring well	S22	S26	S27	S28	S31	S32	S34	S35	S36	S37
PCE	µg/l	0.27	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05
TCE	µg/l	20	24	78	40	0.6	< 0.05	< 0.05	< 0.05	0.24	1.2
1,1-DCE	µg/l	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5
1,2-DCE	µg/l	12	15	42	12	< 0.5	7	6	< 0.5	4	< 0.5
VC	µg/l	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5
pH	-	6.7	6.6	6.6	6.5	6.6	8.5	7.3	6.7	6.5	5.8
Eh	mV	-57	-70	-84	-91	-117	-260	-233	-243	-216	-175
O_2	mg/l	0.50	0.33	0.29	0.26	0.77	0.45	0.50	0.80	0.60	0.65
Alkalinity	meq/l	7.8	8.4	8.2	8.5	6.2	2.3	6.2	6.0	5.9	5.8
Ca	mg/l	126	93	91	117	56	33	44	41	32	65
Mg	mg/l	60	38	39	48	26	25	24	19	26	39
K	mg/l	4.9	9.8	9.2	9.4	6.5	7.2	5.6	4.8	4.7	4.2
Na	mg/l	75	73	80	66	36	28	43	41	38	60
Chloride	mg/l	30.3	26.9	24.1	30.2	35.7	26.9	40.7	16.1	25.7	19.5
Sulfate	mg/l	194	162	168	188	174	157	149	162	147	135
Fe (filtered)	µg/l	16	16	6	3	6	6	8	250	< 1	8

Tab. 5 - Mean groundwater concentrations of organic contaminants and inorganic chemicals after PRB installation

project. Stefano Marconetto, Chiara Ariotti, Raffaella Granata and all the staff who worked hard during the installation of the PRB.

REFERENCES

CLEMENT T.P. (1997). RT3D – *A modular computer code for simulating reactive multispecies transport in 3-dimensional groundwater aquifers*. Battelle Pacific Northwest National Laboratory. PNNL-SA-28967, Richland (USA).

DAY R.S., O'HANNESIN S.F. & MARSDEN L. (1999) - *Geotechnical techniques for construction of reactive barriers*. Journal of Hazardous Meterials **B67**: 285-297.

DI MOLFETTA A.& SETHI R. (2005) - *Barriere reattive permeabili*. In Bonifica di siti contaminati. Caratterizzazione e tecnologie di risanamento. A cura di Luca Bonomo, McGraw Hill, ISBN 88-386-6278-9.

DI MOLFETTA A. & SETHI R. (2006) - *Clamshell excavation of a permeable reactive barrier*. Environmental Geology. ISSN: 0943-0105.

DI MOLFETTA A. SETHI R. & S. DAY (2006) - *Comparison between Clamshell and Backhoe Excavators for the Emplacement PRBs*. Remediation of Chlorinated and Recalcitrant Compounds: The Fifth International Conference, May 22-25, 2006 Monterey, California.

GAVASKAR A.R. (1999) - *Design and costruction techniques for permeable reactive barrier*. Journal of Hazardous Materials **68**: 41-71.

GILLHAM R.W. & O'HANNESIN S.F. (1994) - *Enhanced degradation of halogenated aliphatics by zero-valent iron.* Ground Water 32: 958-967.

ITRC (2005) - *Permeable Reactive Barriers: Lessons Learned/New Directions*. The Interstate Technology & Regulatory Council, Permeable Reactive Barriers Team.

ORTH & GILLHAM R.W. (1996) - *Dechlorination of Trichloroethene in Aqueous Solution Using Fe0*, Environmental Science & Technology 30 66-71.

ORTH, FELLOW A., DAUDA T. & MCKENZIE D.E. (1998) - *Reductive Dechlorination of DNAPL Trichloroethylene by Zero-Valent Iron*. Practice Periodical of Hazardous, Toxic, and Radioctive Waste Management July 123-128.

PULS R.W. & BARCELONA M.J. (1996) - *Low flow (minimal drawdown) groundwater sampling procedures*. EPA Groundwater Issues. EPA/540/S-95/504. April 1996. 12 pp.

SETHI R. (2004) - *Barriere reattive permeabili a ferro zero-valente: modellazione dei fenomeni di trasporto e degradazione multicomponente*, Ph.D. Thesis in Environmental Geoengineering. Politecnico di Torino, 2004.

ZOLLA V., ROLLE M., SETHI R. & DI MOLFETTA A. (2006) - *Performance evaluation of permeable reactive barrier using zero-valent iron at a chlorinated solvents' site.* XV International Symposium on Mine Planning Equipment Selection (MPES 2006), 20 - 22 September 2006, Torino – Italy.