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TDP 3 - Design, Installation and Performance Assessment of a Zero Valent Iron Permeable Reactive Barrier in Monkstown, Northern Ireland

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Executive Summary

The Monkstown site has been operational since 1962 in the manufacture and assembly of electronic equipment and was purchased by Nortel Networks in the early 1990s. Soil and groundwater contamination consisting predominantly of trichloroethene (TCE) and its degradation products dichloroethene (DCE) and vinyl chloride (VC) was discovered during due diligence environmental investigations. Although there was no regulatory requirement to remediate the site at the time, Nortel Networks undertook a voluntary cleanup which consisted of excavation and landfilling of contaminated soil and the installation of a zero valent iron (Fe^0) permeable reactive barrier (PRB) system to treat shallow groundwater in an area of the site known as the eastern car park.

The geology at the site consists of more than 18 m of superficial deposits overlying fine to coarse-grained Sherwood Sandstone bedrock of Triassic age. The drift is characterised by a complex succession of stiff, red-brown clayey till, with intercalated, discontinuous lenses of silts, sands, gravels, and peat, overlain by approximately 0.1 to 1.1 m thickness of made ground.

Shallow water tables occur at depths ranging between 0.45 and 7.82 mbgl. Shallow horizontal groundwater flow in the vicinity of the eastern car park is interpreted to be in an easterly to northeasterly direction. Calculated hydraulic conductivities range from 3 x 10^{-6} metres per second (m/s) in coarse silty sand to 5 x10^{-9} m/s in clay.

During site characterisation, concentrations of TCE in soil were found to range from 0.3-1,000 µg/kg. Highest concentrations of TCE in groundwater were orders of magnitude greater than other contaminants, with values up to 390,000 µg/L suggesting the presence of free phase TCE.

Modified backhoe excavating trench

Laboratory scale feasibility studies, involving column tests on sample of groundwater taken from the site, were used to help design the remedial scheme. The tests showed that TCE reacted very rapidly (half lives of 1.2 to 3.7 hours) with Fe^0, generating cis-1,2-Dichloroethene (c-DCE) as an intermediate degradation product with calculated half lives ranging between 12-24 hours. The column test demonstrated that a significant plume of dissolved iron would be expected to occur downgradient from the PRB resulting in the potential precipitation of siderite ($FeCO_3$) and iron oxide (Fe_2O_3).

A conceptual model of the site hydrogeology, developed by Golder Associates during the site characterisation programme, was simulated using the two dimensional, finite difference, steady state groundwater flow model FLOWPATH. The purpose of the groundwater flow model was to assist in the design of the PRB system and to give additional confidence that the system would operate as designed. The results of the modelling exercise provided an order of magnitude estimation of system parameters and supported the viability of a PRB design at the site. The model demonstrated that the hydraulic regime at the site would not be adversely affected by the installation of a PRB system and that contaminants would not be diverted around the cut-off wall.

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Based on field observations, laboratory experiments and modelling, it was decided that the Fe^0 PRB system would be placed in the eastern car park at the property boundary. A cement bentonite cut-off wall would be installed to funnel contaminated groundwater to a vertically aligned underground reaction cell containing Fe^0. It was recognised that some levels of historic TCE contamination remained in subsurface locations downgradient from the PRB installation.

Following the installation of the PRB, a groundwater monitoring programme was established to verify whether the system was operating as designed. The monitoring programme consisted of water level readings and geochemical sampling. Water levels were measured to ensure that the PRB system had not adversely affected groundwater flow conditions. Continuing geochemical monitoring of groundwater upgradient, within and downgradient of the reactive cell, is used to demonstrate that discharge from the reactive cell meets design criteria.

The major ion chemistry shows the predominant groundwater type upgradient of the PRB to be "calcium bicarbonate". Groundwater passing through the reactive cell changes from "calcium bicarbonate" type to "magnesium-sodium sulphate-chloride", type indicating loss of calcium bicarbonate through calcite precipitation. Contaminant concentrations of TCE are progressively removed as the groundwater flows down through the reactive cell.

Significant decrease in TCE concentrations in some upgradient wells can be explained by: (i) the removal of highly contaminated material during excavation of the PRB and cut-off wall, although some contaminated material remains, and/or (ii) the tail end of a slug of contamination that moved through the site. The degree to which natural variation, natural attenuation, seasonal fluctuations and disturbance during drilling/excavation affect TCE concentration in wells cannot be determined from the existing data.

Monitoring wells downgradient of the PRB exhibit detectable concentrations of TCE and DCE due to historic contamination. Until such time as levels stabilise and reduce to levels below those found in upgradient wells, downgradient monitoring wells cannot be used to confirm capture to the contaminant plume because their concentration could mask transgressions of the plume through the cut-off wall.

Monitoring of water levels within the reaction vessel itself indicates periodic reversals of groundwater flow across the reactive cell, making groundwater flow through the reaction vessel difficult to quantify. Estimates, based on potential capture by the cut-off wall and using hydraulic parameters derived from other areas of the site, suggest maximum flow rates of between 1-6 m^3/day, with a residence time within the reaction vessel of between 17.4 and 105 hours.

Estimates of volumetric flow and residence time, along with observed non-detectable concentration of TCE and DCE in groundwater leaving the reactor at R1, confirm that the reactive cell is operating as designed and meeting the design criterion concentration of 10 µg/L TCE.

Investigations by Queen's University Belfast showed that for the Monkstown site, there was some loss in reactivity of the granular iron at the entrance to the reactive cell. Mineralogical observations showed the presence of calcite and siderite precipitation on the iron in the entrance sample, which was restricted to a very narrow zone. This is likely to cause a reduction in the reactivity and permeability of the Fe^0 over time. At a distance of 10-40 cm into the reactive cell centre, there is evidence of corrosion and increased surface area leading to an increase in the iron reactivity.

Excavated trench

No evidence for significant biological fouling was found within the reactive cell since it was first installed.

The remediation costs at Monkstown using a PRB system were £735,500. This included site investigation costs, excavation and disposal of 500 m^3 of heavily contaminated soil, capital costs of the system and monitoring projected forward to 10 years. The estimated equivalent costs for alternatives are £964,500 for landfilling/pump and treat and £865,000 for containment/pump and treat.

Cost effectiveness of the Fe^0 PRB system was considered in terms of contaminant disposition, installation ongoing operation, and longevity of the system. The PRB system was less expensive to install, and expended less energy than the landfilling/pump and treat options. In terms of ongoing operation, the system has no requirements for man-made energy and is considered to have very high operational cost effectiveness. In terms of system replacement, the longevity for the Fe^0 PRB system at Monkstown is expected to be moderate (at least 10-15 years) for minor replacement (iron) and very high (50 years) for any major component replacement.

Lessons Learned

The PRB at Monkstown was the first application of Fe^0 PRB technology in Europe and one of the first in the world. Critical analysis of its design and installation provides the opportunity to identify a number of lessons, which were learned from the experience and are discussed below:

1. Involvement of the regulator particularly at an early stage is essential. Although there was no regulatory requirement to carry out work at the site, Nortel established a positive and open relationship with the regulator, which resulted in confidence by the regulator that the site was being managed in a responsible way. This led the way for open discussions between parties and to the selection of an innovative solution, which was agreed to by both parties.

2. The conditions at Monkstown that were conducive to the application of Fe^0 PRB technology were:

   • chlorinated solvent contamination in shallow groundwater moving offsite
   • low groundwater velocity
   • no evidence of significant biodegradation or other degradation processes for contaminants of concern
   • the presence of a competent aquitard below the contaminated aquifer into which the cut-off wall could be tied
   • the lack of identified discrete sources of contamination

3. The natural head difference across the barrier was less than 0.1 m. Auxiliary pumping was used to recirculate contaminated groundwater from a local "hot spot" downgradient of the barrier at GA13 to MWU, located immediately upgradient of the barrier. The recirculation was carried out to take advantage of the unused capacity of the reactive cell. This unused capacity allowed for flexibility in varying the contaminant load and groundwater flow. The recirculation resulted in an increase in the driving head and a lower groundwater residence time within the PRB. While the residence time was adequate to treat the contaminants at the site, there may be situations where treatment processes will be affected adversely. Re-circulation of contaminated groundwater back into the treatment system requires regulatory approval.

4. The long term chemistry data show a decrease in contaminant concentrations upgradient of the barrier over time. This could be explained by: (i) the excavation of highly contaminated material from the trench which was dug in preparation for the PRB; (ii) the tail end of a slug of contamination that moved through the site; and (iii) other processes such as natural variation, natural attenuation, seasonal fluctuations and disturbances associated with drilling/excavation. While this was not obvious from the initial investigations, it reinforces the need for adequate characterisation and time series sampling.

5. This project illustrates the importance of understanding site specific conditions and the complexities of full-scale natural systems. Reasons for the rapid decline in TCE concentrations in upgradient wells and the gradient reversals observed within the reaction vessel remain unclear. The project also shows the need for proper planning at all stages of site characterisation, remedial planning, installation and monitoring in order to optimise available funding. It demonstrates the multidisciplinary nature of environmental remediation and the need to involve experienced environmental professionals.

6. The use of PRB at Monkstown is a good example of the cost effective application of a new technology. Site specific conditions led to a novel design for the reactive cell. This project illustrates the importance of adequate site characterisation, laboratory studies, flexibility of approach and ongoing monitoring in the design and implementation of remedial systems.

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