

# Aquifer Contamination and In Situ Remediation

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## ABSTRACTS FOR TALKS AND POSTERS.

THE TALKS AND POSTERS BELOW ARE LISTED IN THE ORDER THEY APPEAR IN [THE PROGRAMME](#)

### MANAGEMENT OF CONTAMINATED MEGA SITES IN GERMANY

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#### Abstract

Risk assessment, risk management and remediation at contaminated megasites with complex and multiple source zones and contaminant plumes are a great challenge for regulators, problem owners, consultants and scientists. The decisions made for measures on risk reduction and remediation depend largely on the information gained during the site investigation programs. Since, on one hand the society and the ecosystems need to be protected and on the other hand site investigation and remediation actions can be costly, economical and social considerations have to be taken into account in the decision making process.

There is increasing interest in cost-effective remediation strategies such as natural attenuation (NA), enhanced natural attenuation (ENA) and the use of permeable reactive barriers (PRBs) to control and prevent continued migration of contaminant plumes and thus reduce risks associated with them. Since these strategies rely on the natural flow of groundwater to carry the contaminated groundwater, it is very important to determine what pathways the contaminants follow during subsurface migration. At many sites, subsurface heterogeneity makes it difficult to define the spatial distribution of contaminants without extensive and costly characterization. This problem is exacerbated if those heterogeneities are sufficient to result in strongly preferred migration pathways, i.e. pathways of limited cross-sectional area that nonetheless account for the majority of contaminant flow. In addition, the cost-effective in situ remediation strategies in comparison to conventional pump-and-treat technologies, for example, require a detailed understanding of the processes taking place in the subsurface. This increases the amount of additional information needed in the decision making process.

Work on three contaminated German megasites Bitterfeld, Zeitz and Leuna will be presented where innovative site characterisation and groundwater remediation technologies are being developed and tested.

### UNCERTAINTY IN QUANTIFYING DNAPL SOURCE ZONE DISTRIBUTION FOR IN SITU REMEDIATION DESIGN AND PERFORMANCE ASSESSMENT

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The limited availability of reliable methods to determine the spatial distribution of DNAPL within a source zone remains one of the principal limitations in assessing the performance of in situ remediation technologies. Establishing the mass of contaminant in the subsurface and,

in particular, quantifying uncertainty in mass estimates is an essential prerequisite to the successful selection, design and implementation of in situ remediation.

The research described here is part of project SABRE, an international collaboration examining in-situ enhanced bioremediation of a chlorinated solvent source zone. The study site is characterised by a trichloroethene source zone, associated with a former manufacturing facility, which impacts both a shallow sand and gravel aquifer and the underlying mudstone. The principal objectives of this phase of the study were to identify the location of the source zone(s), estimate DNAPL mass and quantify confidence in the mass estimates.

At present, no single technique is available that adequately characterises DNAPL source zone architecture(s) in heterogeneous geologies. Instead, a range of site characterisation methods are typically applied, based on establishing sequential multiple lines of evidence. In this study we describe a phased investigation, with each successive phase building upon the information gathered and assessed in the preceding phases, where propagation of uncertainty is addressed through the use of 2d kernel smoothing and fuzzy logic techniques to derive confidence values for the individual and combined datasets.

The results of the study reveal a number of individual DNAPL zones, defined by unique geological, hydrogeological and contaminant characteristics. Further analysis reveals mass distribution characteristics within these zones and defines the upper and lower confidence limits, which are used to design the in situ remediation programme. The detailed 3D reconstruction and visualisation of the site data is also presented and a quantitative method to estimate uncertainty in DNAPL mass distribution is examined.

## **OPTIMISING DATA POINT DENSITY FOR MASS FLUX-BASED ASSESSMENT OF *IN SITU* REMEDIATION PERFORMANCE**

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Significant effort is spent on the design and implementation of *in situ* remediation systems, but in many cases, little on robust treatment performance monitoring schemes. It is common to make use of sparse networks of long-screened monitoring wells installed during initial site investigation, but this gives rise to considerable uncertainty due to spatial heterogeneity of permeability and source distribution. Comparative analysis of influent and effluent mass flux is a more reliable approach, particularly where treatment is near source. Mass flux can be estimated from multilevel fence data, but little guidance is available on how to estimate the appropriate vertical and horizontal spacing of sampling points.

We installed an aerobic biobarrier to stimulate biodegradation of a BTEX plume arising from a petrol spill in Strathroy, Ontario. The multilevel array installed both up and downgradient of the barrier was intentionally over-designed to allow for performance monitoring optimisation analysis. We assumed that mass flux estimated from the total dataset was 100% accurate. By systematically deleting data, recalculating mass flux and comparing to the full dataset, we were able to establish the fewest number of points necessary to accurately (>90% of true value) represent mass flux, and an approximation of the most appropriate strategy to position those sample points. For this relatively uniform sand aquifer, the minimum number of ML points per m<sup>2</sup> of flux fence was 15. Since point density is related to spatial complexity, more heterogeneous systems will demand even more resolution.

## **EVALUATION, DESIGN AND OPERATION OF A PERMEABLE REACTIVE BARRIER (PRB) FOR CARBON DISULPHIDE-CONTAMINATED GROUNDWATER**

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The site, located in Stretford, Greater Manchester, had been used as a carbon disulphide (CS<sub>2</sub>) manufacturing facility for over 50 years. As part of the overall programme of site remediation, a zero-valent iron (ZVI) funnel and gate PRB system was implemented for treatment of dissolved CS<sub>2</sub> contamination present in the shallow groundwater (sand-gravel aquifer underlain at 6-8 m bgl by thick glacial till). This is the world's first application of ZVI for the treatment of CS<sub>2</sub> contamination anywhere in the world.

A laboratory column test programme at Queen's University Belfast was undertaken using site groundwater spiked with field-derived CS<sub>2</sub> to determine the most effective ZVI matrix, the reaction order and kinetics of CS<sub>2</sub> degradation at representative concentrations and field temperature, the products of the reaction process and other essential parameters for process design. A transient MODFLOW model was developed for the post-remediation case to establish the optimum PRB layout, estimate the hydraulic flux over the design life of the system and evaluate the effects of the PRB on groundwater levels.

The design treatment performance, together with the laboratory and modelling data served as inputs to the design of the full-scale system, which required excellent HSE performance, compliance with the future site use, minimum maintenance, easy monitoring, decommissioning, a structural design life of 20 years and a ZVI life of 10 years. The PRB performance was also to be warrantable.

The final system comprises a bentonite slurry wall (length 680 m x depth 7.5 m, keyed into 1.5 m of the underlying glacial till; design permeability of  $1 \times 10^{-9}$  m/s) and two gates (width 10 m x length 10 m x depth 5.8m), each consisting of two parallel treatment trains comprising a downflow-upflow reactor pair.

Field performance of the system has been monitored over 12 months of operation with performance exceeding design specifications. CS<sub>2</sub> concentrations at the PRB outlet and downgradient have been significantly below target concentrations and groundwater levels on the site within acceptable specifications.

## **A KEROSENE SPILL ON THE CHALK – A RISKY BUSINESS**

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In August 1999 kerosene leaked from an above ground storage tank into the Chalk aquifer in Kent. The contaminated soil and groundwater presented a risk to a nearby public water supply (PWS) borehole. A series of measures were immediately implemented, including a dewatering spill containment system. Further site investigation followed, together with a controlled waters risk assessment. The double porosity model used in the risk assessment predicted significant uncertainty in concentrations arriving at the PWS over time. The results also highlighted the need for maintaining the dewatering containment system and for further remedial action. Subsequent remediation included the use of hydrocarbon skimming and capture and a multi-phase vapour extraction system. Mass balance calculations indicated that 58% - 72% of the spilt volume remains within the Chalk.

Limited information on the nature of the Chalk was available, resulting in significant uncertainty in the site conceptual model. In order to understand better the travel times, concentrations and residual risk to the PWS from the remaining kerosene, a programme of investigation was undertaken. This consisted of shutdown of the dewatering pump under controlled conditions, single borehole dilution tests and natural gradient tracer test. The

results indicated that the conceptual model should be revised to describe solute transport through both a low permeability flow zone, characterised by narrow fracture apertures, and a high permeability flow zone characterised by wider fracture apertures.

A quantitative risk assessment was carried out using the refined conceptual site model. The assessment provided evidence to support the case for ceasing ongoing containment and remediation operations. The assessment provided further guidance on the design for medium term monitoring to ensure no adverse effects resulted from the end of active dewatering operations at the site. This case study highlights the need for risk assessment to inform remedial strategy at all stages.

## **SEQUENTIAL *IN SITU* BIOREMEDIATION: COMBINING AGGRESSIVE TECHNOLOGIES WITH MICROBIAL DEGRADATION**

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Chlorinated ethenes as trichloroethene (TCE) are among the worst groundwater pollutants. Remediation of these compounds from polluted soil and groundwater is a challenging task because of their complex spreading pattern in the subsurface. Thermally enhanced remediation technologies have proven effective at sites heavily contaminated with chlorinated ethenes, although these technologies are not always sufficient to decrease contaminant levels to reach clean-up goals. Chlorinated ethenes can also be biologically degraded and the use of bioaugmentation (injection of dechlorinating microorganisms and electron donors) has been suggested as a follow-up technology after thermal treatment.

The purpose of the project was to identify the potential for biodegradation after thermal treatment by use of laboratory microcosm experiments. This was evaluated by determining the effects of thermal treatment on (1) environmental conditions and survival of dechlorinating microorganisms, (2) the potential for bioaugmentation to enhance reductive dechlorination and (3) the applicability of the technologies, including optimal temperature conditions for bioaugmentation after thermal treatment. The focus of this work was reductive dechlorination of trichloroethene (TCE). The experimental work was related to Ft. Lewis, East Gate Disposal Yard (EGDY), WA, USA.

The project has demonstrated that reduced conditions can be obtained after full-scale electrical resistance heating (ERH) and that microorganisms present after heating were capable of dechlorinating TCE to cDCE. Upon bioaugmentation, dechlorination of TCE to ethene was observed in the majority of microcosms, including laboratory-heated and in-situ heated aquifer materials. This demonstrated a potential and need for bioaugmentation after ERH. The combination of thermal treatment and enhanced bioremediation can be applied either concomitantly or sequentially. The combination of thermal treatment and bioremediation can also be applied for aerobically degraded contaminants such as oils and BTEX. This combination has the advantage that microorganisms capable of degrading various hydrocarbons have been observed to survive thermal treatment.

## **PUMP-AND-TREAT REMEDIATION OF DISSOLVED CHLORINATED SOLVENT PLUMES AT THE BORDEN RESEARCH SITE, CANADA**

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Processes limiting pump-and-treat (P&T) remediation are investigated at the field scale through the extraction of dissolved trichloromethane (TCM), trichloroethene (TCE) and perchloroethene (PCE) plumes. The plumes formed over 475 d from a multicomponent dense nonaqueous-phase liquid (DNAPL) source intentionally emplaced in the Borden aquifer research site, Canada. Extraction wells were located to both provide source containment and along the plume-centreline to capture and remove the dissolved plumes. The detailed field data set was compared to 3-D HydroGeoSphere numerical-model simulations that assumed ideal transport (e.g. linear equilibrium sorption, aquifer homogeneity) to obtain, by difference, the influence of non-ideal processes. Field data were collected over 550 d of P&T and demonstrated remediation of the leading plume zone to low  $\mu\text{g/L}$  concentrations; concentration tailing over 4 orders of magnitude; a steady state plateau in the well containing the dissolving DNAPL; influences of extraction rate changes; and, tailing from slow flushing of inter-well stagnation-zones. The model effectively simulated the above observations suggesting ideal transport assumptions could generally represent the P&T undertaken including much of its observed tailing. Non-ideal sorption processes did subtly contribute to field-scale PCE tailing as modeled versus observed differences became more significant at late time. This was endorsed by supporting lab studies that indicated enhanced PCE sorption to low- and high-permeability strata and moderate nonlinear and competitive sorption influences.

## ENVIRONMENTAL CONTROLS ON MTBE DEGRADATION IN THE UK CHALK AQUIFER

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Ether oxygenate compounds are added to unleaded petroleum fuel to increase combustion and reduce atmospheric emissions. Methyl-tert-butyl-ether (MTBE) and tert-amyl-methyl-ether (TAME) are two ether oxygenates commonly found in UK petroleum fuels. MTBE and TAME can enter groundwater through accidental spillage of unleaded fuels containing these compounds. There is considerable interest in the fate of ether oxygenates in groundwater due to their uncertain biodegradation potential, although very little is known about their behaviour in UK aquifers. This presentation describes the results of a laboratory study which has assessed the potential for degradation of MTBE and TAME in the UK Chalk aquifer. The study is based on an unleaded fuel-contaminated site, where previous research has identified the broad controls on contaminant distribution and degradation processes for a plume of BTEX, MTBE and TAME in the aquifer. The laboratory study focused on deducing the contribution of different environmental factors (e.g. dissolved oxygen concentration, contaminant concentration, groundwater nutrient status, effect of co-contaminants and mixing between plume and uncontaminated groundwater) on the potential for MTBE and TAME degradation in microcosms which simulated conditions found in the contaminant plume and uncontaminated aquifer. Using aquifer materials and groundwater samples from the site, the study has quantified degradation rates for MTBE and TAME over a 15 month period under aerobic and anaerobic conditions. The results demonstrate that MTBE and TAME degradation depends on the availability of dissolved oxygen in groundwater and is influenced by the presence of co-contaminants in plumes. Stable carbon isotope analysis of MTBE-degrading aquifer microcosms has been used to confirm these relationships and the role of biological pathways in MTBE degradation in the laboratory experiments. The results of this work will be helpful for risk assessment and in developing management strategies for MTBE-contaminated sites on the Chalk aquifer, where monitored natural attenuation, bioremediation or engineered remediation are being considered.

## PHYTOREMEDIATION OF TRICHLOROETHENE

Dr. Ian F. Ross

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Trichloroethylene (TCE) is one of the most prevalent groundwater contaminants due to its use as a metal degreaser and dry cleaning agent. TCE is very stable in the environment having persisted in some aquifers for decades. It is known to be hepatotoxic and there is a growing body of evidence suggesting that it may be a carcinogen.

The use of bioremediation has been suggested as a more cost effective remediation solution in many aquifers. The microbial biodegradation of TCE can occur either anaerobically through dehalorespiration or aerobically through co-metabolic dehalogenation.

There has been a growing interest in phytoremediation for treatment of TCE contaminated aquifer. Poplars and cottonwoods are frequently proposed for phytoremediation applications mainly because they are phreatophytic plants, meaning that they can extend their roots to the water table and pump from the zone of saturation.

Arcadis Geraghty and Miller International Ltd (Arcadis GMI) have implemented a remedial strategy using over 140 polar trees to address impacts from TCE (and other chlorinated solvents). Characterisation of the geology of the site showed it to be underlain by mudstones, that in their uppermost sections are highly weathered and present as clays. A shallow perched groundwater body that is present at depths of approximately 1.5m below ground level.

Therefore, phytoremediation of this site was seen to be advantageous as the it should allow penetration of a root network into the relatively impermeable ground, thus promoting in situ biodegradation and phytoextraction of contaminants.

Whilst implementing this remedial approach it became clear that the mechanisms by which plants remediate TCE contaminated soils are not fully understood. Therefore, a research project managed by Arcadis Geraghty and Miller International Ltd (Arcadis GMI) has been established to attempt to elucidate the dominant mechanisms by which TCE is degraded in phytoremediation systems.

The aims of this project are to begin the unravelling of the contribution that plants and their associated rhizosphere communities make towards TCE degradation, using the innovative technique of stable isotope analysis. The fate and distribution of TCE within the plants will be investigated. The physiological, functional and genetic composition of the microbial community will also be characterised. Plant secondary metabolites will be utilised in an attempt to stimulate microbial transformation of TCE since aerobic dehalogenation is a cometabolic process that requires a primary substrate in order to induce the responsible monooxygenase enzymes.

## **AROMATIC HYDROCARBON INVASION INTO A CLAY INFLUENCED BY THE PRESENCE OF PALAEO-ROOT HOLES**

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### **Abstract**

The assumption that clay strata provide good protection of underlying aquifers is increasingly proving to be unfounded. The occurrence of micro-scale fractures and other heterogeneities are becoming recognised as potential preferential flowpaths within the low permeability deposits. Our research based at a former UK industrial facility contaminated with aromatic hydrocarbons aims to assess transport of dissolved-phase aromatic solutes within a discrete clay bed underlying the site. The exact transport processes vary spatially and are thought to be determined by the occurrence of palaeo-root holes which are sporadically present in the clay stratum. The clay stratum studied is a 1-2 m thick lacustrine clay of Holocene age at around 6 m below ground surface surrounded above and below by a shallow sandy aquifer.

Downward hydraulic gradients of 0.3-0.5 occur across the clay. Detailed depth profiles were determined from cores retrieved from thirteen locations, of which three principal hydrocarbon invasion profiles were identified; (i) diffusion-based invasion into fairly homogeneous clays; (ii) advection dominated invasion thought to be primarily through connected palaeo-root holes; (iii) reverse diffusion outwards from the clay stratum into the upper aquifer. Root connectivity has been demonstrated through serial sectioning of the advection dominated cores; the hydraulic conductivity of which have been measured up to  $2.4 \times 10^{-1}$  m/d. Connectivity in the diffusion based cores was not present and hydraulic conductivity values were approximately  $3 \times 10^{-5}$  m/d. Interpretation via 2D models (FRACTRAN) is also presented. Overall results to date suggest that where the clay deposits are homogeneous, slow diffusion dominated invasion will offer significant protection to lower aquifers. Conversely, where the clays contain root holes, rapid invasion via advection may dominate and complete penetration of the clay may be possible, especially where large hydraulic gradients exist. The evidence for reverse diffusion at this site may have some implications in producing an additional source zone, once remediation is perceived to be complete.

## **THE DIPOLE FLOW AND REACTIVE TRACER TEST AS A NOVEL AQUIFER ASSESSMENT TOOL**

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Monitored Natural Attenuation (MNA) of contaminated groundwater relies upon *in-situ* Natural Attenuation (NA) by biological, chemical and physical processes without the need for overly intrusive and often costly remediation strategies. NA is increasingly accepted as a cost-effective method to reduce contaminant concentration, mass or flux to a level which is deemed acceptable based upon the nature of the contaminant and the potential end use or receptors for the affected groundwater.

Over-cautious risk assessments have, tended to favour often more costly 'hard-engineering' remediation strategies, such as pumping with *ex-situ* treatment. If site investigation (SI), at the risk assessment stage, were able to provide sufficiently reliable information to characterise the geochemical and biodegradation properties of an aquifer, then MNA may be an increasingly widely used and cost effective remediation strategy, gaining greater acceptance from industry and regulators.

The Dipole Flow Reactive Tracer Test (DFRTT) offers a potentially cost effective method for reliable SI to quantify site-specific parameter values for reactive transport modelling that is used for performance assessment of NA. Developing the initial Dipole Flow Test (DFT) design of Kabala (1993) further, Sutton *et al.* (2000) describe the Dipole Flow Tracer Test (DFTT) as a single borehole technique utilizing inflatable packers to create two isolated chambers within the borehole. By use of a pump a forced gradient dipole flow field is created to circulate groundwater through the surrounding aquifer.

We have initially succeeded in demonstrating the application of the Dipole Flow Test in a fractured sandstone aquifer during field trials at the Site for Innovative Research on Natural Attenuation (SIReN) (Swannell *et al.*, 2001). Initial results confirm the ability of the DFT to characterise the hydraulic properties of the aquifer and demonstrate successful tracer injection and recovery in the sandstone formation. Additionally, the development and calibration of a numerical model as an integral part of the DFRTT has been able to replicate tracer Break Through Curves (BTCs) from field trials. Development of a sandbox scale aquifer

model is progressing to demonstrate the DFRTT under controlled laboratory conditions with focus to development of a suite of reactive tracers to for future field application.

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### **ARE PERMEABLE REACTIVE BARRIERS (PRBS) A VIABLE TECHNOLOGY FOR REMEDIATION OF DIFFUSE NITRATE POLLUTION?**

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There is an increasing realisation of the damage caused by intensive agriculture to soils and water. Release of nitrate from agricultural land has caused some water bodies in the U.K. to exceed the 50 mg l<sup>-1</sup> EU limit for drinking water which can contribute to eutrophication. The Environment Agency has designated that up to 55% of England can be classified as 'Nitrate Vulnerable Zones' with this predicted to rise in the future. With the implementation of the Water Framework Directive by 2015, it is vital that sources of diffuse pollution are addressed. Permeable reactive barriers (PRBs) have emerged as a tool for groundwater remediation in the last 10 years. Selected materials including zero-valent iron (ZVI), zeolites and granulated activated carbon (GAC) have been used as sorbents for a variety of organic and inorganic contaminants. To date, however, the application of this technology has been focused on case specific problems for the industrial sector. One possible reason why this has not been expanded to conventional agriculture is the scale of operation. However, low cost reactive barriers of readily available waste/natural materials, installed at field boundaries (targeting lateral flow following vertical drainage) could, potentially, provide an effective solution for groundwater pollution from nitrate.

Anaerobic denitrifying bacteria utilize nitrate as a terminal electron sink in waterlogged soils. Denitrification proceeds through intermediates including NO<sub>2</sub><sup>-</sup>, NO and N<sub>2</sub>O to give N<sub>2</sub>, with the production of intermediates largely controlled by pH, O<sub>2</sub> and carbon availability. The present challenge is that within the field environment, a reactive material, and subsequently, a barrier, must be able to respond rapidly to changing conditions such as fluid flows, redox and contaminants, whilst maintaining a high permeability. This study considers the use of combinations of waste/natural materials to remove nitrate from agricultural leachate under both aerobic and anaerobic conditions and to minimize/treat associated intermediate compounds. The study further intends to consider the problems associated with variable field conditions and how to minimise their impact on the permeability and efficiency of a PRB.

### **IMPACTS OF HIGHWAY RUNOFF ON GROUNDWATER QUALITY**

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## ABSTRACT

Approximately 50% of the highway run-off derived from the M25 situated in the Colne Valley, Hertfordshire (Junction 16 to 23) is discharged directly to the underlying unconfined Chalk aquifer. Despite little or no pre-treatment, approximately 20 years of discharge to groundwater has resulted in no detectable deterioration in the groundwater quality as monitored in observation boreholes sampled by the Environment Agency or down-hydraulic gradient public water supply pumping stations.

A qualitative methodology has been developed for assessing the relative sensitivity of an aquifer to contamination by the discharge of highway runoff to groundwater. The methodology has been applied to this section M25 and used to identify three sensitive sites in the vicinity of active soakaways. At each site a shallow observation borehole has been installed to below the water table and a more detailed investigation of processes active in the vicinity of active soakaways undertaken.

The water quality of highway runoff entering the aquifer has been measured by event sampling of water in the soakaways and water draining directly from the M25 surface at each study site. This is compared with groundwater quality measured at regular intervals in the observation boreholes and water quality data available for down-gradient public water supply pumping stations. The relative significance of attenuation processes within the unsaturated zone of the Chalk has been assessed and the probable fate of chemical constituents derived from the highway runoff identified. The observed attenuation in the unsaturated zone has been combined with dilution estimates for the saturated Chalk aquifer to assess the implication of highway runoff to groundwater quality in the Chalk aquifer and in particular down gradient public water supply pumping stations.

## PERFORMANCE PREDICTION AND VERIFICATION OF IN SITU REMEDIATION SYSTEMS

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Increasingly, in situ remediation technologies are being offered by service providers, driven by several factors including regulatory pressures, redevelopment of brownfield sites, increasing diversity in available technologies and escalation in costs of landfill disposal of contaminated soils. In situ technologies have demonstrated economic advantages over alternatives and can be implemented with relatively minimal disruption to host site operations.

However, in situ technologies suffer from performance uncertainties including (i) failure to meet remedial objectives in design timescales and (ii) post-closure “rebound” due to dissolution from adsorbed and residual-NAPL phases. The scope of site characterisation carried out in commercial implementation may not address adequately these performance uncertainties.

The research described herein is drawn from the international collaboration project “SABRE”, which comprises a field and laboratory demonstration of in situ enhanced bioremediation of a chlorinated solvent source zone. The site is characterised by a trichloroethene (TCE) source zone, which impacts a shallow sand and gravel aquifer.

Prior to start of SABRE, the research site had been subjected to site characterisation based on a scope and methodology typical of a commercial project. Detailed site characterisation, which has since been carried out, has identified a number of factors that may limit the performance of most in situ technologies. In particular, the aquifer comprises a heterogeneous layered deposit with intercalated silt and silty sand layers, the overlying

alluvium is more permeable than previously assumed and is in hydraulic continuity with the aquifer, and DNAPL has penetrated underlying mudstones.

Uncertainties in the performance of the technology are assessed based on simple modelling studies. Verification requirements of the project are evaluated based on an assessment of post-closure contaminant release from residual NAPL and non-NAPL sources. The findings are extrapolated to other remediation technologies and aquifer conditions. It is suggested that the required post-closure monitoring period may be longer than is generally assumed in commercial projects.

## **DYNAMIC EFFECTS IN TWO-PHASE FLOW BEHAVIOUR IN POROUS MEDIA: INCLUSION OF MICRO-HETEROGENEITY AND VISCOSITY EFFECTS**

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### **Abstract**

A correct description of multiphase flow behaviour is vital to quantify nonaqueous phase liquids (NAPLs) transport in the subsurface, design accurate soil remediation technique and make reliable prediction about their efficiency. This involves the determination of various fluid and porous media parameters and, the constitutive relationships among capillary pressure ( $p_c$ ), fluid phase saturation ( $S$ ) and relative permeability ( $k_r$ ). The determination of  $p_c$  relationships is particularly difficult because of two effects: (i) presence of micro-heterogeneities in the flow domain and (ii) dynamic effects in constitutive relationships.

The time period for obtaining the equilibrium curves ranges from many days to weeks depending on depends on soil (e.g., pore size distribution, micro-heterogeneities), fluid properties (density, viscosity, degree of saturation), scale of observation and boundary condition, etc. At shorter durations flow processes do not necessarily occur under static conditions and large saturation changes may occur. The relationships depend on the rate of change of fluid saturation,  $\frac{dS}{dt}$ , and his dependence is known as the dynamic effect. Hence, there is an increasing interest in characterizing the significance of dynamic effects in two-phase flow behaviour in porous media.

Micro-scale heterogeneities (fractures, layers, lenses) with their distinct multiphase flow properties may occur at length scales below those of typical laboratory measurement devices (core scale) and affect the constitutive relationship. Therefore, the empirical multiphase models are not sufficient to account for the physics of the flow under dynamic condition in a heterogeneous porous media.

We use an extended linear relationship proposed in the literature which, correlates  $p_c$  to the difference between the fluid phase pressures at dynamic condition,  $p_c^d$ , and the equilibrium capillary pressure,  $p_c^e$ . This relationship includes a capillary damping coefficient, called dynamic coefficient  $\beta$  which, establishes the speed at which flow equilibrium is reached. A series of quasi- static (equilibrium) and dynamic capillary pressure curves are obtained for homogeneous and heterogeneous porous media utilising numerical experiment and dynamic coefficient is calculated. Different viscosity values for NAPL were used to investigate fluid viscosity effect on dynamic coefficient.

For micro-heterogeneities of the type used in our study, we find that with the increase in the intensity of heterogeneity, dynamic coefficient increases. However, this dependence is not a linear function and depends on a complex interplay of various factors such as fluid viscosity. Values of dynamic coefficient obtained in this work are higher than most previously reported values, but this is likely considering both 3D and micro-heterogeneity effects.