

A NEW TECHNOLOGY FOR REMEDIATION OF CONTAMINATED SITES IN LOWLAND AREAS

Somasundaram Valliappan¹, Nasser Khalili² and R.K. Niven³

ABSTRACT: A new in situ remediation method, upflow washing, is described in which contaminants are removed by an upward fluidizing flow of water and/or gas produced by a jet inserted into a granular contaminated formation. Contaminant removal is achieved by the buoyant release of NAPL droplets and elutriation of finer particles. Experiments on contaminant removal by fluidization within a controlled column indicate significant reductions in diesel levels (95-99.9%) may be achieved by gas-liquid upflow washing (GLUW), for a wide range of initial diesel concentrations (10,000 to 150,000 mg/kg) and for soil fines contents of zero to 10%. In uniform sands, the water and gas velocities examined during GLUW have no significant bearing on diesel remediation efficiency, suggesting that water velocities may be reduced to a level at which the fluidized bed is largely gas-supported. Significant reductions in lead concentrations (59-88%) from soils containing 1,500-1,960 mg/kg precipitated lead may also be achieved by GLUW.

INTRODUCTION

Current remediation technologies for subsurface contamination include ex situ methods, which involve the excavation, treatment and disposal of contaminated soil, and in situ methods, in which contaminants are extracted and/or treated within their geological environment. Ex situ methods are relatively fast, well-established, and are used for most remediation projects worldwide. However, they suffer from rapidly rising costs due to increasing restrictions on landfill disposal, and involve the bulk handling of large quantities of contaminated soil, dramatically increasing the environmental, occupational health and safety risks. They are particularly inappropriate in lowland areas with high water table due to the large volume of contaminated water they create.

Present in situ remediation methods overcome, to a certain extent, some of the above problems. However, they suffer from a major drawback in that they rely on the mobility of a fluid (normally water or air) within a static or "fixed bed" medium. This limits their application to the extraction of soluble contaminants and light non-aqueous phase liquids (LNAPLs) from moderate to high hydraulic conductivity formations over long time frames (USEPA 1990). Indeed, it is well established that groundwater pumping often produces a porous medium containing isolated droplets or ganglia due to interfacial tension forces (Wilson & Conrad 1984; Travis & Doty 1990; Nyer 1995). Without altering the original soil medium, extraordinary physical, chemical or biological means will be necessary to extract or degrade such ganglia. Sparingly, soluble contaminants such as metals, often associated with finer particles, are also

¹ Professor, School of Civil and Environmental Engineering, University of New South Wales, Sydney, NSW 2052, AUSTRALIA.

² Associate Professor, Ditto.

³ School of Civil Engineering, Australian Defence Force Academy, Canberra, ACT, 2600, AUSTRALIA.

Note: Discussion on this paper is open until June 1, 2001.

largely trapped and difficult to remove. Such trapped contaminants do, however, gradually dissolve and disperse over decades or centuries, and so must be addressed during remediation.

Furthermore, most in situ remediation technologies introduce additional risks and unnecessary complexity to the remediation process, without attempting to overcome the limitations imposed by the porous media. Many methods, including bioremediation, air sparging, and new methods of surfactant flushing and electrokinetics, can produce clogging and diminution of flow rates long before remediation is complete (Allred & Brown 1994; Acar & Alshawabkeh 1993). Biological methods require thorough control over in situ temperatures, chemical and/or nutrient conditions, whilst treatment barrier methods are critically dependent on reaction rates. Methods which use or generate chemical reagents, such as surfactant and electrokinetics, involve the serious risk of additive and/or contaminant escape. Finally, no existing method is suitable for both metal and organic removal, leading to the use of conflicting treatments (USEPA 1990).

To overcome these problems a new *in situ* remediation method, upflow washing, has been developed at the School of Civil Engineering, UNSW, in which contaminants are removed by an upward fluidizing flow of water and/or gas produced by a jet inserted into a granular contaminated formation. Fluidization is effected by the application of liquid, referred to as liquid upflow washing (LUW), or by the concurrent application of gas and liquid, referred to as gas-liquid upflow washing (GLUW). In contrast to "fixed bed" methods (e.g. pump and treat), fluidization breaks up the soil skeleton, allowing the buoyant release of trapped LNAPL ganglia. Fluidization also produces elutriation, selective removal of finer particles, and therefore enables the removal of contaminants which are sorbed or attached to such fines, including organics and heavy metals. Upflow-washing will therefore result in the purging of contaminant-rich fines and free products to the soil surface, where they can be removed, treated and disposed of as appropriate. The technique is intended for sandy sites, and should be particularly effective in lowland areas where the ground water is at shallow depths.

The advantages of the proposed upflow washing technique over the existing in situ remediation methods are: i) the high turbulence of fluidized beds, particularly three-phase beds, allow the release of LNAPL ganglia trapped by interfacial tension forces. Once released, they are buoyant at any flow velocity, and will rise to the fluid surface, ii) the elutriation of finer particles from a fluidized bed enable the removal of sorbed or precipitated contaminants, controlled only by their distribution with particle size. By installation of an appropriate collection system, upwashed contaminants may be collected and removed at the soil surface, iii) a fluidized system, once established, will allow much greater flow throughput, eliminating the dependence upon in situ hydraulic conductivity, potentially reducing both the time and volume of fluid necessary for remediation. It is recognized that fluidization is only appropriate for silty to coarse sandy sediments (operational details will be discussed later). However, in the cases where it is applicable, upflow washing should be more effective than existing in situ methods for the remediation of both organic and metal contamination, with the potential for cost and time savings over existing methods.

This paper consists of several parts. Firstly, contaminant retention mechanisms in soil and relevant fluidization theory are outlined briefly. Observations and analyses of experiments on the hydraulics of in situ fluidization by a simple jetting system are presented, with correlations for fluidized zone geometry. The details of experiments on the liquid and gas-liquid upflow washing of diesel and metal contaminated soils are reported. The results are compared to those in which contaminated soils were subjected to "fixed bed" flushing under a vertical hydraulic gradient, to represent removal by groundwater and/or product recovery. Some aspects of in situ application of the technology are discussed.

BACKGROUND

Organic Solute and NAPL Retention in Soils

Non-aqueous phase liquids (NAPLs) may be retained in granular soils by two main mechanisms. The first involves the sorption of dissolved organic to soil minerals and organic matter, and the second, at higher contaminant loadings, involves the capillary trapping of NAPL droplets due to interfacial tension forces. Sorption arises from the so-called hydrophobic repulsion of organic molecules by water molecules, as well as partitioning and/or preferential attraction of organics onto soil minerals and organic matter (Karickhoff et al. 1979; Griffin & Roy 1985).

Establishment of an immiscible phase (NAPL) leads to the formation of isolated droplets or ganglia, trapped by interfacial tension forces (Wilson & Conrad 1984). Depending on the soil permeability, such ganglia may be difficult or impossible to remove by hydraulic loading alone (Wilson & Conrad 1984; Nyer et al. 1996). Ganglia, however, slowly dissolve over decades or centuries, posing a health risk for downgradient groundwater users. In fine to medium sands, residual saturations of 2-10% NAPL in the vadose zone and up to 20% beneath the water table have been reported (Wilson & Conrad 1984; Fetter 1993).

Except in organic-rich soils, the maximum sorbed concentration of medium-chain hydrocarbons will be several orders of magnitude lower than that retained by capillary forces, and regulatory limits.

Retention of Metals in Soils

Metal contamination and the retention of metals by soils may occur by contact with metal-bearing solutions and/or discrete metallic particles (and in a few cases by metal vapours or liquid metal). Depending on subsurface conditions, contaminating solutions can lead to the sorption and/or precipitation of metals onto various mineral surfaces. It is important to recognise that sorption and precipitation are highly interrelated processes, especially in the presence of soil minerals, such that the two must be considered a spectrum of processes (Stumm 1992; Appelo & Postma 1993). Sorption is a necessary precursor to crystal nucleation, and soil mineral surfaces catalyse nucleation by lowering the activation energy barrier (Stumm 1992; Fetter 1993). Metals may be incorporated into other precipitants by sorption and entrapment within the growing solid (Stumm 1992). In contrast to sorption/precipitation, contaminating solids (eg, atmospheric particulate fallout or paint flakes) lead to direct metallic solid contamination of the soil. If such solids partially dissolve and become active within the soil, they can lead to "secondary" sorption and/or precipitation processes.

CONTAMINANT REMOVAL BY FLUIDIZATION

To examine the efficiency of liquid upflow washing (LUW) and gas-liquid upflow washing (GLUW) for contaminant removal a series of experiments was conducted on fluidization of diesel and lead contaminated sands within a fluidization column. The aims of the experiments were: i) to investigate and observe the mechanics of both immiscible organic and precipitated heavy metal removal from soils by fluidization under controlled conditions; ii) to compare the contaminant removals achieved in the above experiments to those from experiments representative of *in situ* groundwater and/or product recovery systems ("pump-and-treat"); and iii) to determine the factors controlling contaminant removal, including the effect of soil composition, water and gas flow rates, and total flushed volume or time.

Diesel Experiments

Experiments were conducted in a 77 mm ID cylindrical glass column with a detachable base, shown in Fig. 1. A 200 μm stainless steel mesh and perforated teflon disk at the column base functioned as a soil support. Water was pumped by peristaltic pump, and N_2 supplied at 200 kPa by gas cylinder. Flow rates were measured by rotameter. More experimental details are given in Niven and Khalili (1998a).

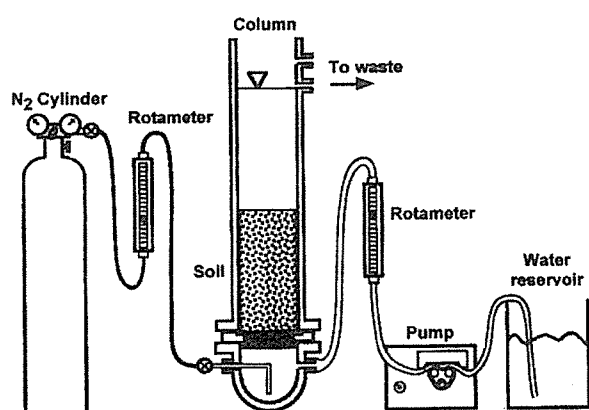


Fig. 1 Experimental column apparatus

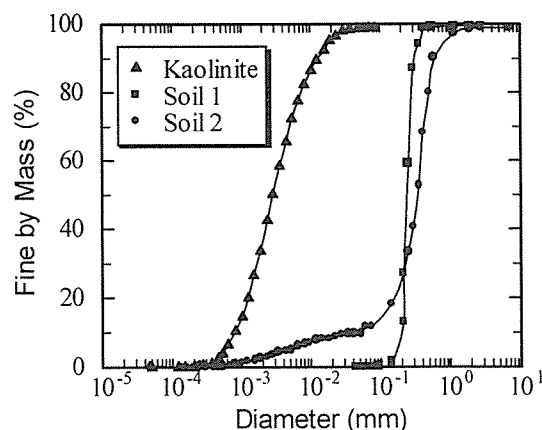


Fig. 2 Soil grain size distributions

Two soils were used for the diesel experiments: a uniform, low organic matter quartz sand (Soil 1), and a brown silty quartz sand (Soil 2). In several experiments, clayey sands were prepared from mixing various proportions of white kaolin clay with Soil 1. Several soil properties are given in Table 1, and particle size distributions in Fig. 2. Diesel concentrations were in the range $\sim 10,000$ to $150,000$ mg/kg, and hence the soils were in the moderate to highly contaminated range compared to typical cleanup thresholds of 1,000 and 5,000 mg/kg.

In each experiment 1 kg of sand was mixed with diesel, immediately before the experiment. The diesel added was determined by weight. The contaminated soil was then added to the column, saturated, and one of the following flow regimes applied: (i) fixed bed flushing (FBF), in which a constant head (500-650 mm height) was maintained above the bed, creating a downward flow regime through the soil; (ii) liquid upflow washing (LUW), in which water was pumped upwards at a fluidizing velocity; or (iii) gas-liquid upflow washing (GLUW), in which both nitrogen and water were supplied to the base so as to fluidise the soil in toto. A pulsed method (LUW/GLUW) was used in some experiments, and the effects of bed height, diesel aging and soil prewetting were also studied separately (Niven and Khalili 1998; Niven 1998). At the end of each experiment, any floating product and water above the soil was removed, and the soil collected on a plastic sheet, homogenized and sampled.

In most experiments the samples were analyzed for Total Petroleum Hydrocarbons by 1,1,2-freon extraction and infrared absorption (IR) spectrometry. The instrument was calibrated against diesel rather than the normal analytical reference. In later experiments, the worldwide ban on freons necessitated analysis by gas chromatography (GC), results of which were converted to "diesel concentrations" by a calibration curve (Niven 1998). For each experiment the diesel removal efficiency was determined. Several samples were also analyzed for TPH by gas chromatography (GC) using the fingerprint method. A quality assurance / quality control program was conducted involving reference, duplicate and blank sample analyses, indicating acceptable accuracy and precision (Niven 1998).

Table 1 Column experimental flow conditions (Niven and Khalili 1998a; Niven 1998)

Experiment	Figures	Soil	Flow regime	Water velocity (m/s)	Gas velocity (m/s)	Water Vol. ^a (PV)
Diesel	Figs. 3a, b & Fig. 4	Soil 1	FBF	Variable	-	60 ± 10
			LUW	2.6e-3	-	70
			GLUW	2.5e-3	0.031	70
			LUW/GLUW (3 min/4 min)	2.5e-3	0.031	57 ± 7
	Figs. 5a, b	Soil 2	FBF	8.3E-5 to 1.8e-4	-	124 ± 4
			LUW GLUW	1.6e-3 1.6e-3	- 0.031	123 119 ± 8
Lead and Lead + Diesel	Figs. 7a, b & Fig. 8	Prep 9	FBF	7.5e-4	-	86
			LUW	1.5e-3	-	85
			GLUW LUW/GLUW	1.6e-3 1.6e-3	0.031 0.031	91 210
		Prep 10	FBF	9e-4	-	139
			LUW/GLUW	1.6e-3 LUW 2e-4 GLUW	0.031	123

FBF = fixed bed flushing; LUW = liquid upflow washing; GLUW = gas-liquid upflow washing; LUW/GLUW = cyclic liquid/gas-liquid upflow washing; PV = pore volumes. ^a = bar graphs only.

Experiments were conducted to determine the effect of soil type, diesel concentration, flushing duration and water and gas flow rates on diesel removal (Niven and Khalili 1998a; Niven 1998). Several experimental variables are included in Table 1; for more details, readers are referred to the original literature. As the water flow velocities used for LUW and GLUW were in most cases higher than those for FBF (the latter being controlled by hydraulic conductivity), the results could not be compared directly on the basis of flushing time. For this reason, to allow unbiased comparisons between experiments, many of the experimental series were conducted using a constant flushed water volume. The effect of flushed volume (or time) was also studied. For the water and gas flow rate experiments, water flow rates were selected both above and below the minimum fluidization velocity for a two-phase system (Niven and Khalili 1998b), to determine the efficiencies of predominantly gas-supported as well as liquid-supported fluidized beds.

Lead Experiments

Comparative upflow washing and fixed bed flushing experiments were conducted on lead contaminated soils in a similar manner to the diesel experiments, using the same apparatus (Fig. 1; Khalili & Niven 1996; Niven 1998). Two batches of soil were used (Preps 9 and 10), each a 1% mixture of kaolinite in Soil 1 sand, contaminated in the laboratory with 1960 and 1,560 mg/kg lead respectively. Soil preparation involved the precipitation of Pb (II) hydroxide in the presence of the soil, and flushing of the soil with distilled water until a low electrical conductivity was reached.

Flow rates during both LUW and GLUW are given in Table 1. In all but one case, water velocities were above the minimum fluidization velocity of the soil (Niven and Khalili 1998b); however for one GLUW experiment a low water velocity was used. For each experiment, effluent water samples were collected and analysed for suspended solids using a turbidity meter; the results were correlated with suspended solids concentrations as described in Niven & Khalili (1996b). Initial and final lead levels in the bulk soils were determined by acid digestion and atomic absorption spectroscopy (AAS). To determine the effect of Pb

distribution with particle size, the original and residual soils from several experiments were wet sieved, and each sieve fraction analysed for Pb. The <45 μm solids from the sieve wash waters were also analysed.

Lead and Diesel Experiments

Two experiments were conducted in which lead-contaminated soil (Prep 10) was then contaminated with 20,000 mg/kg diesel. Samples of this soil were subjected to each of the flow regimes, using the method described. Flow conditions were the same as for Prep 10 experiments above. Samples were collected and analyzed for diesel and lead by the above methods.

EXPERIMENTAL RESULTS

Diesel Experiments

Results of experiments on soil 1 are shown in Figs. 3a and 3b. Application of GLUW was much more effective for diesel removal (97-99.6% of diesel removed by mass) than either LUW (average 12-34%) or FBF (average 27-84%) for the flow rates used. The removal with pumped volume data indicate that FBF plateaus off at a high diesel concentration, whilst diesel levels in GLUW systems rapidly fall to low levels within the first 5-10 pore volumes (PV). The LUW system was intermediate between these extremes, with an initial rapid diesel removal, followed by a more gradual trend towards the level achieved by GLUW. The LUW results exhibited a high degree of scatter. This appeared to be related to the formation of diesel droplet-sand grain associations, and their segregation to the upper surface (but not out) of the bed. There was no significant difference between the GLUW and LUW/GLUW systems at the flow rates used.

The effect of added clay to Soil 1 is shown in Fig. 4. GLUW achieved the highest diesel removals (97-99.1%) from both clayey and clay-free sands. LUW was much more successful in the presence of clay (87-88%) than in its absence (average 34%), whilst fixed bed flushing was relatively unaffected (19-46%). The increase in clay content from 5 to 10% did not seem to affect diesel removal efficiencies.

Results of the experiments on Soil 2 are shown in Figs. 5a and 5b. Both GLUW and LUW were highly effective for diesel removal (99.5-99.8% and 98-99.3% respectively) compared to FBF (14-89%), for a similar throughput of water. GLUW produced final diesel levels of 58-235 mg/kg. Note the removal efficiencies were much greater than in Soil 1. In these experiments an opaque, dark brown effluent was observed during LUW and GLUW, and final up-washed soils were yellow-brown. In the FBF system, little turbidity was produced, and the final soil remained dark brown.

The variation of diesel removal efficiency with water and gas flow rate, for Soil 1 containing 20,000 mg/kg diesel, are illustrated in the 3D plot in Fig. 6. Here the final diesel levels obtained by GLUW exhibited no real dependence on either gas or liquid flow velocity. In contrast, results for LUW are much higher, indicating that the presence of the gas is important for contaminant removal. The results indicate that the water velocity during GLUW may be reduced to or below the minimum fluidisation velocity, producing a largely gas-supported fluidized bed, without impairing contaminant removal performance. This conclusion is quite significant, as it may enable dramatic reductions in the quantity of water used (and therefore requiring treatment) during remediation.

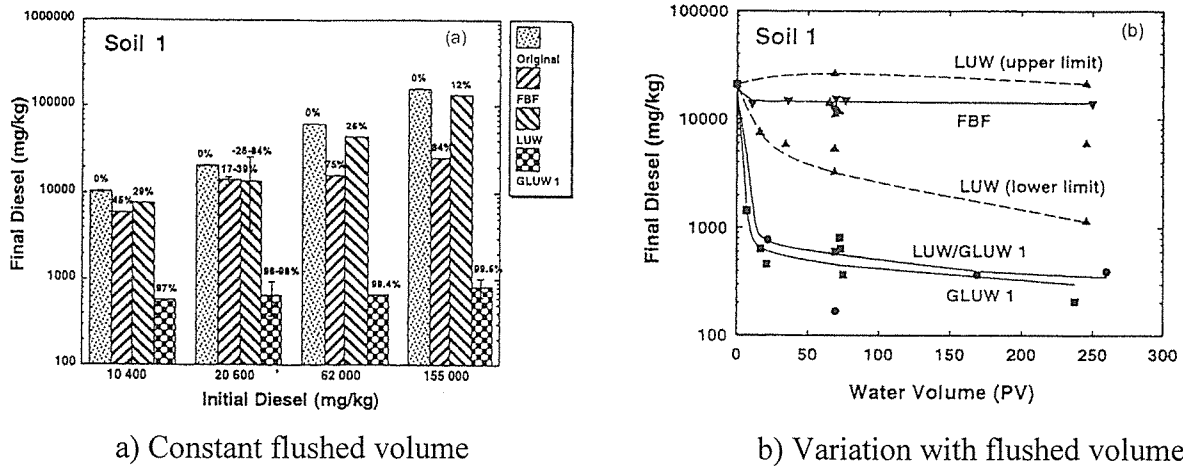


Fig. 3 Diesel removal results in Soil 1

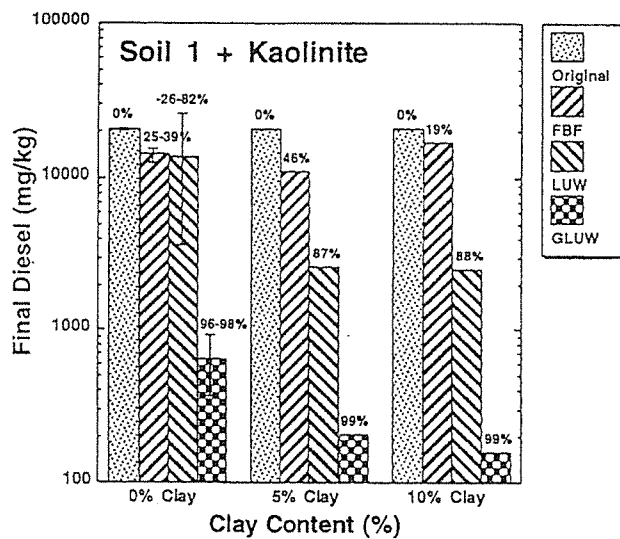


Fig. 4 Diesel removal results from Soil 1 (the effect of added clay)

Mechanisms of diesel removal from the uniform and clayey sands are examined in Niven and Khalili (1998a) and Niven et al. (2000a and b). Diesel removal occurs predominantly by the release of immiscible liquid droplets and in clayey sands, by elutriation of fines coated with or somehow associated with diesel. Monitoring by Dräger tubes indicate that diesel removal by volatilisation is non-detectable ($<10 \text{ mg/m}^3$). Measured aqueous diesel solubilities indicate that diesel removal by dissolution is also a minor process.

It is therefore apparent that in both uniform and clayey sands, GLUW results in significant reductions in diesel concentrations in soils, to levels well below target clean up limits used in practice. LUW is less effective, particularly in the absence of fines, whilst fixed bed treatment is largely unsuccessful for the flow throughputs studied. Both LUW and GLUW become more effective when fines are present in the soil. For uniform sands, the water and gas velocities examined during GLUW have no significant bearing on remediation efficiency. Diesel removal occurs mainly by immiscible droplet release and the elutriation of diesel-associated fines.

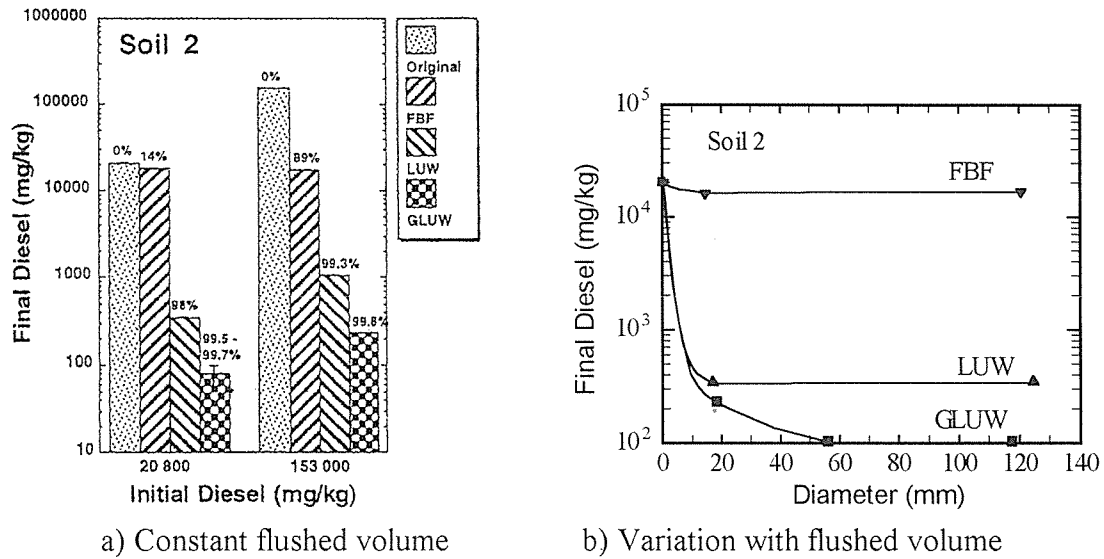


Fig. 5 Diesel removal results of Soil 2

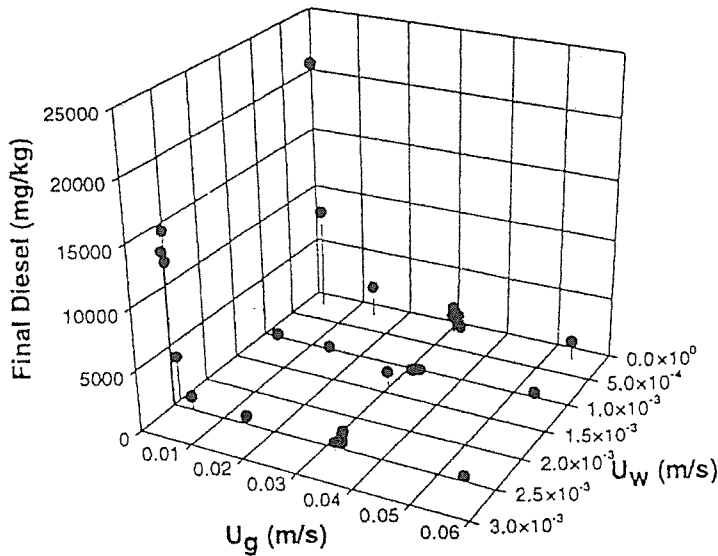


Fig. 6 Effect of gas and water velocities during GLUW

Lead Experiments

Results of the upflow washing experiments on lead soils are shown in Fig. 7a. As for the diesel experiments, GLUW was much more effective for lead removal (59-88%) than fixed bed flushing (13-14%). Again LUW was less efficient than GLUW. For both soils, very little lead was removable by fixed bed flushing. Here the cyclic LUW/GLUW system performed marginally better than GLUW alone.

The results of sieve analysis and lead fraction analysis for the original Prep 9 soil, and its FBF and GLUW-treated residual soils, are shown in Fig. 7b. They indicate that in the original soil, Pb was highly concentrated in the clay component, but that appreciable levels of lead were present throughout all sand fractions. The resulting Pb distribution after FBF is similar to the original. In contrast, GLUW causes near-total elutriation of highly contaminated fines from the system, leaving a residual soil in which the lead concentration reflects the sand-bound component. By examination of Fig. 7b, it appears that some decrease in the sand-bound lead

also occurred during GLUW. Whilst this may be an artefact of the sieve analysis process, it may also indicate that particle attrition occurs during upflow washing. All upflow washing systems resulted in rapid elutriation of fines, attaining a maximum level of removal (8-13 g) in the first 20-30 minutes. In contrast, elutriated solids levels in the FBF experiment were not significantly different from deionised water. The LUW system was not nearly as effective as the GLUW systems for solids removal; and of the latter, the pulsed system was somewhat more effective. Thus in all cases the degree of elutriation corresponds with the relative efficiency of the method for Pb removal.

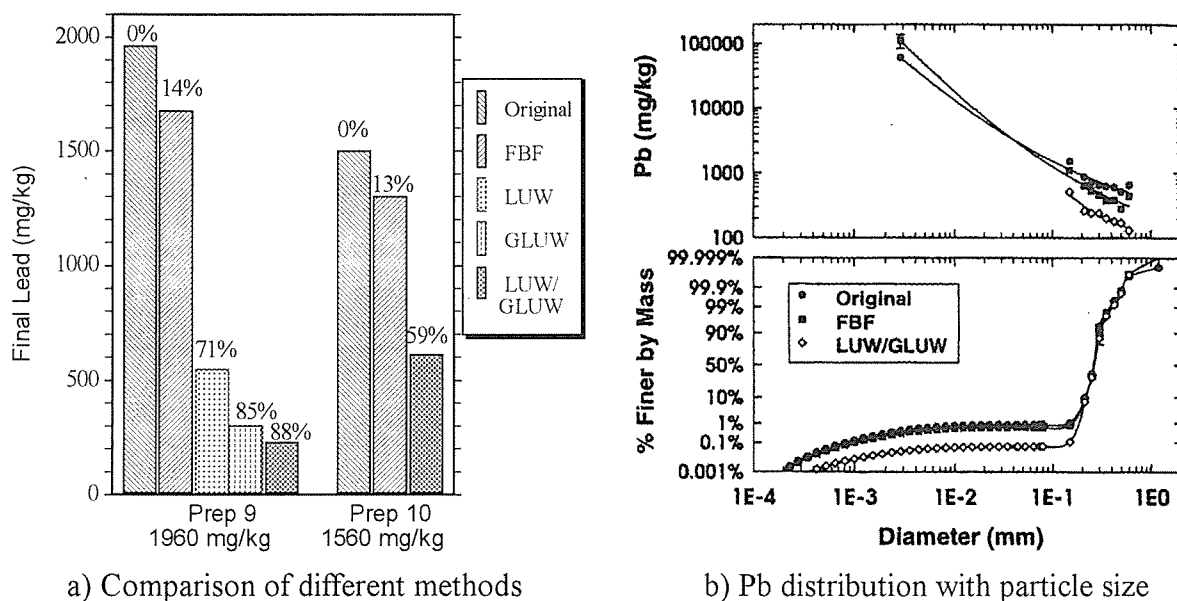


Fig. 7 Lead removal results

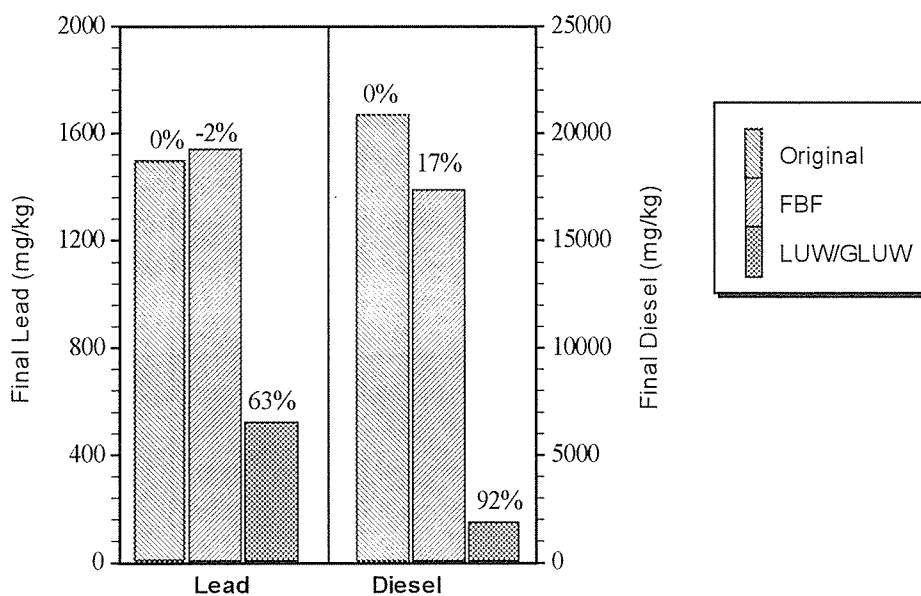


Fig. 8 Lead and diesel removal results washing of lead soil.

Thus, in slightly clayey sands containing in situ precipitated metal, metal removal is achieved by the elutriation of fines during fluidization. The GLUW systems are thus more effective than LUW for metal removal, owing to their greater degree and rate of elutriation. As soluble metal levels were quite low, fixed bed treatment was much less successful in the soils

examined. Water velocity appears to be more important in this system than for the diesel experiments, whilst for the gas velocities examined, some increase in removal rate (but not degree of removal) is experienced with increasing gas flow rate. Sieve analysis results suggest some degree of attrition during GLUW. Final metal levels depend upon the initial distribution of metal with particle size in the original soil.

Lead and Diesel Experiments

Results of experiments on both lead and diesel contaminated soils are shown in Fig. 8. The results indicate that lead removal was inhibited in the presence of diesel during FBF. Apart from this, the removal of both contaminants together by upflow washing was similar to that achievable for each contaminant individually.

IN SITU ACCOMPLISHMENT OF FLUIDISATION

An important aspect in the application of the proposed remediation technology is the in situ accomplishment of a fluidised zone. It is evident that in situ fluidisation could not be achieved by installing a jetting system below a given depth, and applying pressure from the tip. Indeed, beyond a certain depth this will only lead to hydraulic fracturing of the surrounding soil, which may not be desirable. However, by applying the jetting system at the ground surface, it would be possible to initiate a small fluidised zone, which then can be expanded downwards by gradual lowering of the jet. The overlying fluidised zone will form a preferential flow pathway for the injected water, and can be maintained fluidised as long as sufficient flow is applied.

Comprehensive investigations have been conducted on this concept, in which different "clean" soils have been placed into a small tank and subjected to a water jet from a hollow glass tube (Niven & Khalili 1998b). It has been shown possible to generate an in situ fluidised bed by directing a water jet onto the soil surface, and gradually lowering the jet into the fluidised zone formed. For each of the soils used, the result was the formation of a truncated conical fluidised zone, surrounded by undisturbed soil, with a mobile but relatively clear interface between the two regions. The half-cone angle was 75° in a uniform medium-grained quartz sand. This half-cone angle did not change with increasing water velocity, or with positioning of the jet in the centre or along the walls of the tank.

Water flow required for the process may be supplied by commercially available single or multistage centrifugal pumps, whilst gas may be supplied by an air compressor. Upwashed contaminants can be contained within a ring or other device surrounding the jet at the surface, and pumped or overflowed into wastewater storage tanks and/or an on-site treatment facility. Depending on contaminant type, an appropriate method of treatment might be to induce fluidization using a relatively high water flow rate; then charge the system with gas, producing a gas-liquid-solid fluidized bed, and thus enabling the water velocity to be reduced; and then to increase the water flow rate again at the end, to flush the treated zone. Treatment of an entire site may be effected by repeated treatments or lateral migration of the fluidized zone.

Several field trials have been conducted within uncontaminated, sandy deposits on the banks of Botany Bay, Sydney, NSW, using systems similar to those described above (Khalili & Niven 1996b). The sand in the trial area was approximately 300 μm diameter, with a "dirty" appearance, indicating the presence of silt and/or clay fines. Thin layers of peat were also present in the sequence. In one trial, a centrifugal pump operating at 12.5 l/s with 75 mm tubing was used to create several in situ fluidized zones of up to 0.9 m diameter and 0.6 m deep. In a

second trial, a pump operating at 3-6 l/min attached to 50 mm diameter tubing was used to generate fluidized zones 2.1 m deep and about one metre in diameter. In both trials, the point of interest was the observed upwashing of dark, grey-black suspended matter, evidently peaty material, as well as broken shell fragments to 50 mm diameter, indicating the rupture of peat and shell seams in the sequence. The dimensions of the fluidized zones accorded with the correlation equations are presented in Niven and Khalili (1998b).

CONCLUSIONS

A new in situ remediation method, upflow washing, has been developed in which contaminants are removed by an upwards fluidizing flow of water and/or gas produced by a jet inserted into a granular contaminated formation (Khalili & Niven 1996; Niven & Khalili 1998a and b). Contaminant removal is effected by the buoyant release of NAPL droplets and, in systems containing fines, the elutriation of these fines from the system. The method is therefore suited to both organic and metal removal.

Experiments on LNAPL (diesel) removal by fluidization within a column environment indicate that GLUW results in significant reductions in soil diesel levels (97-99.9%), for initial diesel concentrations in the range 10,000 to 150,000 mg/kg, and for clay or silt fines contents of zero to 10%. Diesel removal occurs mainly by immiscible droplet release and the elutriation of diesel-associated fines, while volatilisation and dissolution are minor processes. Final diesel levels after GLUW are generally in the range 200-1,500 mg/kg in uniform sands and <250 mg/kg in sands containing fines. LUW and fixed bed flushing are somewhat to much less effective. Both LUW and GLUW become more effective when fines are present in the soil. In uniform sands, the water and gas velocities examined during GLUW have no significant bearing on remediation efficiency, suggesting that water velocities may be reduced to a level at which the fluidized bed is largely gas-supported, and that water usage may be minimised. The removal efficiencies of diesel by in situ jetting experiments within small tanks are very similar to those obtained in the column experiments.

Experiments on precipitated metal removal by fluidization within a column environment demonstrate metal removal to be achievable by the elutriation of fines during fluidization. GLUW resulted in significant reductions in Pb levels (59-88%) compared to LUW (17%) from soils containing 1,500-1,960 mg/kg lead. The effectiveness of GLUW systems was directly related to their higher degree and rate of elutriation. As soluble metal levels were quite low, fixed bed treatment was much less successful. Initial elutriation rate constants exhibited an increasing trend with gas velocity, and sieve analysis results suggested some degree of attrition occurred during GLUW. Contaminant removal from diesel and Pb contaminated soils indicated that upflow washing resulted in similar efficiencies to those obtained for each contaminant individually.

In several field trials at uncontaminated sites, it has been found possible to generate fluidized zones, of similar geometry to that predicted.

REFERENCES

- Acar, Y.B. & Alshwabkeh, A.N. (1993). Principles of electrokinetic remediation, *Environmental Science and Technology*, 27(13): 2638-2647.
- Allred, B. & Brown, G.O. (1994), Surfactant-induced reductions in soil hydraulic conductivity, *Ground Water Monitoring and Remediation*, Spring: 174-184.

- Appelo, C.A.J. and Postma, D. (1993). *Geochemistry, Groundwater and Pollution*, A.A. Balkema, Rotterdam, Brookfield: 536.
- Fetter, C.W. (1992). *Contaminant Hydrogeology*, Macmillan Publishing Co., New York, 458p.
- Grace, J.R. & Wairegi, T. (1986). Properties and characteristics of drops and bubbles, *in* Cheremisinoff, N.P. (ed), "Encyclopedia of Fluid Mechanics, Volume 3, Gas-Liquid Flows", Gulf Publishing Co., Houston, pp. 43-57.
- Griffin, R.A. and W.R. Roy (1985). *Interaction of Organic Solvents with Saturated Soil-Water Systems*, Environmental Institute for Waste Management Studies, University of Alabama, Open-File Report No.3: 86p.
- Karickhoff, S.W., Brown, D.S. and Scott, T.A. (1979). Sorption of hydrophobic pollutants on natural sediments, *Water Research*, 13: 241-248.
- Khalili, N. and Niven, R. (1996). Upflow washing: a new in situ technology for organic and metal remediation, 3rd International Symposium on Environmental Geotechnology, June 10-12 1996, San Diego, CA, USA.
- Niven, R.K. (1999). PhD Thesis, University of New South Wales, Sydney, Australia.
- Niven R.K. & Khalili, N., (1998a), In situ gas-liquid-solid fluidisation for the remediation of hydrocarbon contaminated sands", *Canadian Geotechnical Journal*, 35(6): 938-960.
- Niven, R.K. & Khalili, N. (1998b), In situ fluidisation by a single internal vertical jet, *Journal of Hydraulic Research*, 36(2): 19-229.
- Nyer, E.K. (1995), Life cycle design for in situ remediations, *Ground Water Monitoring and Remediation*, Spring, 90-93.
- Nyer, E.K., Fam, S., Kidd, D.F., Johns, F.J., II, Palmer, P.L., Boettcher, G., Crossman, T.L., Suthersan, S.S. (1996). *In Situ Treatment Technology*, Lewis Publishers, CRC Press, Inc., Boca Raton, Florida, 329p.
- Stumm, W. (1992). *Chemistry of the Solid-Water Interface*, John Wiley & Sons, New York.
- Travis, C.C. & C.B. Doty (1990). Can contaminated aquifers at Superfund sites be remediated, *Environmental Science and Technology*, 24(10): 1464-1466.
- USEPA (1990). *Subsurface Contamination Reference Guide*, Office of Remedial Response, U.S. Environmental Protection Agency, Washington DC, USA, EPA/540/2-90/011.
- Westrich, B. & Kobus, H. (1973), Erosion of a uniform sand bed by continuous and pulsating jets, *Proc. Int. Association for Hydraulic Research Congress*, Vol.1, Istanbul, A13: 1-3.
- Wilson, J.L. and S.H. Conrad (1984). Is physical displacement of residual hydrocarbons a realistic possibility in aquifer restoration? *Proc. Conf. Petroleum Hydrocarbons and Organic Chemicals in Ground Water*, Houston, Oct. 1984, Dublin OH: 274-297.