CONF-950868--20

LBL-37554
UC-400

Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

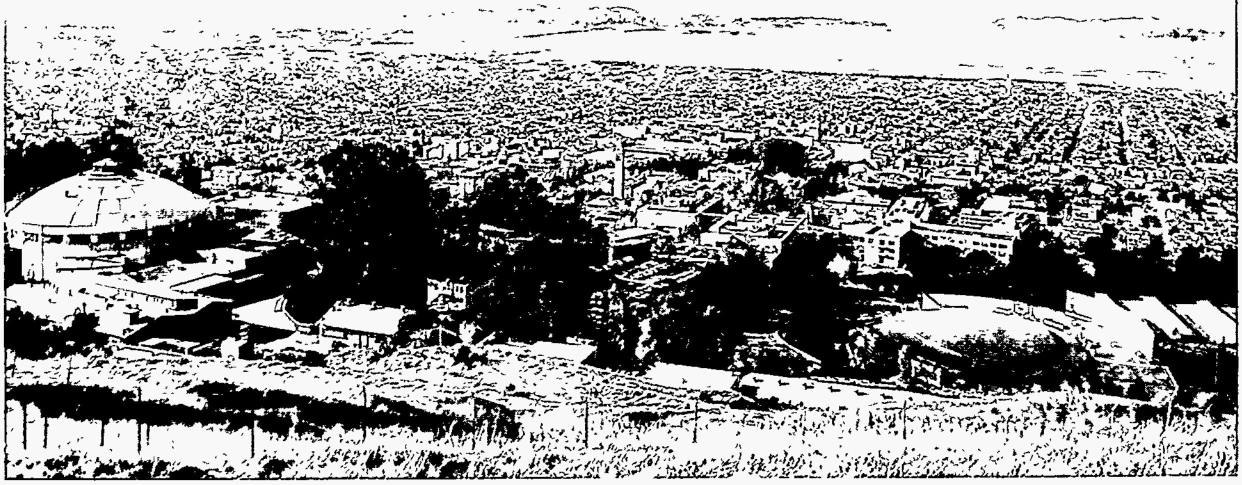
EARTH SCIENCES DIVISION

Presented at the ER(Environmental Remediation) '95 Conference, Committed to Results: Barriers for Long-Term Isolation, Denver, CO, August 13–18, 1995, and to be published in the Proceedings

A Field Test of Permeation Grouting in Heterogeneous Soils Using A New Generation of Barrier Liquids

G.J. Moridis, P. Persoff, J.A. Apps, L. Myer, K. Pruess, and P. Yen

August 1995



Prepared for the U.S. Department of Energy under Contract Number DE-AC03-76SF00098

LBL-37554

A FIELD TEST OF PERMEATION GROUTING IN HETEROGENEOUS SOILS USING A NEW GENERATION OF BARRIER LIQUIDS

G.J. Moridis, P. Persoff, J.A. Apps, L. Myer, and K. Pruess

Earth Sciences Division
Lawrence Berkeley National Laboratory
University of California
Berkeley, CA 94720

and

P. Yen

Bechtel Corporation
San Francisco, CA 94720

August 1995

This work was supported by U.S. Department of Energy, Office of Environmental Management, Office of Technology Development, under Contract No. DE-AC03-76SF00098.

ABSTRACT

A field demonstration of permeation grouting was conducted at a gravel quarry near Los Baños, California, with the purpose of demonstrating the feasibility of the concept. Two grouts were used: a form of colloidal silica that gels after the addition of a gelling agent, and a polysiloxane that polymerizes after the addition of a catalyst. Both create relatively impermeable barriers in response to the large increase in viscosity during gelation or polymerization, respectively. The grouts were successfully injected at a depth between 10 and 14 *ft*. Subsequent exhumation of the injected gravels revealed that both grouts produced relatively uniform bulbs. Laboratory measurements of the grouted material retrieved from the field showed at least a four order of magnitude reduction in permeability over the ungrouted material.

CONTENTS

Section **Page**

FIGURES

Figure **Page**

TABLES

Table **Page**

INTRODUCTION

The development of *in situ* contaminant containment technologies is necessitated by (a) the need to control and/or suppress the release of contaminants from buried sources, (b) the need to prevent the spread of existing plumes, and (c) the difficulty and cost associated with the recovery of contaminants from the subsurface by conventional means. The activities described in this paper advance the technology of permeation grouting, which will ultimately lead to powerful and more economical containment methods with broad applicability to a large variety of sites and a diversity of contaminant problems.

APPROACH

The basis for permeation grouting is to inject low viscosity liquids into the subsurface to produce impermeable barriers through a chemically or physically induced substantial increase in viscosity. Through appropriate emplacement of these liquids, a contaminated zone can be contained by entrapping and immobilizing both the contaminant source and the plume. The application of two general types of barrier fluids are described in this paper (1,2,3). The first is Colloidal Silica (CS), which consists of an aqueous suspension of silica micro spheres in a stabilizing electrolyte. It has excellent durability characteristics, poses no health hazard, is practically unaffected by filtration, and is chemically and biologically benign. The increase in viscosity of the CS following injection is due to a controlled gelation process induced by the presence of either a neutralizing agent or a concentrated salt solution, which are added immediately prior to injection at ambient temperatures. The CS has a tendency to interact with the geologic medium, and therefore, special formulations or techniques are required to minimize or eliminate the impact of such interactions.

The second type of barrier fluid is an organic liquid belonging to the PolySiloXane (PSX) family, chemically and biologically inert silicon-based chain polymers. PSX increases in viscosity through a vulcanization-like process in which a catalyst induced cross-linkage of the polymer chains causes the formation a high viscosity elastic product. The cross-linking process is controlled by the quantities of the catalyst, cross linker, and (occasionally) retardant added to the PSX prior to injection. PSXs are largely unaffected by aquifer or waste chemistry.

Permeation grouting technology can be applied in three ways. The first, conditions permitting, results in permanent immobilization of the contaminants in the affected aquifer region by sealing and entombing them in a "monolith" of grout. In the second option, an impermeable container is created to surround and isolate the contaminated region for treatment at a later time. Finally, the third option allows sealing of permeable aquifer zones, thus confining the effects of traditional cleanup techniques (such as pump and treat) to less permeable zones.

Substantial preparatory work was conducted to ensure the success of permeation grouting technology in the field. The work included identification and characterization of promising materials, evaluation of their containment potential by means of laboratory and pilot-scale experiments, and the development of appropriate numerical simulators. Many institutional issues involving interactions with regulatory agencies and industry partners also required resolution.

Lawrence Berkeley National Laboratory (LBNL) staff completed a wide search for fluids with desired properties and identified CS and PSX as promising candidates. The rheological and wettability properties of these barrier fluids were measured. Laboratory studies of barrier fluid flow and emplacement in porous media were conducted, and it was determined that both CS and PSX are effective in sealing porous media. Alternative processes were developed to alleviate possible effects of the soil chemistry on the CS gel times, and ways to control the gel time and the texture of the gels were identified. Protocols for the sequential injection of CS were established, and it was demonstrated that hydraulic conductivities could be reduced to less than 10^{-8} *cm/s* after two injections. Processes to control the viscosity and gel time of PSX were also identified. PSX cross linkage times are far less sensitive to the soil chemistry than CS gelation. Furthermore, hydraulic conductivities could be reduced to 10^{-10} *cm/s* after a single injection.

In collaboration with the manufacturers, new CS and PSX formulations were developed to meet barrier fluid requirements, (the CS formulation selected being unaffected by the soil chemistry, and the new PSX formulation having an initial viscosity low enough to allow injection using existing equipment). A series of laboratory tests were conducted to investigate the barrier performance of the selected CS and PSX formulations at all length scales of interest: from sub-millimeter (pore micro models) to one-dimensional experiments (column studies) to two-dimensional studies (ranging from 1 *ft* x 1 *ft* x 1 *ft* to 7 *ft* x 6 *ft* x 0.5 *ft*). Preliminary waste compatibility tests were conducted, and it was concluded that both CS and PSX are not significantly affected by a wide range of wastes contained in the buried tanks at Hanford.

The general-purpose TOUGH2™ model (4), was appropriately modified to predict the flow and behavior of gelling/cross-linking fluids when injected into porous media, (5). The expanded TOUGH2™ was used to design the laboratory experiments (one- and two-dimensional) of barrier fluid injection, and to conduct a sensitivity analysis of the relevant parameters (6).

In interactions with industry and regulatory agencies, LBNL developed an agreement with Bechtel to collaborate in the area of barrier fluid emplacement. LBNL also signed a confidentiality agreement with Dow Corning, the manufacturer of PSX, as a result of which Dow Corning made available to the project the new low-viscosity PSX used in the experiments and the field test. Agreements for possible applications of the barrier technology at a number of potential sites were concluded and a Categorical Exclusion under NEPA regulations for the first-level field test was obtained, due to the environmentally benign nature of the barrier fluids.

In preparing for the field test, LBNL staff developed a design package for the application of the barrier fluid technology using TOUGH2™, completed a preliminary evaluation of geophysical techniques for monitoring barrier performance and emplacement, identified a local site in California with a subsurface geology similar to that at Hanford, and obtained permission from the owner and the regulators to conduct the first-level test at that site. Following the signing of the Host Site Agreement, the field test was conducted in January, 1995.

THE FIRST FIELD-LEVEL DEMONSTRATION

In the following sections, various aspects of the field demonstration are described. These include the objectives of the demonstration, a site description, specification of the barrier liquids, and the four stages in executing the demonstration: (a) well drilling and permeability measurements, (b) barrier fluid injection, (c) grouted bulb (plume) excavation and sample recovery, and (d) laboratory investigations of grouted samples.

Objectives

The objectives of the test were to demonstrate the ability to:-

(1) inject colloidal silica and polysiloxane using standard permeation grouting equipment,

(2) track the grout fluid movement using tilt meter measurements of ground surface deformation,

(3) control of the grout fluid gel or cross linking time under *in situ* chemical conditions,

(4) create a uniform grout plume in a very heterogeneous matrix comprising cobbles, gravels, sands, silts and clays,

(5) create intersecting/merging plumes of grout, and

(6) decrease the permeability of the grouted soils.

The demonstration was not intended to prove the creation of continuous and/or impermeable barriers. Such an effort would be significantly larger in scope and involve merging and overlapping the injected barrier liquid plumes, as well as multiple injections.

The Site

The test site was located in central California in a quarry owned by the Los Baños Gravel Company. The quarry is situated along the western flank of the San Joaquin Valley, adjacent to the eastern margin of the central California Coast Ranges. The quarry exploits river gravels in a 100 km^2 alluvial fan generated by Los Baños Creek at the foot of the California Coast Range. The deposits exposed at the quarry are primarily coarse sands and gravels, deposited on a distributary lobe of Los Baños Creek adjacent to its present channel. They are heterogeneous, with discontinuous and lenticular coarser and finer strata, and occasional lenses of well-sorted cross-bedded sands. Large gravel and cobble clasts are commonly set in the sandy matrix, and range between 1 and 10 *cm* and sometimes larger. The matrix is predominantly coarse sand (0.5-1 *mm*), and comprises varicolored lithic fragments, along with grains of feldspar, quartz, and quartzite. Induration, where present, is caused by infiltration (illuviation) of clay into pores between sand grains; a fine film of yellow-brown clay can be seen binding the sandy matrix in most samples.

Prior to development of the Los Baños quarry, the area was under agricultural use. Upon development of the quarry, the uppermost soil layers were stripped and staged in piles away from the area of gravel excavation.

Barrier Liquids

The barrier fluids selected for injection included one type of PSX (2-7154-PSX-10, hereafter referred to as PSX-10; Dow Corning, Midland, MI) and one type of CS (Nyacol DP5110; PQ Corporation, Valley Forge, PA). In preliminary experiments, other variants of PSX and CS products were also tested. All fluids tested are environmentally benign and carry no warning label requirements.

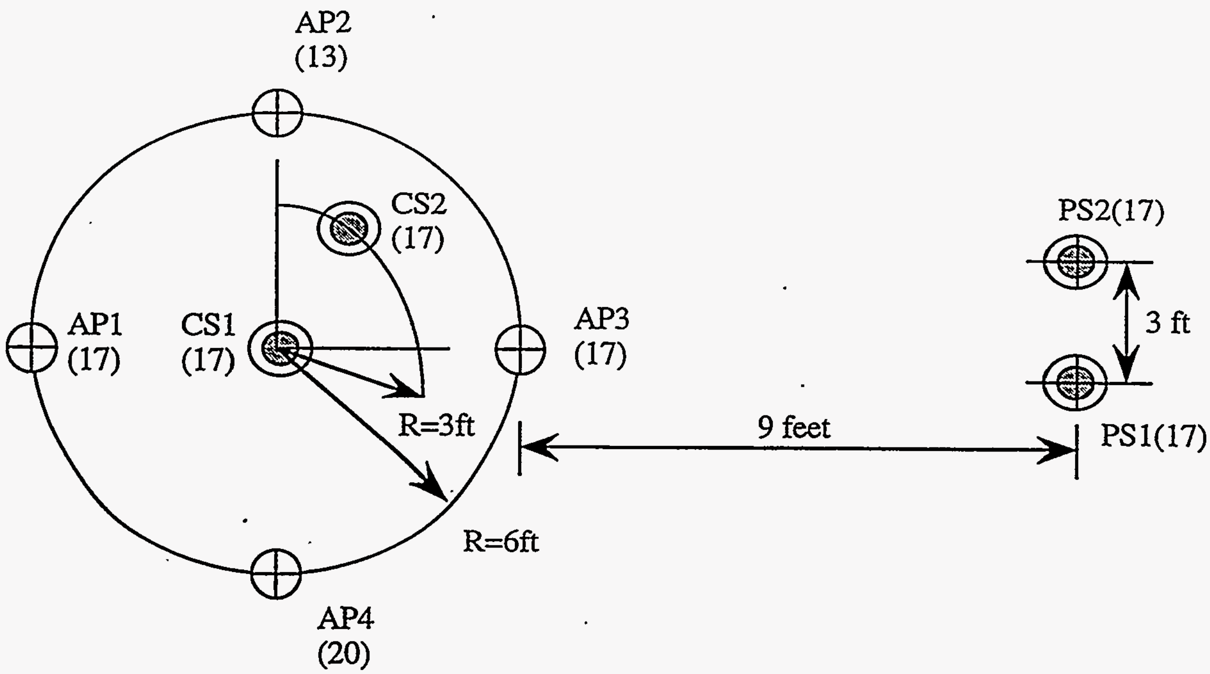
Nyacol DP5110 is a CS in which silica on the particle surfaces has been partly replaced by alumina; its solid content is 30 wt. % and its pH is 6.5. A technical grade aqueous solution of $CaCl_2$, HB-23 (Hill Bros. Chemical, San Jose, CA) was used to promote gelation for the final tests and the field demonstration. The concentration of the $CaCl_2$ solution was nominally 35 wt. % (4 *mol/L*).

PSX-10 is a polydimethylsiloxane, divinyl terminated to provide active sites for cross linking. It is formulated by the manufacturer with a cross linker (a small cyclic siloxane molecule) that can react with the terminations of the long chains, in the presence of small concentrations an organically-coordinated platinum catalyst. The polydimethylsiloxane and cross linker are delivered already mixed, but unreacted. The platinum based catalyst is added by the user at the level necessary to achieve the desired gel-time.

Well Drilling and Permeability Measurements

Four injection and four observation wells were drilled with a layout shown in Figure 1 The injection wells were drilled to a depth of 16 *ft*, while the observation wells were drilled to depths ranging between 12 and 20 *ft*.. Following well completion, all the wells were fitted with appropriate tubing, and probes were punched an additional foot through the bottom of the wells for air permeability measurements.

Air permeability measurements included static single point permeameter tests using constant head air injection tests, and a new dual probe dynamic pressure technique developed at LBNL for measurement of air permeability between wells (7). The latter uses a sinusoidally varying pressure with a mean near-atmospheric pressure at the injection well. Pressure responses are continuously monitored at several observation wells. The single point permeameter technique provides



EXPLANATION

Grout injection and air permeability measurement hole.

Air permeability measurement hole.

(17) Depth in feet, including 1 foot past the end of PVC.

NOTES

1. Holes CS1, CS2, PS1, PS2, AP1 and AP3 are 17 feet deep.
2. Holes AP2 and AP4 are 13 and 20 feet deep, respectively.

Figure 1. Plans of well locations at the injection site.

information on the permeability immediately surrounding each well, while the dual probe technique provides information on the permeability between wells.

The static permeability measurements, conducted in all eight wells, indicated permeabilities ranging from a high of $1.0\times10^{-10}\ m^2$ to a low of $3.6\times10^{-13}\ m^2$. For all but two wells the values ranged from 5.6×10^{-11} to $8.1\times10^{-11}\ m^2$. Injections into holes AP1, CS1, and CS2 using the new dual probe dynamic pressure technique, yielded inter-hole permeabilities between $3.5\times10^{-9}\ m^2$ and $1\times10^{-11}\ m^2$. These permeabilities are between 1 to 2 orders of magnitude higher than those obtained using the static technique. The apparent lack of agreement is due to conceptual differences between the two approaches: the static technique in essence measures the permeability at the point of injection, whereas the dynamic technique measures the mean permeability between a source and a receptor well along paths that are not necessarily the shortest. Though the magnitudes of the static and dynamic measurements differ, trends are consistent between the two techniques. These observations substantiate the validity of the two methods, and support the hypothesis that the differences between static and dynamic values are due to scale effects.

After completing the air permeability tests, all observation wells were plugged to prevent barrier liquids from flowing into the observation wells and bypassing the area to be grouted. The bottoms of the injection wells were also plugged.

Barrier Fluid Injection

The barrier liquids were injected through 3 ports in each well (at depths of 10, 12, and 14 *ft*) using the tube-à-manchette technique. Approximately 400 gallons of CS grout was injected into two wells, CS1 and CS2. About 120 gallons of PSX-10 was injected into a single well, PS1. The smaller scale of the PSX-10 injection test was dictated by budget considerations, as it is still a developmental product and economies of scale in its production have not yet been realized.

The barrier liquids (CS and $CaCl_2$ brine, PSX-10 and catalyst) were premixed at the surface using the agitators of the mixing tank and the recirculation equipment of the grouting system. For the CS injection, food-color dye was added to enhance its visibility during subsequent excavation of the site. Green dye was added to the batches injected into CS1, and purple dye into the CS2 batches. The same quantity of barrier fluid (66 gallons for CS, 40 gallons for PSX-10) was injected at each depth. Standard chemical grouting equipment was used for delivering the barrier fluids to the hole. The procedure for injection followed those typically used in tube-à-manchette grouting. The injection sequence was carried out in order to maximize complete permeation of the soil in the vicinity of the wells. Thus injection began at the lowest port (14 *ft*), followed by injection through the uppermost port (10 *ft*) and, finally, injection through the intermediate depth port (12 *ft*).

The barrier fluids were injected without any significant rise in pressure, (which would have indicated premature gelling). During injection the volume of injected grout and injection pressure were monitored. Average values of injectivity, a measure of the apparent permeability at each injection port, decreased with depth with values at the 14 *ft* depth an order of magnitude or more lower than those at shallower depths.

Eight tilt meters were installed at the injection site. The tilt meter array recorded ground movement every 60 seconds throughout the test, and was able to detect movement of the injected fluids. Tilt meters measure the angle of deviation of the land surface from the vertical axis. Because angular changes detected by tilt meters are minuscule (nano- to micro-radians), LBNL staff decided to apply this technology to track the swelling and uplift at the earth's surface caused by the intrusion of the barrier liquids. Deducing the movement of fluids through the subsurface from surface tilt requires the solution of an *inverse* problem, which cannot presently be conducted in the field in real-time, although such is anticipated with the rapid advancement of computer technology.

Excavation and Visual Inspection

The excavation of the grouted plumes was facilitated by the proximity of the wells to the 20 *ft* high exposed face of the quarry and the use of heavy earth moving equipment. The ground was excavated to a depth of up to 21 *ft*. Both CS and PSX-10 had satisfactorily gelled/cross linked in the subsurface. Despite the extreme soil heterogeneity, both the CS and the PSX-10 created fairly uniform plumes, indicating that the potential problem of flow along preferential pathways of high permeability (such as a gravel bed overlying a tight silty or clayey zone) can be overcome.

The CS grouted and sealed fractures and large pores in the clays. In open zones (such as gravels with cm-sized pores) it did not fully saturate the voids, but appeared to have sealed access to them. CS did not impart substantial structural strength to the matrix, but permitted vertical sections of the matrix (with the exception of very loose and friable materials) to stand, as shown in Figure 2.

PSX-10 was singularly successful in grouting the extremely heterogeneous subsurface at the site. PSX-10 created an almost symmetric plume, grouting and sealing gravels, cobbles, sands, silts, and clays. PSX-10 filled and sealed large pores and fractures, as well as accessible small pores in the vicinity of these pores/fractures. In extremely large voids in open zones, it coated the individual rocks in the gravel and sealed access to and egress from these zones. PSX-10 also invaded clays and silts (Figure 3), which is unusual. The mechanism through which this penetration is achieved has not been determined, but is under investigation.

PSX-10 is relatively easy to identify in the subsurface. Unlike CS, PSX-10 imparted structural strength and elasticity to the grouted soil volume, and gave sufficient strength to incoherent gravels to permit vertical walls to stand. It fully penetrated clean sands, which resisted desegregation due to the considerable elasticity of the cross linked PSX-10.

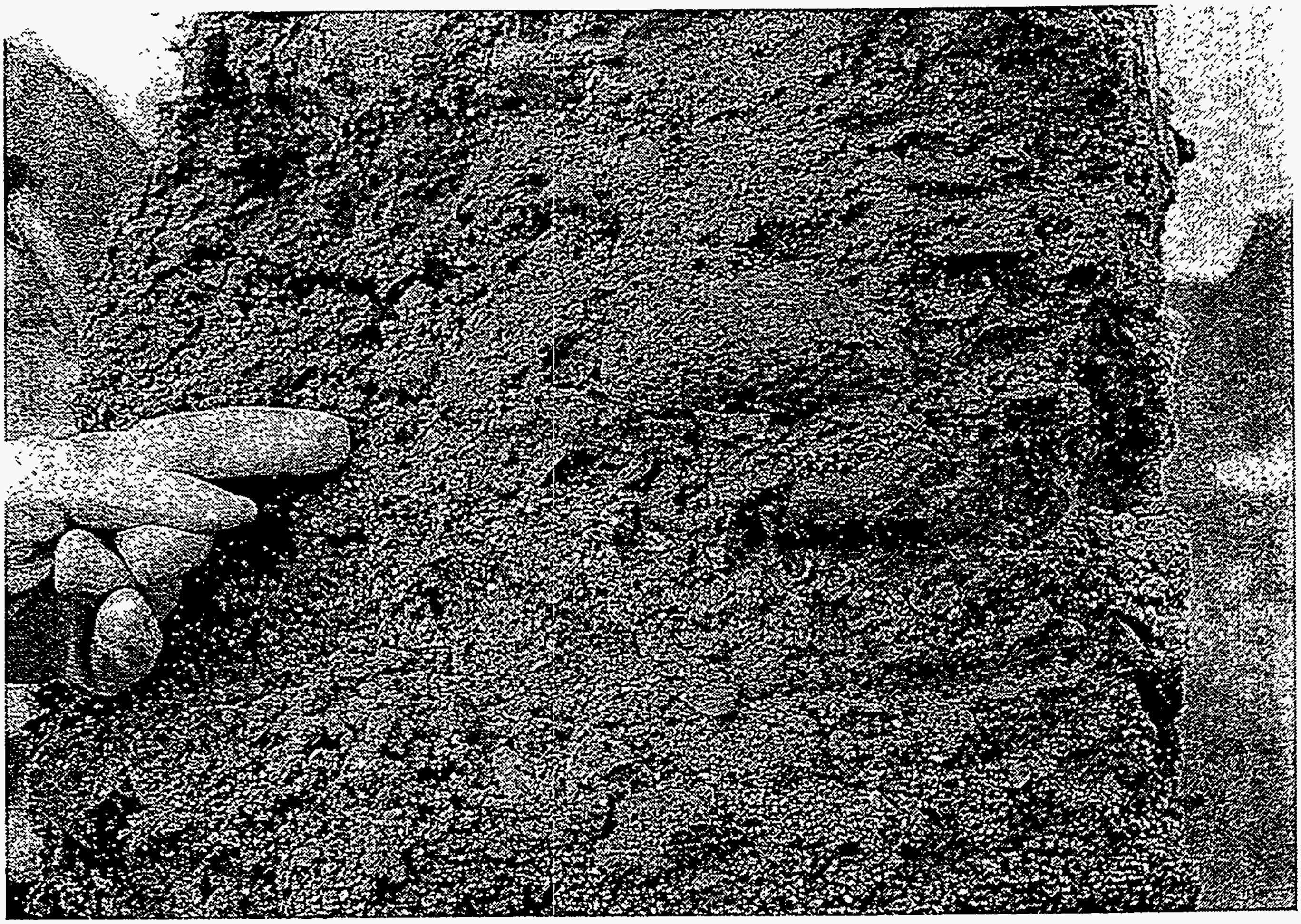


Figure 2. Excavated portion of the CS grouted soil. Note the extreme heterogeneity of the soil, indicated by the particle size and the appearance of the granular material.

Figure 3. PSX-10 grouted soil at the interface of sandy and argillaceous zones. Note the hair-like PSX strands of various sizes in the clay.

Post-Excavation Analyses

The grouted plumes were excavated primarily to determine the volumetric extent of the grouted zone. LBNL staff also took advantage of the excavation to recover boulder-size samples of grouted sand from which smaller samples could be taken for permeability measurement in the laboratory. After excavation, grab samples of ungrouted matrix were taken at various depths from locations adjacent to the grouted bulbs. Both moisture content and material gradational analyses were performed on these samples.

The moisture content of the ungrouted soil was low, but increased with depth from about 2.5 wt. % to 5 wt. %, with most of the increase occurring at depths of 10 *ft* and greater. The gradational analysis showed an increase in fines with depth from 1-2 wt. % to 8-9 wt. %. An abrupt increase in fines is seen at depths greater than 10 *ft*. A correlation in moisture content with fines would be expected. The gradational analysis also correlated with the injectivity profile and visual observations that the amount of fines increased with depth.

The permeability of grouted sand depends primarily upon two factors: the permeability of the grout itself, and the degree of grout saturation in the pore space. The lower limit of permeability is achieved when the pore space is completely filled with grout. To estimate this lower limit, special samples were prepared by a method in which sand is poured into liquid grout in molds. This method ensured a complete filling of pore space by the grout, and resulted in an absolute lower limit of permeability that is unattainable with a single injection under field conditions. Other samples were prepared in the laboratory by injecting grout upward into sand packs in order to minimize the amount of trapped air. Samples prepared in this manner represent the lower limit of permeability that could be achieved by injection in the field.

The permeabilities of the grouted sand samples were measured using a Wykeham-Farrance flexible wall permeameter (Humboldt Equipment, Durham, NC). Samples from the field were cored or carved from the boulder-sized chunks for insertion into the permeameter. Coring using a soil-sampling tube was possible only with a material containing no pebbles. The extreme heterogeneity of the formation at the Los Baños site made it difficult to sample and make permeability measurements. Hence, the number of field samples subjected to permeability testing was limited.

In Table 1, the three types of samples are represented; i.e., samples prepared by pouring the sand into the grout, (a); samples prepared by laboratory injection into sand packs, (b; and field samples, (c). These three types of samples have increasing ungrouted voids. Because the field samples are expected to have the greatest amount of ungrouted voids, multiple injections will be required to achieve permeability reductions of type (ii) in field applications (2). This goal was not pursued in the first-level field injection, as the reduction of permeability to a near-zero level was not among the objectives of this field demonstration for the reasons discussed earlier.

Table 1. Hydraulic Conductivity Measurements on Laboratory and Field Samples of Grouted Sand					
Sample	**Sample Type**	**Sample Length (*in*)**	**Hydraulic Gradient (-) x10^3**	**Cell Bias Pressure (*psi*)**	**Hydraulic Conductivity (*m/s*)**
Hanford sand, PSX-10,#1	laboratory injection	4	69.767	14	4.08×10^{-12}
Hanford sand, DP5110, #1	laboratory injection	2	13.953	20	1.03×10^{-09}
		2	13.953	40	6.33×10^{-10}
		2	13.953	60	4.60×10^{-10}
		2	41.86	60	4.20×10^{-10}
Los Baños sand, PSX-10, #1	cored field sample	3	9.302	5	2.28×10^{-6}
		3	9.302	10	1.52×10^{-6}
		3	9.302	20	1.14×10^{-6}
		3	27.907	20	1.24×10^{-6}
Los Baños sand, PSX-10, #2	cored field sample	3	4.651	10	4.52×10^{-6}
		3	4.651	20	2.75×10^{-6}
		3	4.651	40	2.15×10^{-6}
Hanford sand, DP5110, #2	sand added to DP5110	3	9.302	5	6.48×10^{-10}
		3	9.302	10	3.39×10^{-10}
		3	9.302	20	2.02×10^{-10}
Los Baños sand, DP5110, #1	carved field sample	2	6.977	5	3.96×10^{-6}
		2	6.977	10	3.07×10^{-6}
		2	6.977	20	2.59×10^{-6}
Los Baños, DP5110, #2	carved field sample	2	6.977	5	6.02×10^{-6}
		2	6.977	10	3.63×10^{-6}
		2	6.977	20	2.85×10^{-6}
Hanford, PSX-10, #2	laboratory injection	3	46.512	10	2.90×10^{-6}
		3	27.907	20	3.37×10^{-7}
		3	27.907	40	1.70×10^{-8}
		3	55.814	40	1.18×10^{-8}
		3	55.814	60	6.03×10^{-9}

A review of the hydraulic conductivity data confirms that it increases with the increase of ungrouted voids. In comparing the laboratory prepared samples with nearly complete grout saturation, (i.e., type a), those grouted with PSX-10 had lower hydraulic conductivity than those grouted with CS. Sands with an initial hydraulic conductivity on the order of 10^{-4} *m/s,* can attain an ultimate hydraulic conductivity of 10^{-10} *m/s* after grouting with CS, while PSX-10 reduces hydraulic conductivity even further to 10^{-12} *m/s*. These differences reflect the different permeabilities of the grout materials. CS gel contains a significant volume of water, and diffusion of dye through the aqueous component can be observed in a matter of hours in a plug of gelled CS, indicating a potential for diffusive transport. No such diffusion occurs in PSX-10.

The Hanford-PSX-10 #2 sample shows unusually high hydraulic conductivities for laboratory-grouted cylindrical samples, which was due to an imperfect outer cylindrical surface that allowed flow between the rubber membrane and the grouted core. With increasing confining pressure, the hydraulic conductivity decreases, confirming the visual observation of surface imperfections. Such side-flow effects are expected to be far more pronounced in the cored or carved field samples.

In the case of field grouted sand and pebbles, the observed hydraulic conductivities reflect incomplete saturation of the pore space. Damage to samples during recovery, transport, storage and trimming to fit the apparatus could also have contributed to increases in hydraulic conductivity. Similar values were observed whether CS or PSX-10 grout was used, but this may be immaterial, because they were from different samples taken from different locations and with different soil textures. Partial saturation of pore space is also suggested by the observation of the larger than expected plumes. This supports the view that grout desaturation occurred due to plume spreading. LBNL's plume emplacement model predicts that this phenomenon will always occur in the vadose zone.

The problem arising from plume spreading and incomplete sealing can be solved by multiple, sequential injections of grout. *Moridis et al.* (2) demonstrated this technique in sand packs. Because plume spreading does not occur in sand packs, the desaturating effect was achieved by saturating the sand pack with grout and then forcing air through the sand pack to displace the grout. Hydraulic conductivities ranging from 3×10^{-7} to 1×10^{-5} *m/s* were observed after the first injection, which are similar to those of order 10^{-6} *m/s* observed in Los Baños field samples. After two or three such injections, hydraulic conductivity was reduced to 1×10^{-10} *m/s*, i.e. close to the type (a) laboratory result.

The grouted Los Baños material is 2 orders of magnitude less permeable than the ungrouted sand fraction of these materials. The sand fraction is less permeable than the actual geologic matrix due to its finer texture. Compared to the field measurements of air permeability, these samples indicate a permeability reduction by 3 to 4 orders of magnitude. In that respect, the results are very encouraging.

Data from the tilt meter measurements was inverted in order to relate the tilt meter measurements to the shape and extent of the injected grout plume. Based on the inversion results, the ground motion due to injection could be predicted. The peak vertical displacement of the land surface due to injection of CS was found to be 0.18 micrometers. The preliminary work suggests that tilt measurements can be used to monitor subsurface injections. However, further refinement of the technique is required for future application.

SUMMARY AND CONCLUSIONS

A first stage field injection of colloidal silica and polysiloxane grout was successfully completed. The fluids were injected at depths of 10 *ft* to 14 *ft* in a heterogeneous unsaturated deposit of sand, silt and gravel, typical of many arid DOE cleanup sites and particularly analogous to the conditions of the Hanford Reservation. Both grouts effectively permeated gravel and sand beds. Despite the extreme heterogeneity, both the CS and the PSX-10 created fairly uniform plumes. Within the grouted plumes, both large and small pores were grouted. The CS grouted plume did not have substantial cohesiveness or strength, but allowed vertical sections of the soil to be exposed. Unlike CS, PSX-10 imparts structural strength and elasticity to the grouted soil. PSX-10 is relatively easy to identify in the subsurface and gave sufficient strength to very loose gravels without any cohesiveness to form vertical walls. Samples of grouted materials from both barrier fluids were recovered from the field test site and taken to the laboratory for permeability measurements. An approximate four order of magnitude permeability reduction of the geologic medium was achieved, even though the emphasis of the field test was not specifically targeted at the attainment of maximum permeability reduction.

Characterization of pre-injection *in situ* permeability at the site was carried out using both single hole and dual probe dynamic pressure air permeability methods. The dual probe technique, sampling a larger volume of material, gave permeabilities at least an order of magnitude higher than the single hole measurements. Tilt meters were used successfully to monitor surface displacements during grout injection. The resulting data was then inverted to model the shape of the subsurface plume, which would have produced the observed surface displacement. In conclusion, LBNL staff believe that the first field test was an unqualified success, and that its objectives were achieved.

ACKNOWLEDGMENTS

The authors are indebted to their colleagues, Drs. Stefan Finsterle, Pat L. Williams and Don W. Vasco, and to members of the LBNL Geophysical Measurements Facility team (Jim Dougherty, Ray Solbau, Phil Rizzo and Don Lippert) for the planning, preparation, support, and flawless execution of the field test. Thanks are due to Mr. Gordon Mills, General Manager of the Los Baños Gravel Company, for his generous help in locating an appropriate site for the field test and facilitating its execution. This work was supported by the U.S. Department of Energy, Office of Environmental Management, Office of Technology Development, under Contract No. DE-AC03-76SF00098.

REFERENCES

1. G.J. MORIDIS, P. PERSOFF, H.-Y. HOLMAN, S.J. MULLER, K. PRUESS, P.A. WITHERSPOON, and C.J. RADKE, "Containment of Contaminants through Physical Barriers Formed from Viscous Liquids Emplaced Under Controlled Viscosity Conditions", FY 1993 Annual Report, Lawrence Berkeley Laboratory Report LBL-29400, Berkeley, CA (1994).

2. G.J. MORIDIS, P. PERSOFF, H.-Y. HOLMAN, S.J. MULLER, K. PRUESS and C.J. RADKE, "New Barrier Fluids for Containment of Contaminants", in Proceedings of ER '93 Environmental Remediation Conference, Augusta, GA. Lawrence Berkeley Laboratory Report LBL-34673, Berkeley, CA (1993).

3. P. PERSOFF, G.J. MORIDIS, J.A. APPS, K. PRUESS and S.J. MULLER, "Designing Injectable Colloidal Silica Barriers for Waste isolation at the Hanford Site", (Gee, G.W. and N.R. Wing, Eds.). 33rd Hanford Symposium on Health and the Environment --In-Situ Remediation: Scientific Basis for Current and Future Technologies, Battelle Press, Richland, WA. Lawrence Berkeley Laboratory Report LBL-35447, Berkeley, CA, 87-100, Nov. 7-11 (1994).

4. K. PRUESS, "TOUGH2 - A General-Purpose Numerical Simulator for Multiphase Fluid and Heat Flow", Lawrence Berkeley Laboratory Report LBL-29400, Berkeley, CA (1991).

5. S. FINSTERLE, G.J. MORIDIS, and K. PRUESS, "A TOUGH2 Equation-Of-State Module for the Simulation of Two-Phase Flow of Air, Water, and a Miscible Gelling Liquid", Lawrence Berkeley Laboratory Report LBL-36086, Berkeley, CA (1994).

6. S. FINSTERLE, G.J. MORIDIS, K. PRUESS, and P. PERSOFF, "Physical Barriers Formed from Gelling Liquids: 1. Numerical Design of Laboratory and Field Experiments", Lawrence Berkeley Laboratory Report LBL-35113 , Berkeley, CA (1994).

7. K. GARBESI, "Toward Resolving Model-Measurement Discrepancies of Radon Entry into Houses", Lawrence Berkeley Laboratory Report LBL-34244, Berkeley, CA (1994).