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HYDRAULIC FRACTURES AS SUBSURFACE ELECTRODES: EARLY WORK ON THE LASAGNA PROCESS

Larry Murdoch, Jiann-Long Chen, Phil Cluxton, Mark Kemper, Jim Anno and Dave Smith
Center for GeoEnvironmental Science and Technology
Department of Civil and Environmental Engineering
University of Cincinnati
1275 Section Rd.
Cincinnati, Ohio, 45237

INTRODUCTION

Fine-grained sediments present the greatest obstacle to in situ remediation at many contaminated sites. Where fine-grained sediments are continuous, discharges from wells are slow and contaminants are recovered at negligible rates. In contrast, at sites underlain by interbedded sand and silt or clay, volumetric discharges from wells can be significant as water is readily recovered from the more transmissive sands. The rate of recovery of contaminants can be rapid as the sands are flushed during initial operations, but the clay interbeds act as persistent sources of contaminants so that concentrations can be maintained at small but serious values for many years.

Hydraulic fractures filled with coarse-grained sand provide high permeability layers that increase fluid flow primarily by reducing the large losses of hydraulic head in the vicinity of a well (1,2). These features have been shown to increase the discharge from wells by an order of magnitude or more (2). Nevertheless, current applications of hydraulic fractures are designed to improve the recovery and removal of contaminants from the subsurface by advective processes. Effects related to adsorption, preferential flow and other processes can result in mass transfer limitations that require a large number of pore volumes of fluid to be moved through porous material before it is remediated using hydraulic flow alone.

Electrokinetics is an effective method of inducing the movement of water, ions, and colloids through fine-grained sediments. In this process, typically a direct current is applied to the sediment, inducing osmotic movement of water away from a positively charged anode and toward a negatively charged cathode (3). Ions and colloids migrate toward the electrode with a charge opposite from the one that they carry (3,4). In addition, electrolysis of water results in a decrease in pH at the anode and an increase at the cathode (4). The acidic conditions at the anode and the basic conditions at the cathode will propagate into the region between the electrodes, potentially forming a sharp discontinuity in pH (4,5).

Based on the results of laboratory tests and limited field applications (7), electrokinetics has been shown to be a promising method of recovering ionic and water-soluble contaminants. However, the process is not without problems. Acidic conditions and electrolytic decay can corrode some anode materials. Sharp discontinuities in pH induced within the soil mass by electrokinetics could result in a deposition front where minerals are precipitated in soil pores, markedly reducing permeability and inhibiting recovery. It may be possible to mitigate problems related to pH by circulating a buffering solution across the electrodes (7).

Another drawback to conventional electrokinetic remediation is that it requires contaminants to migrate from their initial location to an electrode and then up to the groundsurface. In some cases, the migration path could be long or there could be stagnant zones between wells where the rate of migration is particularly slow, both of which result in incomplete remediation of the contaminated zone. Moreover, sharply convergent electrical fields can result in heating and potential losses in the vicinities of electrodes, just as convergent flow paths result in head losses in the vicinities of wells. Electroplating, or pH-related deposition can cause contaminants to be removed from solution prior to arrival at the ground surface.

Recent investigations have shown that it may be possible to address some of the shortcomings of electrokinetics by degrading contaminants in situ. Our colleagues have developed a solid compound (8), which slowly releases oxygen, that can be injected into

hydraulic fractures along with slowly dissolving nutrients to stimulate in situ aerobic biodegradation of organic compounds in soils. In addition, it is feasible to fill hydraulic fractures with metal catalysts, such as iron particles, which Gillum and Burris (9) have proposed as a method of degrading a wide range of organic compounds. By degrading compounds in situ it should be possible to shorten the migration paths of contaminants. Periodically reversing the polarity of the field is intended to repeatedly pass contaminants through a degradation zone while limiting the development of high or low pH conditions in the vicinities of electrodes and reducing fouling of electrodes by precipitation. This approach to in situ remediation is the essence of the so-called "Lasagna" process (Fig. 1; ref 10).

Hydraulic fracturing appears to be a method of improving the performance of electrodes and of creating zones where contaminants are degraded in situ. An investigation into this application was initiated in the summer of 1994, with pilot-scale testing scheduled for 1995 and full-scale testing at a contaminated site anticipated for 1996.

METHODS

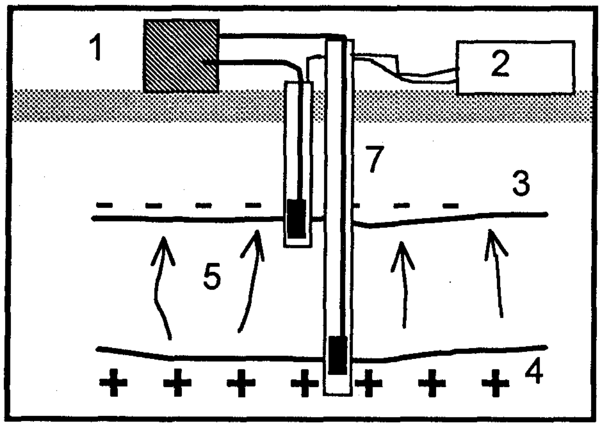

Figure 1. Configuration of fractures, electrical delivery, and fluid delivery system. 1. DC Power supply; 2. Water delivery apparatus; 3. Graphite-filled hydraulic fracture as cathode; 4 anode.; 5. water flow by electroosmosis; 6. graphite contactor on the end of power cable; 7. Well casing.

Recent work on the project has consisted of identification or development of methods to monitor in situ electrokinetics and degradation, as well as preliminary evaluation of hydraulic fractures as electrically and hydraulically conductive electrodes.

Monitoring

The monitoring efforts have assembled techniques to measure the following parameters

- temperature
- moisture content
- fluid pressure/suction
- electrical conductivity
- electrical potential
- pore fluid pH
- pore gas composition

The configuration shown in Figure 1 will result in strong vertical gradients, so monitoring systems have been designed to obtain data along relatively close vertical spacing in order to resolve those gradients. Moreover, we have sought to measure several parameters at each location in order to reduce the number of subsurface devices that must be installed. This effort has produced two types of devices, the T-type and S-type, that will be used to measure the subsurface parameters.

The T-type of monitoring device consists of a 2.5-inch (nominal) PVC pipe that fits snugly into a reamed borehole. The wall of the pipe is penetrated by stainless steel rivets, which are flush on the outside and protrude slightly on the inside. A probe is lowered into the pipe to contact each rivet and measure the electrical potential of that point relative to the cathode, thereby providing a profile of electrical potential. When it is not being used to measure potential, the pipe is thermally insulated and a thermocouple, which contacts the inner wall, is used to measure the temperature with respect to depth. The pipe also provides access for a neutron probe, which has been calibrated for losses due to neutron absorption by the PVC. Neutron probe data will be used to estimate the moisture content of soils in the vicinity of the pipe.

Some of the 2.5-inch PVC pipes are wrapped with a series of stainless steel bands riveted to their exterior. The bands are 1 cm wide and spaced every 5 to 10 cm along the axis of the pipe. A probe that can contact four bands simultaneously is lowered into the pipe and the upper and lower bands are energized with approximately 10V of low frequency AC. The potential difference between the middle two bands is proportional to the electrical conductivity of soil in the vicinity. This modification of the T-type device will be used to monitor changes in electrical conductivity during electrokinetics, which result from electrochemical processes and have been reported in laboratory experiments (11).

The S-type monitoring system is used to measure fluid potentials and composition. It consists of a suite of sensors that are pushed horizontally into the side of a vertical borehole. A prototype device has been fabricated that pushes a tube into the sidewall of a bore to obtain a soil sample and create a hole suitable for either a ceramic-cup tensiometer, or a porous soil-gas sampler. Those devices are installed at various depths along the vertical bore to obtain pore water pressure or suction, and pore gas pressure or composition as functions of depth.

Electrical potential

We created two roughly circular, horizontal hydraulic fractures filled with electrically conductive graphite to evaluate their effect on the electric field in the subsurface. The hydraulic fractures were approximately 3 m in radius, 6 mm thick and contained graphite whose electrical conductivity was approximately 190 S/m when saturated with water. They were separated by 0.9 m vertically, sandwiching roughly 25 m^3 of soil between them. The fractures were enveloped in silty clay soil whose electrical conductivity was 0.05 to 0.1 S/m, or 2000 to 4000 times less than that of the fracture.

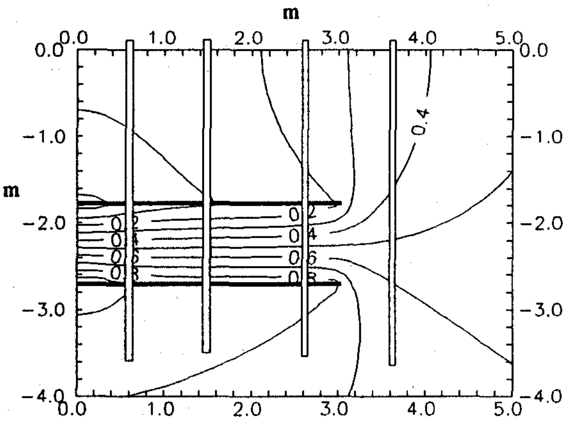

Figure 2. Axisymmetric view of electrical potential distribution in the vicinity of two charged disks representing hydraulic fractures. Potential is with respect to the upper fracture and is normalized to the potential difference between the fractures. Vertical bands are T-type casings used to measure potential.

A potential difference of 40 V DC was maintained between the two fractures with a current of 30 amps. The potential difference could be adjusted by changing the current, with a ratio of current:potential difference of 0.75 amps/volt observed for a wide range of power conditions. The design of the constant current power supply used during the initial tests limited the potential difference to 40 V for continuous operation--greater potential differences could be applied for testing over short durations. T-type monitoring tubes were placed at radial distances of 0.6, 1.5, 2.6 and 3.5 m from the power electrodes (Fig. 2), and rivets were spaced every 7.5 to 15 cm along the length of the tubes.

Preliminary theoretical analyses of the electric field were conducted using both analytical solutions to the potential in the vicinity of a charged circular disk and numerical solutions to the potential in the vicinity of a highly conductive disk. The analytical solution indicates that under ideal conditions of a homogeneous, isotropic medium, the electrical field around two, horizontal, conductive, circular disks beneath an insulated free surface is as shown in Figure 2.

RESULTS

The theoretical analyses indicate that there should be strongly positive vertical gradients between the fractures. Indeed, the strong vertical potential gradients are intended to drive the electrokinetic process. The gradients are more subtle in other regions, with weakly negative vertical gradients over the fractures and weakly positive gradients at radial distances beyond the edge of the fractures (Fig. 2).

Electrical potential was measured along the T-type casings at distances of 0.6, 1.5, 2.6, and 3.5 m, the data were normalized to the applied potential difference and compared to the results of the theoretical analysis (Fig. 3). The field data show that strong vertical electrical potential gradients are produced between the hydraulic fractures, at least within the region bounded by the radial extent of the fractures (about 3 m). The subtle predictions of the character of the electrical field are represented in the field data, with gentle negative gradients overlying the fractures and gentle positive gradients beyond the edge of the fractures. The potential in the vicinity of the lower fracture is less than predicted by the analysis, perhaps because that fracture is thinner than assumed in the analysis.

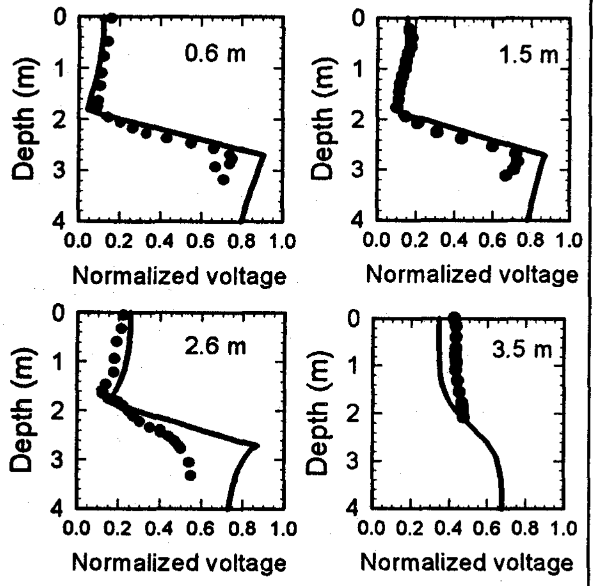

Figure 3. Electrical potential as a function of depth at various distances from the power electrode. Line is from theoretical analysis, points are field data.

The field data and ratio of applied current to potential difference given above indicates that the vertical electrical potential gradient available for electrokinetics is

$$dV/dz = C\,Q/h \qquad (1)$$

where Q is the applied current, h is the fracture spacing, and C is a constant that depends on the design of the fractures. The available results indicate that $C = 0.6$ to 0.9 V/amp for the design used here. Accordingly, for an applied current of 30 amps, the potential gradient is 0.2 to 0.3 V/cm. Gradients 0.2 to 0.4 V/cm are reported during field tests by Langeman and others (1989), and slightly greater gradients are described from laboratory experiments; e.g. Bruell and others (12) used gradients of 0.4 V/cm, whereas Acar and others (11) report gradients of 0.5 V/cm or more. Potential gradients of 0.4 V/cm appear to be achievable over most of the 25 m^3 of soil between the fractures by increasing the current provided by the power supply to approximately 50 amps.

CONCLUSIONS

The field observations indicate that graphite-filled hydraulic fractures behave as broad, sheet-like electrodes capable of providing useful electrical potential gradients distributed over a reasonably large volume of soil. These results indicate hydraulic fractures can be used to create the electrical field required to conduct the Lasagna process outlined by Ho and Brodsky (10). Preliminary measurements of fluid flows suggest that the observed potential gradients will induce electroosmotic migration of water through the region between the fractures. A pilot test designed to provide detailed data on electroosmotic flow is underway, and those data should be available in the near future.

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For more information: Mike Roulier, EPA Project Officer
US EPA Center Hill Lab
5995 Center Hill Rd.
Cincinnati, OH 45223
513-569-7796