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Project Summary

Feasibility of Hydraulic Fracturing of Soil to Improve Remedial Actions

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Hydraulic fracturing, a technique commonly used to increase the yields of oil wells, could improve the effectiveness of several methods of in situ remediation. This project consisted of laboratory and field tests in which hydraulic fractures were created in soil. Laboratory tests conducted using a triaxial pressure cell showed that hydraulic fractures were readily created in clayey silt, even when it was saturated. Laboratory observations are explained using the parameters and analyses of linear elastic fracture mechanics.

Field tests were conducted during the summers of 1988 and 1989. During the 1988 test, hydraulic fractures were successfully created from cemented casing at depths of 2 to 4 m. The tests were limited to one fracture per borehole, and shortcomings resulted from the use of oil well equipment too large for our purposes. During the 1989 test, injection grouting equipment was used with a new method of casing to create as many as four horizontally layered fractures from the same borehole.

Following the tests, the vicinity of the boreholes was excavated to reveal details of the hydraulic fractures. In general, they were slightly elongate in plan view, and they were highly asymmetric with respect to their parent borehole; in each case, there was a preferred direction of propagation. Maximum lengths of fractures in 1989 average 4.0 m, and the average areas was 19 m^2. Maximum thickness of sand in individual fractures ranged from 2 to 20 mm, averaging 11 mm.

Results indicate that it should be feasible to monitor the growth of hydraulic fractures at shallow depths using injection pressure, surface uplift and surface tilt.

This Project Summary was developed by EPA's Risk Reduction Engineering Laboratory, Cincinnati, OH, to announce key findings of the research project that is fully documented in a separate report of the same title (see Project Report ordering information at back).

Introduction

The recovery of hazardous chemicals from contaminated ground is often difficult and sometimes impossible using established techniques, so earth scientists have begun to turn to related fields for innovative ideas. In petroleum engineering, the problem of recovering hydrocarbons from reservoirs is similar to the problem of recovering contaminants from aquifers. A wide range of techniques has been developed to enhance the recovery of oil from reservoirs, and one of the most effective is hydraulic fracturing. The basic process of hydraulic fracturing, as it is used in the petroleum industry, begins with the injection of fluid into a well until the pressure of the fluid exceeds a critical value and a fracture is nucleated. A granular material, which is usually sand and is termed a *proppant*, is pumped into the fracture as it grows away from the well. Transport of the proppant is facilitated by using a viscous fluid, usually a gel formed from guar gum and water, to carry the proppant grains into the fracture. After pumping, proppant holds the fracture open while the viscous gel breaks down into a thin fluid. The thinned gel is then pumped out of the fracture, creating a permeable channelway suitable for either the delivery or recovery of liquid or vapor.

Statement of the Problem

Experience from the study of oil wells suggests that hydraulic fracturing could increase flow rates from wells used to recover groundwater contaminants. To realize this increase, however, hydraulic fractures would have to be created and filled with sand under conditions of contaminated regions. Oil reservoirs are typically deeper and are composed of different materials than contaminated regions, so the applicability of fracturing methods used by petroleum engineers is unknown. Contaminants commonly occur in soils that are weaker and more compliant than limestone or sandstone typical of reservoirs. Effects of soil properties on hydraulic fractures are difficult to anticipate based on the results of previous studies of hydraulic fractures in rock. Moreover, most contaminants occur at shallow depths (several meters to several tens of meters), so intersecting the ground surface and venting could severely limit the length and, thus, the performance of the fracture. Hydraulic fractures virtually never vent when they are created in oil reservoirs, which are several hundred to several thousand meters deep, so the practical problem of creating fractures at shallow depths has yet to be addressed.

Approach

The approach of this research was to adapt methods proven for hydraulic fracturing of rock to applications of hydraulic fracturing of soil. Laboratory experiments were conducted by creating hydraulic fractures in rectangular samples of remolded clayey silt confined in a triaxial pressure cell. Results of those experiments were analyzed using methods of linear elastic fracture mechanics, a branch of elasticity theory that is widely used to analyze hydraulic fractures in rock.

Two sets of field experiments were performed by creating hydraulic fractures in Pleistocene glacial drift at depths of between 2 and 4 m. The first set of tests was conducted during June 1988 in collaboration with a subcontractor who used equipment designed to create hydraulic fractures from oil wells. The second set was conducted during June and July 1989 by investigators from the Center Hill Research Facility (Cincinnati, Ohio), who used equipment that was either rented or designed for the project. Hydraulic fractures were successfully created during the field tests, and then they were exposed on the walls of trenches dug with a backhoe. Detailed descriptions of exposures document the geometries of the fractures, highlighting the potential that this process should have in remediation of contaminated soil.

Laboratory Experiments

Laboratory experiments were designed to create hydraulic fractures by injecting dyed glycerin into rectangular blocks of soil confined in a triaxial pressure cell. An experimental apparatus and a testing procedure were developed to reveal physical characteristics of the fractures and to yield data describing the characteristics of fracture propagation in soil.

Apparatus

The experimental apparatus consisted principally of a pump system, a fracture cell, and a data acquisition computer. The pump system was used to inject fluid at a constant rate into a sample contained in the fracture cell. Typically, the pressure of the injected fluid increased until fracturing occurred, then decreased during fracture propagation. The computer was used to monitor injection fluid pressures as a function of time and to control the flowrate of the pump.

The fracture cell is a rectangular chamber with one moveable side that is used as a loading plate (Figure 1). The loading plate is transparent so that the interior of the cell can be inspected during a test. The other five sides of the chamber are lined with neoprene bladders. The three principal stresses on the sample are controlled independently by adjusting air pressures in the bladders.

Pressure of the injection fluid as a function of time was the primary data recorded during each test. In addition, the samples were split open and the details of the fracture surfaces were described.

Physical Characteristics of the Soils

Most experiments were conducted using a yellow-brown, colluvial clayey silt derived from a pit adjacent to the Center Hill Research Facility. The soil (which will be termed the Center Hill clay) is a type CL soil and it behaves as a plastic material in Atterburg tests over the range of moisture contents used during the fracturing tests (moisture contents were between the liquid and plastic limits). Data describing the physical characteristics of the material are in Table 1.

Samples were formed by compacting soil of various moisture contents in a rectangular mold. The same amount of compactive effort was used for each sample. A narrow slot (0.04 mm in aperture) was cut through the middle of each sample (Figure 1) using a special blade-like tool. The slots were rectangular in shape with the long axis of the rectangle spanning the width of the sample. The purpose of the slot was to provide a starting fracture that was much larger than existing flaws in the sample. The slot was necessary because measurements of critical stress intensity require knowing the length of a fracture when it begins to propagate.

Events occurring during the fracturing tests followed a consistent pattern. Typically, pressure increased nearly linearly with time early in the test. At some point the slope of the pressure record began to flatten, reaching zero slope as the pressure peaked and then becoming negative as the pressure decreased with continued injection.

A thin (on the order of 0.05 mm) fracture trace typically could be first seen on the surface of the sample roughly at the time of maximum injection pressure. Most traces were nearly straight, although in many cases they consisted of a family of straight, subparallel segments arranged either *en echelon* or staggered. The location of the fracture tip was difficult to establish because the aperture tapered gradually until it became undetectable. Thus the tip could be located within approximately 1 cm, but the trace was too thin to locate the tip precisely using unaided visual techniques.

A fracturing test was terminated by stopping the pump and opening a pressure relief valve, which allowed the injection fluid to flow back into the injection tube as the fracture closed. The dyed glycerin was promptly removed from the fracture to inhibit staining of the sample by flow unrelated to the process of hydraulic fracturing.

Results

More than 5 doz. experiments were conducted with the Center Hill clay using a variety of loading conditions, sample preparation techniques, moisture contents and durations of consolidation. Hydraulic fractures were created during every experiment, except in a few cases when the injection tube was plugged with clay as it was inserted. The typical test produced a continuous, parent fracture adjacent to the starter slot. The parent fracture broke into discontinuous, lobate planes with increasing distance from the injection hole. Dye

Table 1. *Characteristics of Soils Used in the Laboratory Study*

Center Hill Clay			
Atterburg Limits (wt. water/wt. solid)	*CH1*	*CH2*	*AVE*
Liquid Limit	*0.429*	*0.438*	*0.433*
Plastic Limit	*0.198*	*0.200*	*0.199*
Plastic Index	*0.231*	*0.238*	*0.234*
Shinkage Limit	*0.188*		
Grain size			
Gravel	*0*	*0*	
Sand	*0.03*	*0.03*	
Silt	*0.61*	*0.62*	
Clay	*0.36*	*0.35*	
Proctor Test (ASTM D698)			
Moisture Content of Greatest Density: 0.197			
Maximum Dry Density: 1.68 gm/cm³ (104.7 lb/ft³)			
Maximum Wet Density: 2.01 gm/cm³ (126.0 1b/ft³)			

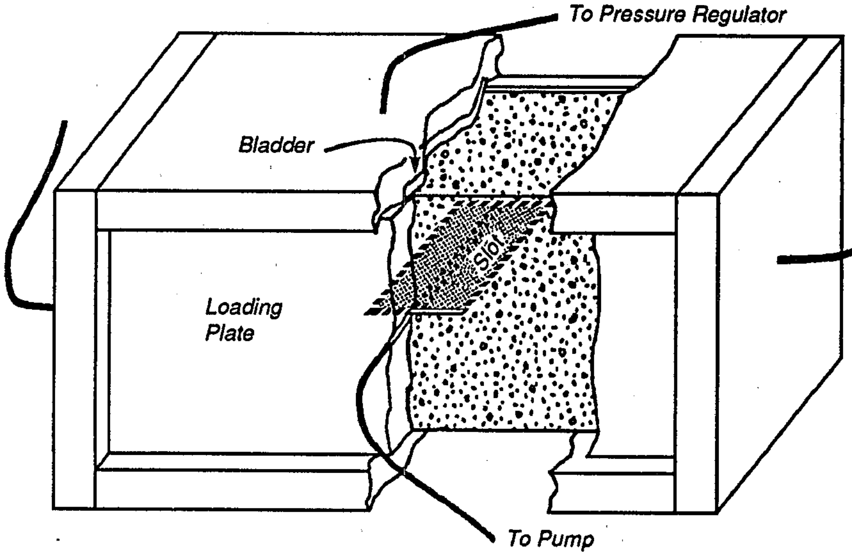

Figure 1. *Cut-away sketch of hydraulic fracturing cell.*

staining formed irregular dendritic patterns near the ends of the lobes (Figure 2), but the leading edge of the fracture was beyond the zone reached by the dyed glycerin and was unstained. These features define four distinct zones on a typical fracture surface: 1) starter slot, 2) parent fracture, 3) fracture lobes, and 4) a pristine or undyed zone at the leading edge.

The lengths of the undyed tip zones are roughly linearly related to the lengths of the parent fractures, according to comparisons of multiple tests. The ratio of the length of the undyed tip to the length of the parent fracture m was strongly dependent on the moisture content of the sample: $m = 0$, moisture < 0.21; m increases from 0 to 0.27 as moisture increases from 0.22 to 0.27; m decreases from 0.27 to roughly 0.06 as moisture increases from 0.27 to 0.32. The length of the undyed zone is important because it marks a part of the fracture that is unwetted by the injected fluid.

Records of driving pressure P_d (the difference between the fluid pressure and confining stress normal to the fracture) were made of all the experiments conducted during this research. In general, forms of the records from the test were similar; an initial period of roughly linear increase in pressure is marked by an abrupt change in slope and followed by a period of diminishing positive slope, followed by a period of decreasing pressure. A series of tests were terminated at various times to determine how fracture development correlates to the forms of the pressure records. The tests indicate that a fracture first started to form approximately at the first break in slope of the injection record. Typical elements of a pressure record and their interpretation are as follows:

Period I: Constant positive slope; represents inflation of the starter slot.

Period II: Slope diminishes, but remains positive; represents stable fracture propagation.

Period III: Slope is negative; represents unstable propagation.

These periods could be broadly identified in most records, although the details of the individual records were highly variable, depending at least on the length of the starter slot and the moisture content of the soil. As the moisture content increased, for example, the pressure marking the break in slope and thus the onset of fracturing decreased markedly. Moreover, a decrease in onset pressure was consistently observed when the length of the starter slot was increased.

Methods of linear elastic fracture mechanics, which are commonly used to ana-

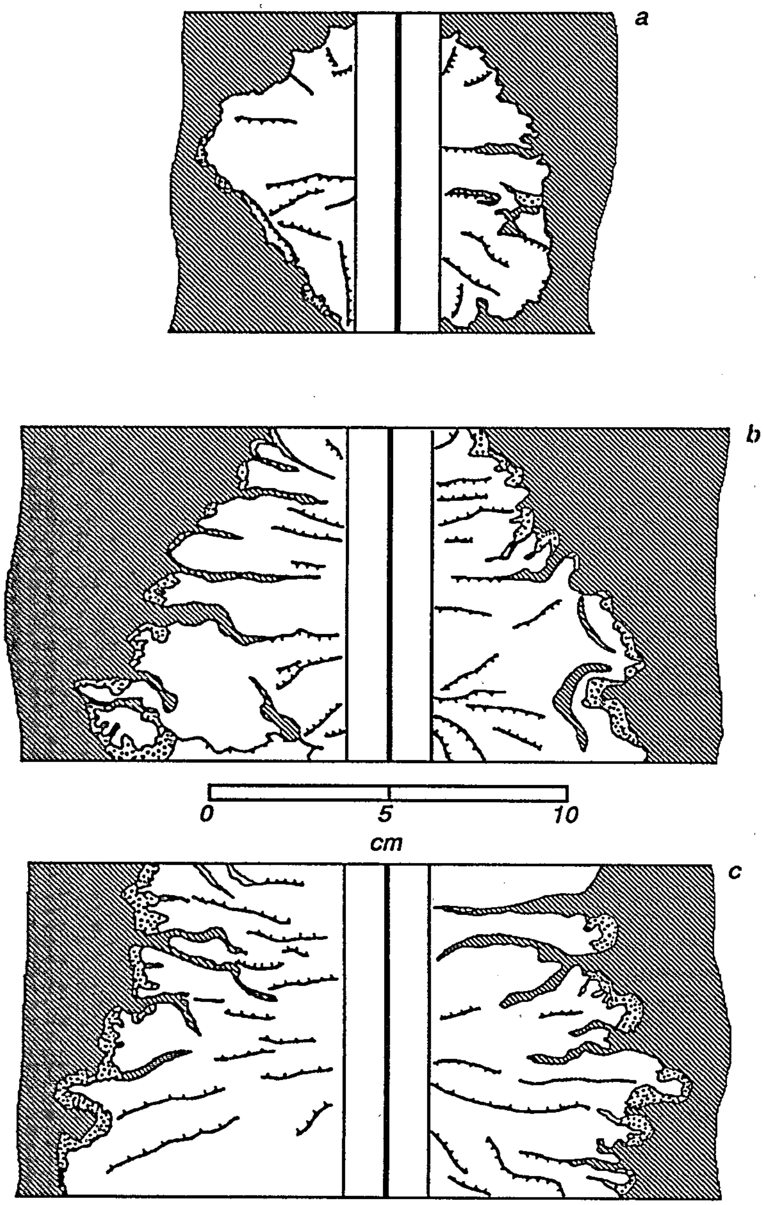

Figure 2. Surfaces of three hydraulic fractures of various lengths. Lines on fracture surfaces are linear features and hatch marks on the lines indicate the lower side of a step. Fractured, but undyed areas are stipled. Heavy lines indicate overlap of lobes.

lyze hydraulic fractures in rock, were used to explain forms of the pressure records (Figure 3). Critical stress intensity, a material parameter proportional to the product of P_d and the square root of the fracture length, appears to adequately predict the onset of propagation in Center Hill clay. It is a strong function of moisture content, decreasing by nearly an order of magnitude because of an increase in moisture from 0.20 to 0.23. Preliminary analyses of fracture propagation can reproduce most of the essential features of the pressure records from the laboratory experiments. The growth of an unwetted zone at the fracture tip was included in the analyses and helps to explain stable propagation at the onset of fracturing.

Field Testing: 1988

The 1988 field test was conducted at a site 10 km north of downtown Cincinnati on the western side of the valley of Mill Creek, a southerly flowing tributary of the Ohio River. The site is on the southeastern side of an area owned by the ELDA Company, who currently uses it as a municipal landfill.

The site is underlain by glacial drift composed of silty clay till overlain by upwardly grading beds of gravel, sand, silt and clay that are probably outwash deposits. Most of the fractures were created in the silty clay till. Regional ground water is several tens of meters below the ground surface — the till was unsaturated during the tests. Consolidation tests and in situ hydraulic fracturing tests indicate that the till is overconsolidated; that is, the lateral stress exceeds the vertical stress.

Boreholes used during the fracturing tests were open over the bottom few dm, and a casing was cemented from the open interval to the ground surface. Depths of the boreholes ranged from 1.6 to 3.8 m. Halliburton Services, a subcontractor, was hired to create the fractures. They used equipment and methods designed to hydraulically fracture oil wells.

Ten hydraulic fractures were created in the till during the 1988 tests. The vicinity of each fracture was excavated and mapped to reveal size, shape, location, and form. Fracture forms differ in detail, but they are characterized by the idealized form in Figure 4. A subvertical fracture occurs in the vicinity of the open interval of the borehole, indicating that shallow notches cut in the walls of the bores were insufficient to nucleate a fracture. The major part of the fracture consists of a planar to trough-like feature dipping shallowly toward the parent borehole. Note that the fracture is highly asymmetric with respect to the borehole; this asymmetry was common. Most of the tests terminated when the fracture vented to the ground surface several meters from the parent borehole. Fractures reached an average length of 5.8 m, an average plan area of 25.5 m^2, and an average dip of 20°.

Field Testing: 1989

Field observations during the first test indicated that it was feasible to create hydraulic fractures, but they also highlighted three shortcomings: 1) sand proppant was sparse or absent in seven out of ten fractures, so those fractures closed completely and would have had negligible effect on flow in the subsurface; 2) the maximum dimensions of the fractures were limited by venting to the ground surface; and 3) the test was conducted using sophisticated

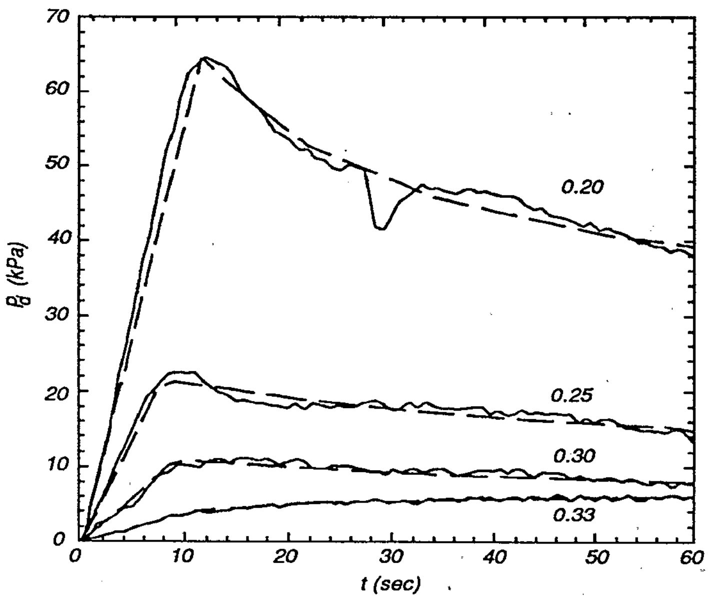

Figure 3. Records of driving pressure as a function of time from experiments and from analytical solution (dashed) for samples of various moisture contents.

equipment that would be inaccessible to most environmental engineers.

The method of creating hydraulic fractures was modified to reduce the shortcomings of the 1988 tests. The new method was tested in the field during June and July 1989 at the ELDA site and at another site also underlain by till.

The injection fluid used during this project is a gel formed from commercially available guar gum and water. The viscosity of the basic gel is roughly 20 centipoise, but it increases markedly upon addition of a borate compound called a *crosslinker.* The crosslinked gel is a thixotropic fluid with an apparent viscosity of roughly 200 centipoise. An enzyme is added that breaks down the gel to roughly 10 centipoise between 12 and 18 hr after injection. Coarse quartz sand (0.8 to 1.5 mm average grain size) was mixed with the crosslinked gel to complete the formulation of the injection fluid. Concentrations of sand ranged to as much as 0.52 (vol sand/vol gel) during the field tests.

The above-ground system consisted of pumps and mixers similar to those used during injection grouting operations. Injection rates ranged between 20 and 60 L/min during the tests.

Below ground, a system of isolating an interval of a borehole was developed specifically for use in unlithified material. The system is based around a lance-like device (Figure 5) composed of a casing and an inner rod, both of which are tipped at one end with hardened cutting surfaces that form a conical point.

During the 1989 tests, the lance was driven 1 to 2 dm below the bottom of a borehole (the borehole was either open or contained a hollow stem auger). A water jet was used to cut a disk-shaped notch extending up to 40 cm away from the borehole.

Hydraulic fractures were created by injecting the sand-laden slurry into the casing. Lateral pressure of the soil on the outer wall of the casing effectively sealed the casing and prevented leakage of the slurry. The fractures nucleated at the notch and grew away from the borehole.

During a typical field test, the onset of pumping was marked by a sharp increase in pressure of the injection fluid to between 0.1 and 0.4 MPa. The onset of fracture propagation, however, was marked by an abrupt decrease in pressure. During propagation, injection pressure either was roughly constant and on the order of 0.06 MPa or pressure decreased slightly with time. After one fracture was created, the rod and point were inserted and the lance driven 7 to 30 cm lower, where another fracture was formed. This procedure was repeated as many as four times for each borehole (Figure 5).

The method of hydraulic fracturing described above was field tested in June 1989 with the creation of 23 fractures at two sites in Cincinnati, Ohio. Nineteen of those fractures were created adjacent to the ELDA Landfill, within 100 m from the site of the 1988 tests.

Results

Hydraulic fractures exposed by excavation after the 1989 tests were remarkably similar in form. Three fractures created at borehole EL6 are a typical example (Figure 6). The fractures are horizontal and equant to slightly elongate in plan. They are highly asymmetric with respect to the borehole, however, with a preferred direction of propagation roughly parallel to the slope of the overlying ground surface. The fractures are stacked one on top of another at a spacing of 30 cm, which is maintained from borehole to leading edge (Figure 7). The major plan axes of the fractures range from 5.5 to 8.5 m, and the maximum thickness of sand is 1.3 to 1.4 cm. The sand proppant is thickest near the centers of the fractures, and it thins as the edges are approached. Apparently, the distribution of sand is independent of the location of the borehole.

Inflow tests were conducted before excavation using a Guelph* permeameter, a device that yields the flowrate required to hold a constant water level in a borehole. Water levels were held at 1.0 m above the bottom of open boreholes during all tests. The average inflow rate into three boreholes in unfractured ground is 0.055 L/min. The rate of inflow into boreholes intersecting hydraulic fractures was initially 0.25 to 2.5 L/min, but decreased to between 0.175 and 0.5 L/min at steady state. We conclude that the steady-state rate of inflow increased by a factor between 3.2 and 9.1 as a result of the creation of the fractures.

Discussion of Field Tests

The principal shortcomings of the initial (1988) field tests were reduced using the method of fracturing described above. All 19 of the excavated fractures were filled with sand proppant, and the maximum thickness of the sand in the fractures was 11.2 mm, on average. The fracturing method thus appears to be a consistent means of creating permeable layers in the subsurface, at least for the field conditions of this test.

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*Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

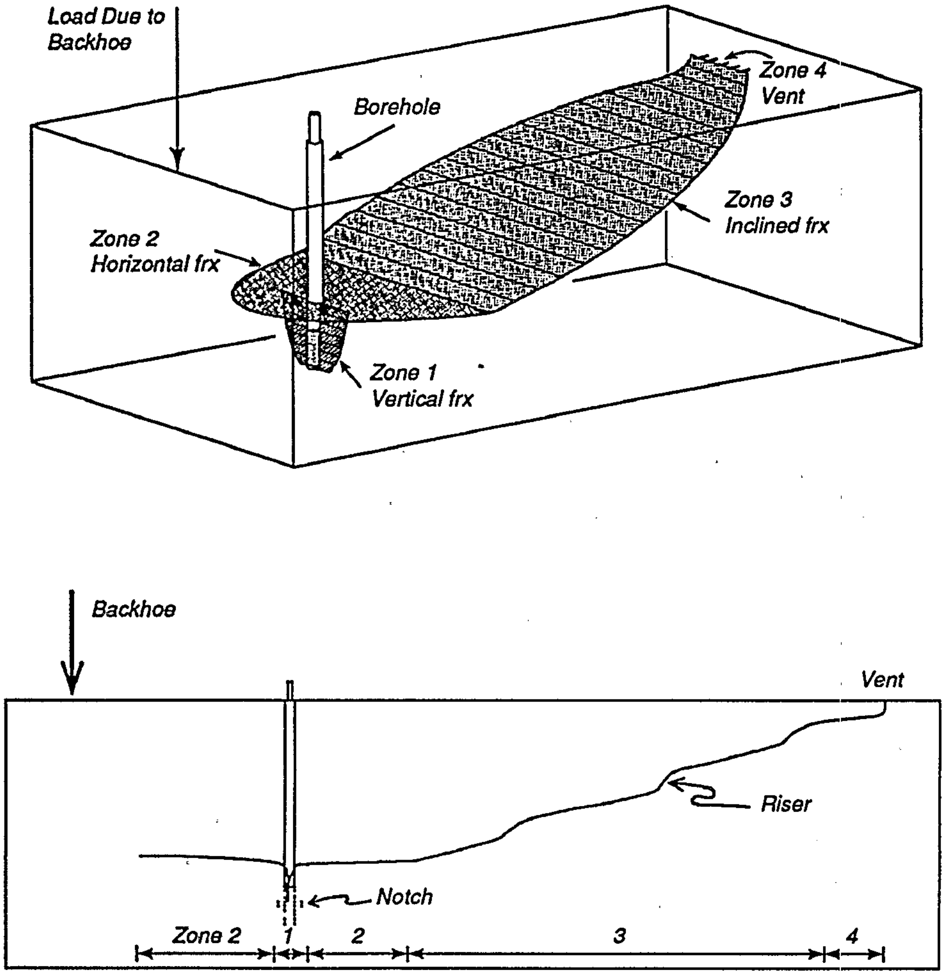

Figure 4. Idealized hydraulic fracture created at the ELDA test site. Inferred from exposures of fractures created beneath level ground. a) Oblique view. b) Section along major axis of the fracture.

Hydraulic fractures created during the 1988 tests climbed gently toward the ground surface where they vented; whereas the ones created during the 1989 tests were essentially horizontal and typically did not vent. There were at least three aspects of the 1989 fracturing procedure that could have inhibited the tendency of hydraulic fractures to vent:

1. *Pumping rate was reduced* from 75 to 420 L/min in 1988 to 20 L/min in 1989.
2. *Density of injection fluid was increased* by increasing the sand content 0.09 to 0.18 during 1988 to as much as 0.52 during 1989. The density increase reduces buoyancy effects.
3. *Radius of the notch was increased.* Vertical fractures nucleated at the wellbores during 1988, but the larger notch caused horizontal fractures to nucleate during the 1989 tests.

The mixers and pump, key components of the above-ground fracturing equipment, were rented from a geotechnical equipment company who designed them to be used for injection grouting. Similar equipment should be widely available and accessible to most environmental engineers. Although propped fractures were consistently created with this equipment, it was far from ideal. The mixers and pump were underpowered for this application, and the pump suffered excessive wear and had to be replaced at the end of the tests. Slight modifications in the design of the pump and mixer should improve the efficiency of the field procedure.

The below-ground equipment performed adequately, facilitating the creation of multiple fractures from a single borehole. As many as four flat-lying fractures were stacked at spacings of 30 cm without intersecting their neighbors. When fractures were created at a spacing of 15 cm, the lower fracture would commonly climb and intersect the overlying fracture several m from the borehole.

It has long been recognized that the orientation of a hydraulic fracture depends largely on the in situ state of stress, with the plane of the fracture normal to the direction of least principal compression. That direction is vertical in shallow bedrock and overconsolidated soil, which explains the horizontal orientations of fractures at the ELDA site. The orientation of hydraulic fractures at other sites, such as sites underlain by normally consolidated soil or fill where the direction of least principal compression is expected to be horizontal, may differ markedly from the orientation of fractures described here.

Conclusions

1. Hydraulic fractures were created at shallow depths (several m) during field testing in glacial drift. Fractures were flat-lying, to gently dipping, slightly elongate in plan, and 6 to 8 m in maximum dimension. They were filled with coarse-grained sand to a thickness of roughly 1 cm.

   Site conditions, particularly the state of stress, are expected to markedly affect the form of hydraulic fractures. As a result, hydraulic fractures created at other sites may differ from those described here.
2. A method of creating hydraulic fractures in unlithified sediment was developed and tested. The method facilitates creating multiple fractures from a single borehole.
3. In the laboratory, hydraulic fractures were created by injecting dyed glycerin into samples of silty clay with a range of moisture contents. Features of the fractures were remarkably similar to features of hydraulic fractures in rock, even when the silty clay was relatively soft and saturated with water. Analyses using linear elastic fracture mechanics can predict hydraulic fracturing of silty clay in the laboratory.

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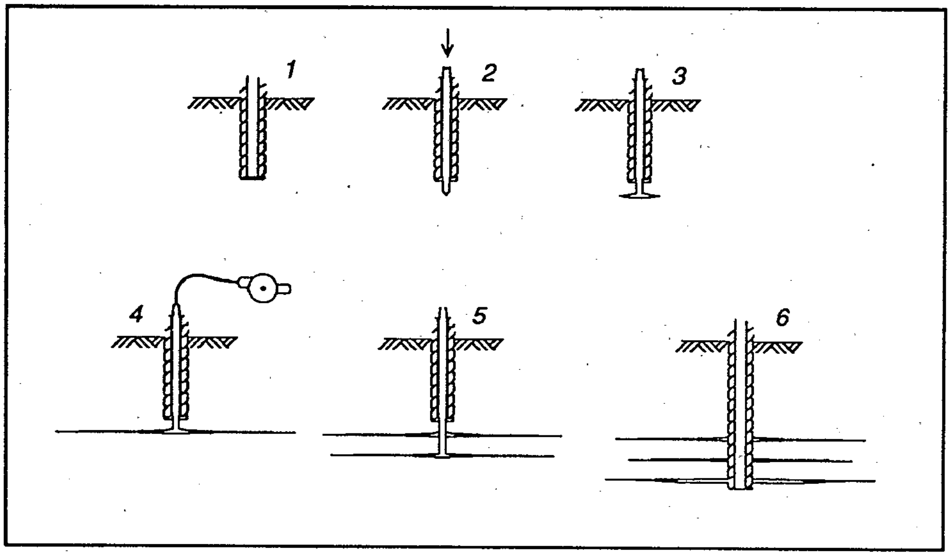

Figure 5. Hydraulic fracturing procedure. 1. Hollow-stem auger, 2. drive lance, 3. cut notch, 4. inject slurry to create hydraulic fracture, 5. advance lance, 6. advance auger.

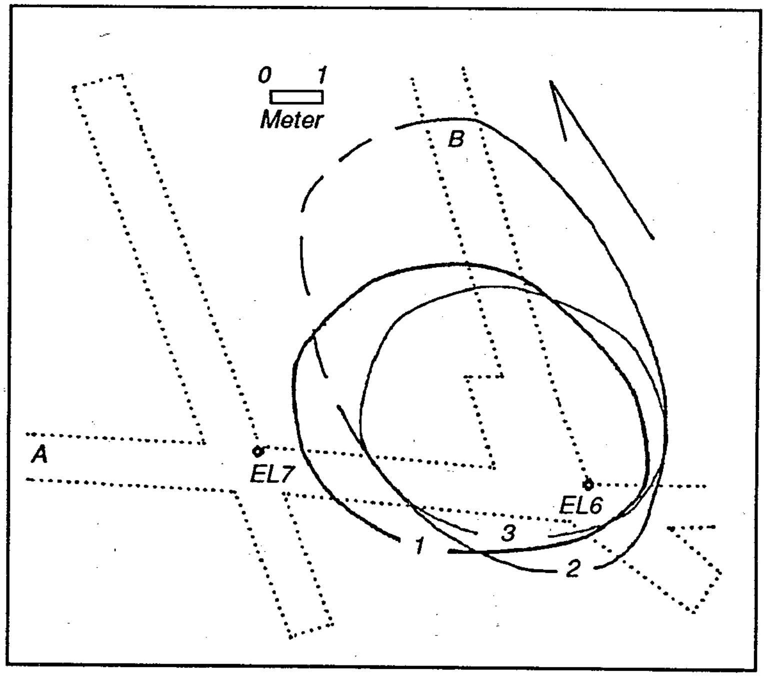

Figure 6. Map of three fractures created at borehole EL6. Dotted line is wall of trench. Dashed line where fracture 2 intersects a neighboring fracture (not shown) was created from borehole EL7.

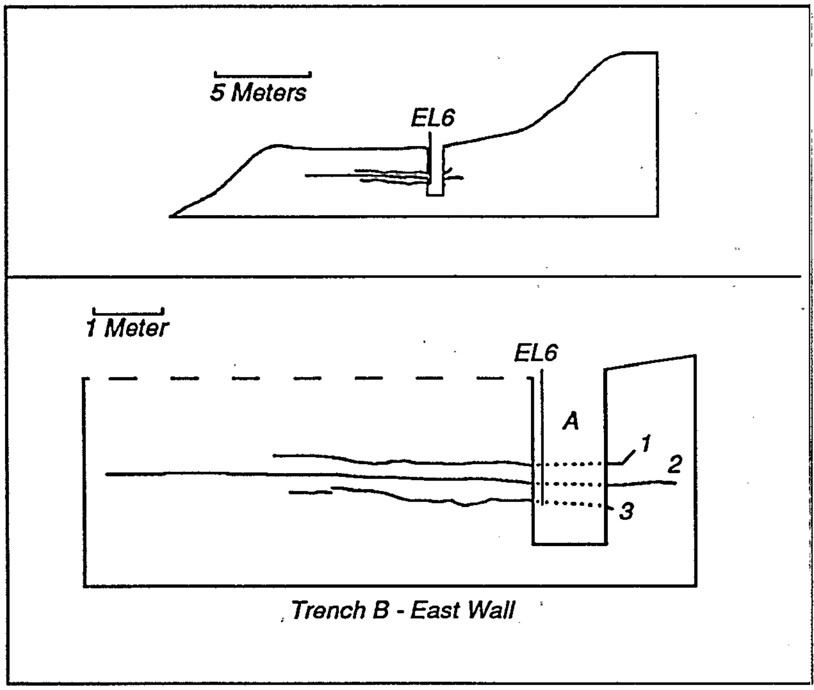

Figure 7. *Cross-sections of three fractures created at borehole EL6 showing topographic profile (upper) and details of fracture traces (lower)*

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The complete report, entitled "Feasibility of Hydraulic Fracturing of Soil to Improve Remedial Actions," (Order No. PB91- 181 818/AS; Cost: $39.00, cost subject to change) will be available only from:

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The EPA Project Officer can be contacted at:

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