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Field-Scale Pilot Test Evaluating Pneumatic Fracturing in Clayey Till

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ABSTRACT: The goal of this study was to evaluate the effectiveness of pneumatic fracturing and to evaluate different methods for documentation of tracer distribution in fractures in a clayey till. A mixture of different tracers was injected with the nitrogen gas flow used in the fracturing process. A number of induced fractures were detected in core samples taken at distances of up to 3 m from the fracturing well. The use of digital imaging of the fluorescence of fluorescein under UV-light proved to be a very efficient way to locate fractures in the core samples. The visual fluorescence observed was in close agreement with the analysis of soil samples and also in fair agreement with the water samples taken from depth specific suction cells. A preliminary mass balance indicated that 90% of the tracer mass was distributed within 1-2 m from the fracturing well. Further investigations are on-going to improve the determination of the actual radius of influence, mass balance and fracture network.

INTRODUCTION

Contaminated sites in Denmark are frequently located in areas with low permeable soil types as clayey till. The primary challenges remediating hot spot areas at such sites are to overcome mass transfer limitations by diffusion and to distribute the reagent in the soil matrix in order to establish contact between the contamination and the reagent intended for clean-up. Pneumatic fracturing has been suggested as a method to overcome these challenges (Shuring, 2002).

A pneumatic fracturing pilot test has been carried out in December 2005 at a clayey till site in Hedehusene, Denmark (Københavns Amt, 2006). This is the first field-scale application of pneumatic fracturing in Denmark. The objective of the pilot test is twofold: (1) Demonstrate whether it is possible to use pneumatic fracturing to create a fracture network to obtain an adequate distribution of reagent in the soil matrix, and (2) Compare an array of methods for documentation of tracer distribution in the clayey till.

Field Site Description. The site situated in Hedehusene, Denmark, is a former station for handling of waste chemicals. The pilot test area is located outside the contaminated area. The geology at the site consists of 14-16 meters of clayey till, underlain by 2-3 meters of fine sand.. The till is a typical Danish basal till with an overconsolidation ratio of around 10 in the upper 9.5 m bgl. Three systems of natural fractures are identified at the site (Christiansen and Wood, 2006): One system of horizontal glacial-tectonic shear fractures, primarily found above the redox boundary at 4 m bgl. The largest density of horizontal fractures is found at 1 m bgl. Furthermore, two systems of vertical glacial-tectonic shear fractures are found. The density of the vertical fractures is also largest in the upper few meters and then decreasing with depth. The vertical fractures are only assumed to be present in the upper 6 meters of the formation.

MATERIALS AND METHODS

Pneumatic fracturing was performed in one borehole at 5 individual 1-meter long depth intervals between 3 and 8 meters bgs. A mixture of tracers has been injected in each interval using Liquid Atomized Injection. The injected tracer mixture consisted of sodium bromide, brilliant blue, and three fluorescent tracers: Fluorescein, Rhodamine WT, and Uvitex (optical brightener). The concentration of each of the tracers in the mixture was approximately 7,000 mg/l. The purpose of injecting tracers was to facilitate identification of the fractures at various distances and depths from the fracturing well and thereby document the actual radius of influence, mass balance and fracture density obtained by the pneumatic fracturing. A total of 50 liters of tracer mixture was injected at each fracturing interval. ARS Technologies Inc. performed the fracturing and injection (www.arstechnologies.com).

During the fracturing and injection in each interval, field observations of pressures in the fracture intervals, pressure response at adjacent wells, and ground surface heave were recorded. The pressure in the fracture interval was recorded by a pressure transducer located in-line within the conduit leading to the injection nozzle. Pressure response was recorded in 4 well clusters located in 4 directions at 5 meter's distance from the fracturing well, corresponding to the expected radius of influence (ROI). The well clusters were screened at three depths each. Pressure response in these wells was recorded using calibrated pressure gauges in target wells and taped-on plastic gloves on the others. Both the pressure response data and the ground surface heave data contributed to a preliminary assessment of the extent of fracture propagation.

A thorough sampling programme was conducted in order to retrieve the fluorescent tracers and bromide at the site (Figure 1). Immediately after the fracturing event, 9 CPT-push tests were performed with a FFD-detector (**F**uel **F**luorescence **D**etector) and three core samples were collected, each of 8-10 meters length. The core samples were split open in a laboratory and photographed under UV-light (312 nm) for visual detection of the fractures. The cores were sub-sampled in areas with visible tracer. Following this, five wells were installed at the site, each screened at three depths. Fractures with high

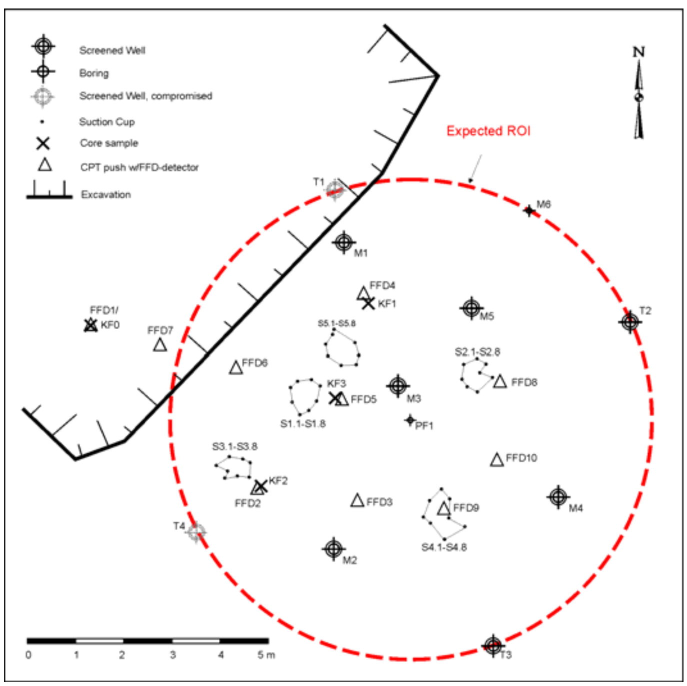

FIGURE 1. Site plan with sampling locations.

concentrations of tracers were detected visually during drilling and selected soil samples were analyzed. 40 suction cups were installed at five locations within the test area at eight discrete depths. Water samples were collected from the well clusters and the suction cups 1½ weeks and 5 weeks after the fracturing event. All soil and water samples were analyzed for bromide, fluorescein, and rhodamine WT.

RESULTS AND DISCUSSION

Comparison of methods for detecting the injected tracers. A close-up picture of core KF3 illuminated with UV-light is shown in Figure 2. In the right hand side of the photo, a distinct fracture can be seen with white coloured fluorescence due to the Uvitex tracer. On both sides of the fracture, in the depth interval of 5.73-5.76 m bgl, a green halo of fluorescent tracer is apparent. The difference in colour between the fracture and the matrix is due to the different properties of the injected tracers. As expected, fluorescein is seen to diffuse fast into the clay matrix, whereas both Uvitex and Rhodamine WT mainly stay in the induced fracture due to sorption. In daylight the fracture appear purple due to the presence of Rhodamine WT. In the middle of the photo a green fluorescent area of fluorescein is observed, but without the presence of a visually detectable fracture.

Similar fracture zones are detected in all three cores (KF1-KF3). In cores KF1 and KF2 soil samples have been analysed in and around the fracture zones. The soil analyses confirm the visual identification under UV-light, and show high concentrations of tracers close to the fractures. The visual detection limit of the fluorescein under UV-light is in the order of 1-10 mg/kg. Due to its properties, the bromide has diffused further away from the induced fractures than both fluorescein and rhodamine WT. Overall there is a very good correlation between the two methods, but the soil sampling and analysis is much more time consuming and expensive than the photographic detection.

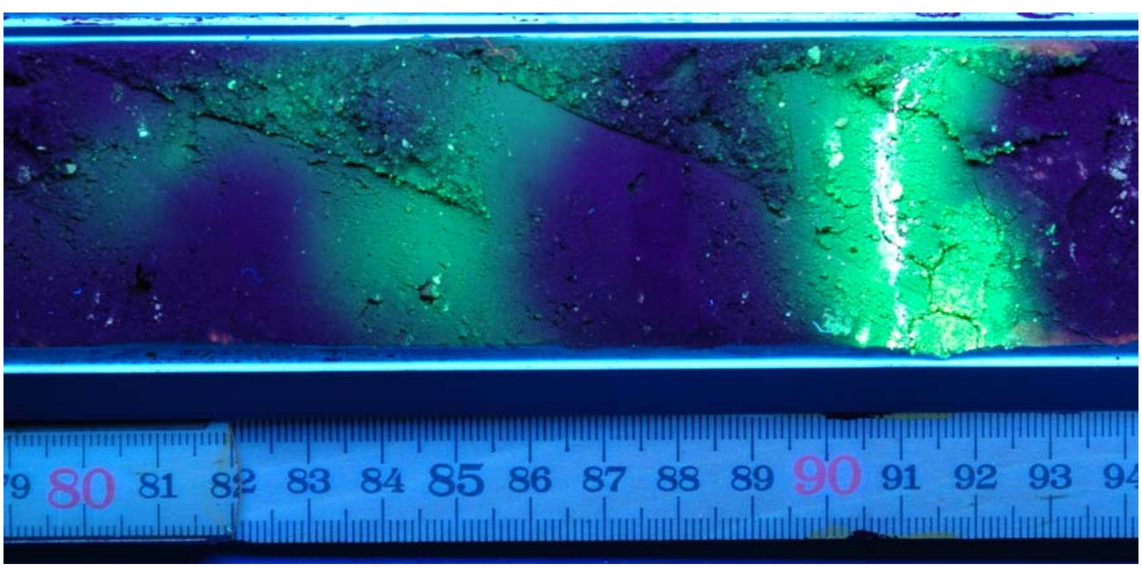

FIGURE 2. Close-up photo of a visible fracture under UV-illumination in core KF3 5.73-5.76 m bgl.

An example of the results for a full profile from surface and down to 8 m bgl. are shown in Figure 3. A very good correlation between the intervals with UV-fluorescence and the soil samples were obtained for all cores. The split spoon samples from every 0.5 m interval shows generally a measurable amount of tracers from 2 to 7.5 m bgl., but most concentrations are lower than can be detected under UV-light. The water samples taken from the suction cells (S5) show elevated concentrations from 4 to 6.5 m — corresponding to the depth interval where visible fluorescence has been detected under UV-light. The water samples from the traditional well screens (M1) show little variation over depth, and are probably affected by a combination of cross contamination during installation and a possible direct contact with water in fractures intersecting the approximately 1 m long screens. The FFD measurement (FFD4) shows 3 intervals with response on the left channel — indicative of the presence of the Uvitex tracer. In general the correlation between the FFD response and the other methods is scattered.

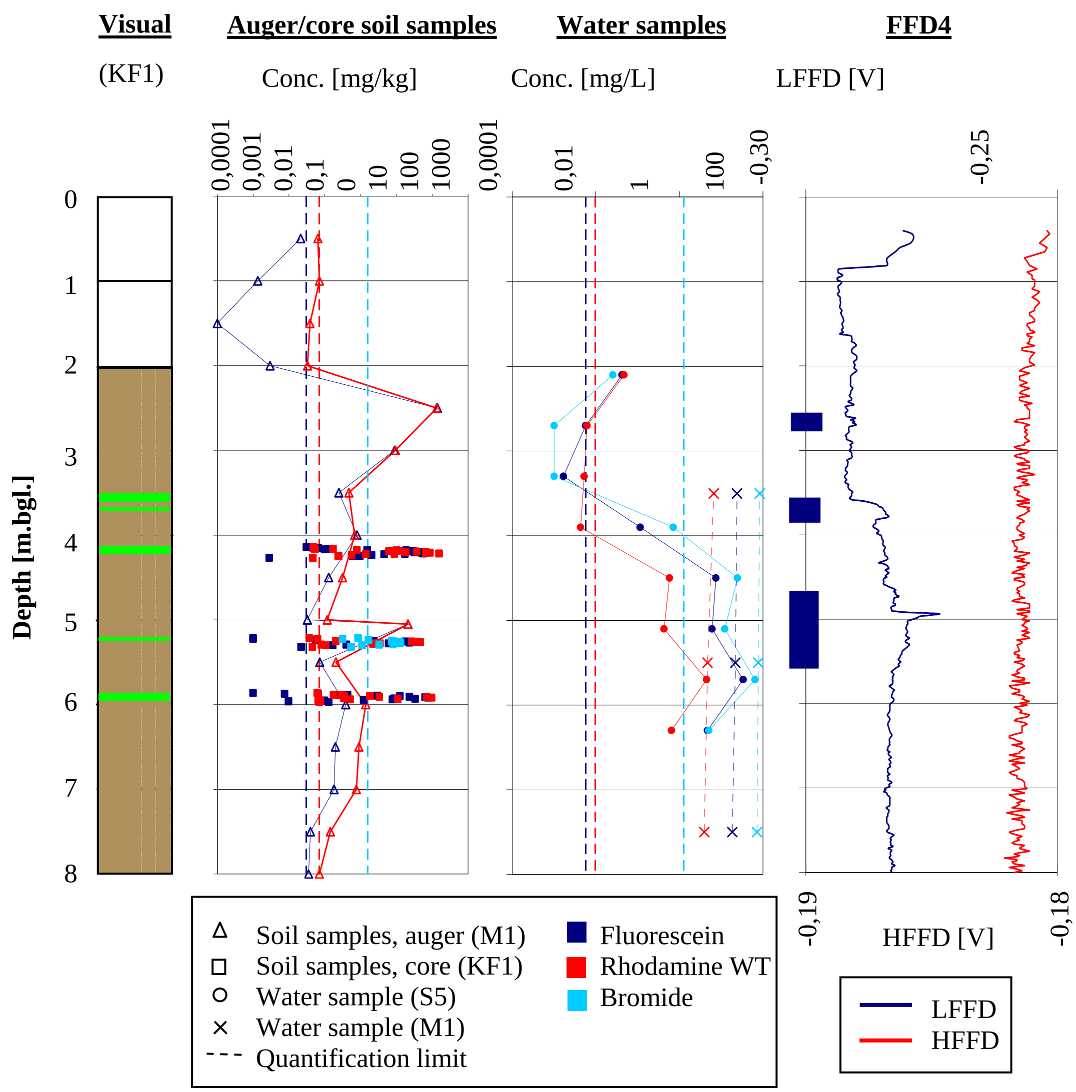

FIGURE 3. Comparison of soil samples, water samples, UV-fluorescence, and FFD-detector.

Distribution of induced fractures. A preliminary conceptual sketch of the distribution of fractures through a cross-section of the test area is shown on Figure 4. Distinct fractures with high concentrations of tracers have been observed over the entire fracturing interval (3-8 m bgl) at distances up to 6.8 m from the fracturing well PF1. The distance between the visible fractures in the 3 cores sampled are between 0.5 and 2.5 m. Close to the fracturing well (<1 m) the visual tracer observations are more closely spaced in soil samples taken with ordinary auger methods (M3). A closely spaced fracture system is observed at greater distances (1.5-3 m) from PF1 at 6-7 m's depth. This suggests that at depths below 5-6 m, where the density of natural fractures has decreased significantly, the possibility of creating a fingered fracture network is greater.

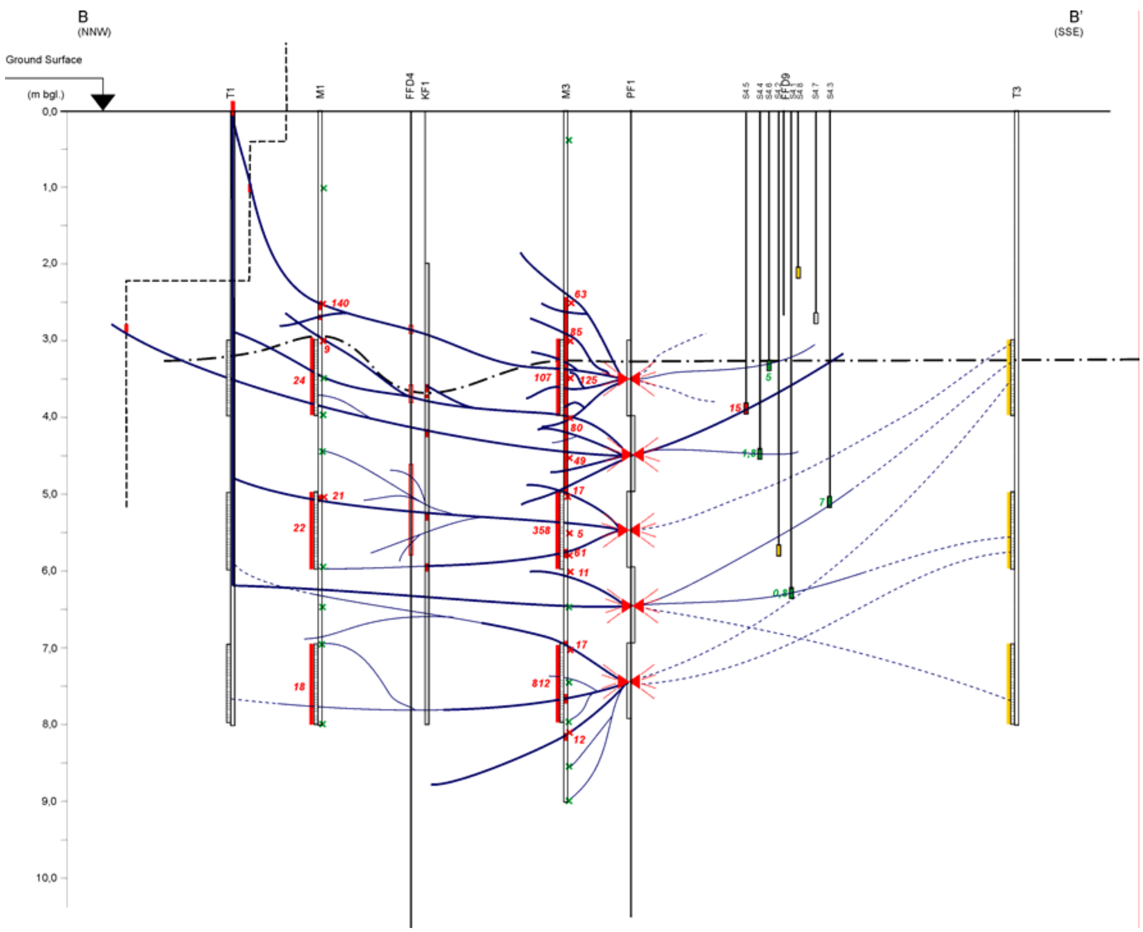

FIGURE 4. Conceptual distribution of fractures based on all measurements.

The fractures tend to propagate towards the surface, either because they propagate in a bowl-shaped manner and/or because horizontal, induced fractures cross natural, vertical or subvertical fractures and then propagate vertically towards the surface in the path of least resistance.

Further core sampling is on-going to improve the documentation of the actual radius of influence and fracture network.

Preliminary mass balance for tracers. **A**pproximately 90% of the fluorescein can be accounted for based on the measured tracer concentrations in soil and groundwater. The rhodamine WT mass is overestimated by approximately 66 %. It is estimated that 90% of the tracer mass is to be found within a distance of 1-2 m from the fracturing well, and from approximately 2 to 6 m bgl. The mass balance is uncertain due to very few measurement points at distances from 0.75 to 2.75 m from the fracturing well. More sampling within this distance from the fracturing well is underway, and will improve the preliminary mass balance calculations.

PRELIMINARY CONCLUSIONS

The pneumatic fracturing of the overconsolidated clayey till has resulted in the creation of a number of fractures visible in core samples. The use of the photographic recording of the fluorescence by fluorescein under UV-light has been found to be a very effective tool to localize the fractures in core samples shortly after fracturing. After some time diffusion will generate considerable halos of fluorescein, that will eventually overlap. By then, rhodamine WT will be better suited to distinguish the fractures, since this tracer sorbs to the fracture surface. These observations combined with subsequent analysis of soil samples and water samples from suction cells further aid in the delineation of the tracer distribution in the soil. Further sampling and soil analysis for the tracers are underway, and will improve the preliminary mass balance calculations for the tracers and improve the understanding of the achieved tracer distribution in the subsurface. This understanding is crucial for future application of the pneumatic fracturing method in cases where chemical reagents need to be efficiently distributed in the soil.

ACKNOWLEDGMENT

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