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TECHNOLOGIES FOR A FAST CHARACTERIZATION OF SUBSURFACE STRUCTURES - AN EXAMPLE FROM THE MILANO-RHO SITE

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ABSTRACT

At large scale contaminated sites the typically applied approach of conventional, drilling-based investigations is prohibitive expensive, and information will be solely available at a limited number of boreholes. Hence, it can be expected that great uncertainty exists about relevant subsurface structures, their physical and geochemical properties, and on the distribution of contaminants in the subsurface. As a progress in site characterization, geophysical methods can be combined with Direct Push technologies. Especially, the combination of Direct Push technologies with pulled geophysical arrays provides a new scientific and economic relevant extension of traditional site investigation concepts.

We will present a field test demonstration, which shows a variety of methods for a rapid and effective site characterization in terms of structure, hydrogeological, and chemical parameters at a field site in Rho (Milano, Italy). The measured data of high quality and resolution will help to improve the conceptual model of the site.

Key Words: DC-geoelectrics, Ground Penetrating Radar, Direct-Push, Cone Penetration Testing, CPT, Injection logging

INTRODUCTION

As a result of industrial, military, and mining activities in Europe during the past century a considerable number of large scale contaminated sites with complex contamination history - so called megasites - exists. The resulting contaminations particularly of groundwater, surface water, and soil have the potential to impact human and environmental health. Even economic development is affected by contaminations due to strategic planning constraints.

In addition, the typically applied approach of conventional, drilling-based investigations of these sites is prohibitive expensive, and information will be solely available at a limited number of boreholes. Hence, it can be expected that great uncertainty exists about relevant subsurface structures, their physical and geochemical properties, and on the distribution of contaminants in the subsurface. This leads to a lack of information preventing a reliable prediction of groundwater flow and the behaviour of contaminants in the subsurface. To bridge this gap, reliable and efficient technologies and methods are required to investigate such megasites to the needed degree of resolution. In this context, the correlation of processes at the micro-scale (dm range) up to dispersals of pollutants at the macro-scale (several kilometres) is one of the major challenges for subsurface. So far an insufficient combination and integration of mapping and measurement results at the different scales causes a lack of understanding of the investigated systems. For this purpose, geophysical methods can be combined with Direct Push technologies. Especially, the combination of Direct Push technologies with pulled geophysical arrays provides a new scientific and economic relevant extension of traditional site investigation concepts.

The purpose of this paper is to present a field test demonstration, which shows a variety of methods for a rapid and effective site characterization in terms of structure, hydrogeological, and chemical parameters at the Milano-Rho site. The site is particularly suited because an extensive characterization by means of conventional methods has already been carried out allowing for demonstrating the effectiveness of the proposed approach of innovative site investigation and remediation tools, that were developed in recent research projects of the University La Sapienza and the UFZ (SAFIRA II).

SAFIRA II RESEARCH PROGRAMME

The SAFIRA II Research Programme (funded by the German Helmholtz Foundation) addresses the cost-effective and sustainable development-oriented management of contaminated land and groundwater at megasites. To increase the re-use of (the partly or formerly) contaminated land at those sites, a management system is developed which allows for a simultaneous consideration of the objectives and requirements arising from "risk management" and from "sustainable land planning" and thus, an improved control of decision making (Schwarze *et al*., 2005).

The major technical element of the SAFIRA II programme is the development of innovative and cost-effective site investigation and remediation technologies for megasites (Bittens *et al*., 2005). Selected techniques focus on the localization and (partial-) removal of contaminant source zones, the treatment of complexly contaminated waters, the stimulation and optimized use of naturally occurring degradation processes, and the intelligent monitoring of remediation performance and overall groundwater quality targets. The performance of these methods and their applicability within the context of the integrated management system will be evaluated at national and international reference field sites. One of these sites was the Milan Rho field site.

THE MILANO-RHO SITE

The site is located in Rho (Milano, Italy) where at a former chemical facility chlorinated solvents intruded into the subsurface, probably acting as source of a contaminant plume that extends over approximately 0.4 km^2. In 1982, an emergency containment action was undertaken, which consisted in the lateral and superficial isolation of a central source zone. Groundwater monitoring downgradient of the potential source area during the last 15 years indicates an almost stable presence of high concentrations of chlorinated solvents (e.g. up to 180 mg/l trichloroethene, 50mg/l 1,1,2,2-tetrachloroethane) in an underlying aquifer. At present, the area is partially used for industrial activities (northern part), whereas in the southern part it is planned to re-use the land as a residential area. At the Rho site several wells have been installed to trace and treat the contamination at the site. From the well logs the following geological interpretation was drawn: A first phreatic aquifer with an average saturated thickness of 35 m extends down to a depth of 45 m and consists of gravels and sands with limited and isolated silty-clayey lenses. A clayey layer at 5-9 m below ground level with a varying thickness between 0.5 and 2 m is locally separating a "shallow aquifer" from the first aquifer. The first aquifer is separated from the underlying second aquifer by silty-clayey lenses varying in thickness between 5 and 10 m. This confined aquifer extends from 50-80 m below ground level and is characterized by average-fine grain-sized sediments. The main direction of the flow of the first aquifer is NW-SE.

More details on the site and the ongoing activities on the Milano-Rho site are given in the paper by LECCESE *at al*., 2007 also published in this issue.

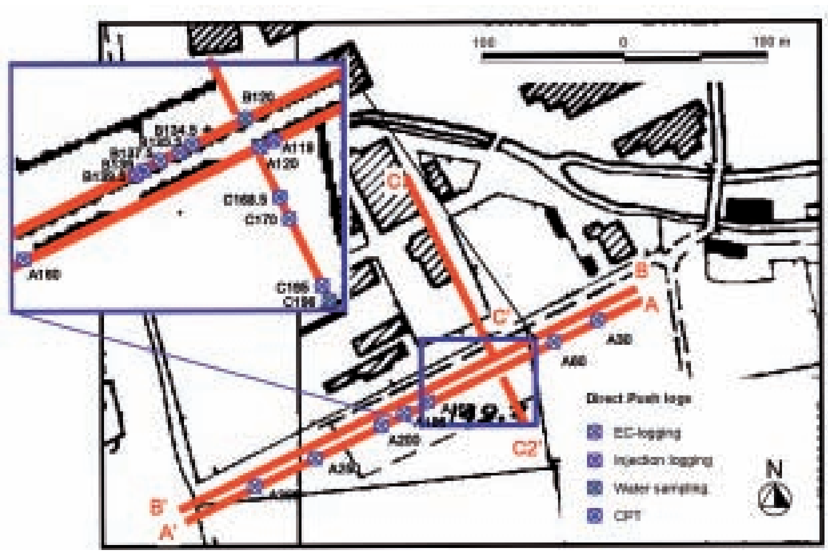

Fig. 1 - Overview of Geophysical and Direct Push investigations (red lines indicate location of the geophysical survey profiles)

SITE INVESTIGATION BASED ON GEOPHYSICAL AND DIRECT PUSH METHODS

At the site several geophysical surface measurements and direct push techniques were conducted in order to demonstrate their suitability for a fast hydrogeological and chemical subsurface characterization. An overview of the investigations implemented at the site is reported in Figure 1.

Geophysical Methods

At present, numerous possibilities for the application of geophysical surface measurements exist that allow for the acquisition of spatially continuous data aiming on a characterization of relevant subsurface structures. For this purpose, DC-geoelectrics and ground penetrating radar (GPR) were applied at the Milano-Rho field site.

DC-geoelectrics is widely applied for mapping hydrogeological bedding and subsurface structures. Extensive descriptions can be found e.g. in KIRSCH (2006) and RUBIN & HUBBARD (2005). For DC-geoelectrics with galvanic coupling two electrodes were used to inject current into the ground, whereas two other electrodes were used to measure the potential.

At the Rho field site, four DC-geoelectric profiles were conducted for fast mapping of subsurface structures. In the following, the first of these profiles is presented utilizing a 1.5m spacing from 0.5 to 335.5 m (profile A-A'). Along the profile, eight borehole logs exist (0151820351, 0151820350, 0151820347, 0151820348, 0151820349, 0151820750, 0151820667, and 0151820666; Figure 2).

Both a Grounding test and Wenner array profile were selected for the measurements along profile A-A'. The Wenner array in comparison to Dipole-dipole and Schlumberger arrays turned out to be the best configuration because of high noise rates at the field site. Even though problems with coupling of the electrode caused by highly compacted material at the surface occurred, the penetration and signal quality during the measurements were sufficient.

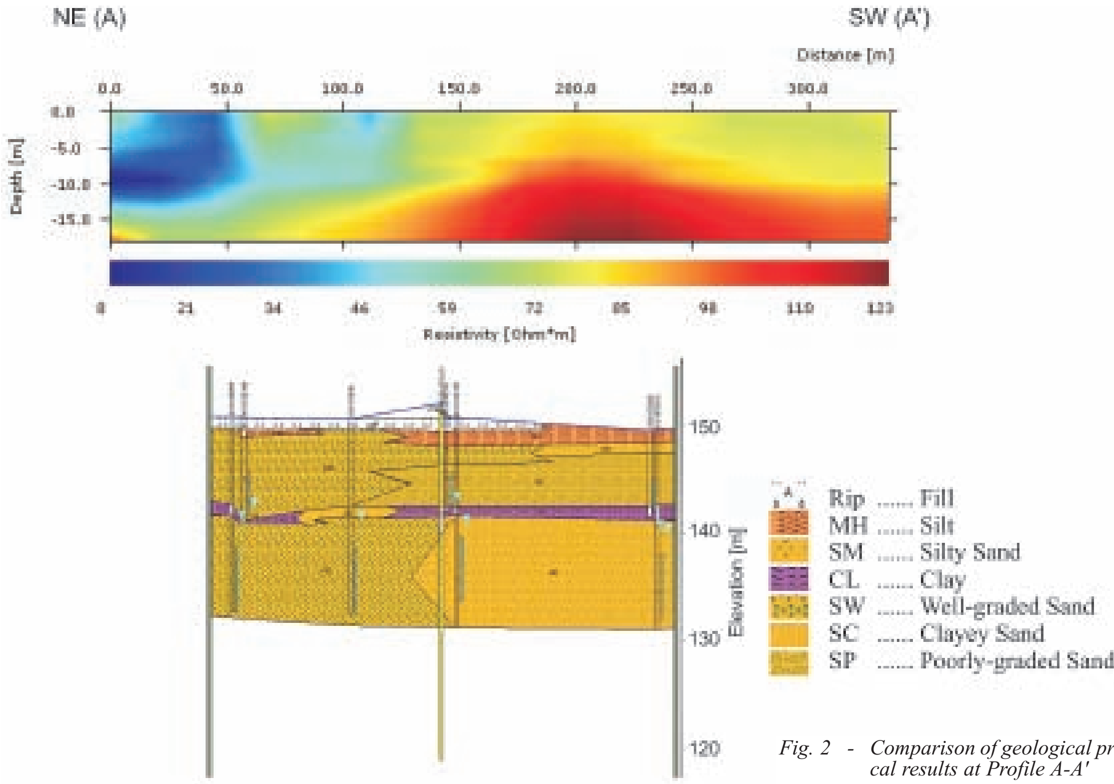

Fig. 2 - Comparison of geological profile and inverted DC-geoelectrical results at Profile A-A'

The inversion of the results is shown in Figure 2 and indicates mainly two different structures within the subsurface. A zone of low resistivity down to 12 m exists at the beginning of the profile until 120 m. The low resistivity zone corresponds with well graded material described in the borehole logs. From 125 m until the end of the profile higher resistivities are mapped, that area corresponds with poorly graded material. Especially the middle part of the profile shows increasing resistivities with depth. The thickness of a suspected clay layer of approx. 1m at a depth of 10 m is below resolution of surface geoelectrics.

Furthermore, OhmMapper® surveys were conducted throughout the field study in completion to the DC-geoelectrical profiles. The OhmMapper® is a mobile geoelectrical technique and more time efficient than DC-geoelectrics with fixed electrodes. Capacitive coupling of the dipoles allows towing the device and promises a faster mapping of the field site. Profile A-A' was studied by towing the OhmMapper® unit utilizing both human power and a Direct Push rig. However, the investigations showed that methods using capacitive couple are not suitable at the Milano-Rho field site due to penetration and noise problems caused by high conductivity areas along and next to the profiles (fences, waste areas and other artificial/backfill materials)

Ground Penetrating Radar (GPR) was a further geophysical method applied at the field site with the aim of mapping geological structures and very near surface layers of the road building ground. GPR is an electromagnetic pulse reflection technique; short pulses are transmitted into the ground and travel time and amplitude were recorded at a receiver (ANNAN, 2004; KIRSCH, 2006). GPR velocity is linked to soil dielectric constant, and is in turn strongly related to soil moisture content. GPR attenuation is a measure of soil electrical conductivity. For the GPR investigations, GSSI SIR 20 in combination with a 200 MHz and a 100 MHz shielded dipole antenna were used for recording common-offset profiles. The surveys were conducted again on the A-A'-profile with two runs of the 100 MHz antennas with a spacing of 1m. Survey with 200 MHz antenna was abandoned. Highly compacted material at the surface caused high scattering and attenuation of the signal. Even data measured with 100 MHz antennas showed almost no penetration (see Figure 3): A multiple caused by very near surface compactions dominates the results. Several structures and a layering of different material can be mapped within the first meter. Therefore all information provided by GPR is only related to building grounds. No additional information on geological structures can be expected by GPR at the site.

Direct Push Investigations

Direct Push technologies refer to a group of equipment that pushes or drives steel rods into the ground. They allow cost-effective, rapid sampling and data collection from unconsolidated sediments or soils (EPA, 2005). At the end of the rods, different types of probes can be attached allowing the collection of groundwater, soil or soil

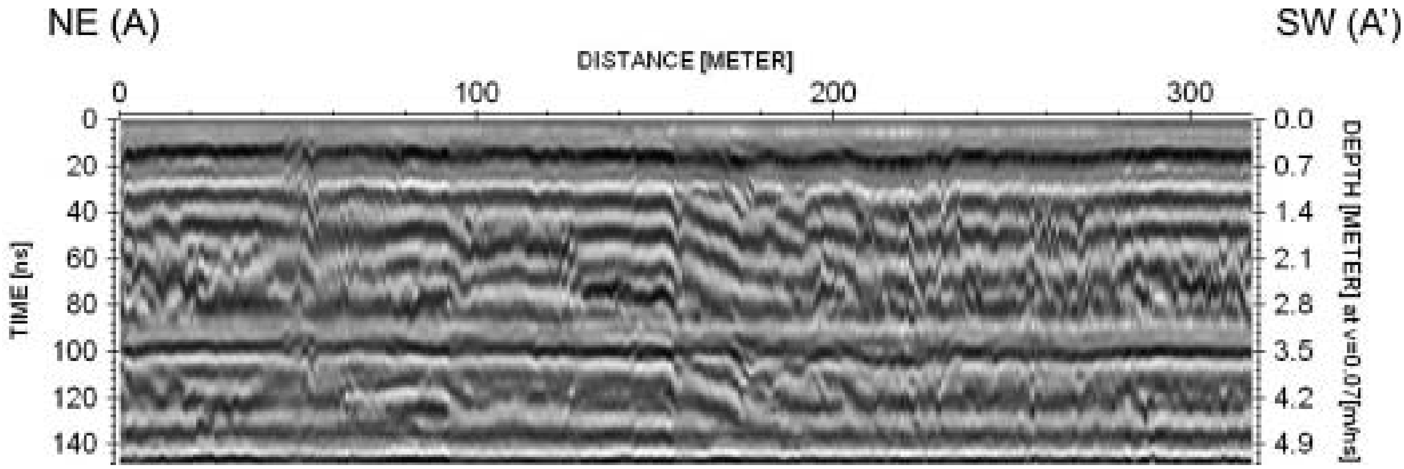

Fig. 3 - GPR measurement along profile A-A' conducted with 100 MHz antenna. Several structures and a layering of different material related to the road's building ground can be mapped within the first meter

gas samples as well as the acquisition of geophysical parameters, and an in-situ screening for contaminants.

Measurements of geoelectrical rock conductivities (EC-logging) and geotechnical parameters (CPT investigations) mainly characterize subsurface structures. The development of direct push based hydraulic methods such as injection testing and slug test contributes to evaluate the distribution of the hydraulic conductivity (DIETRICH & LEVEN, 2006).

At the Milano-Rho field site, EC-logging, Cone Penetration Testing (CPT), and injection logging were applied to demonstrate the suitability of direct push technologies for the delineation of contaminations in the subsurface. In addition, three temporary direct push wells were installed to acquire depth-oriented groundwater samples, while monitoring head variations between the shallow and deeper first aquifer and the clayey layer separating the two of them.

Logging of electrical conductivity

For a "calibration" of the geophysical measurements and for the characterization of geological structures, logs of electrical conductivity (EC logging) were acquired using a four pole geoelectrical probe ("Wenner probe"). This probe uses the concept of geoelectrics for which a current is applied between to poles, while simultaneously the electric potential between two other poles is measured. Thus, the probe allows estimating the electrical conductivity along the sounding with a vertical resolution of about 5 to 10 cm. However, the EC profile does not directly reveal subsurface lithology, but it can be interpreted to some degree as electrical conductivity increases with an increase in the amount of fines contained in the subsurface. For further details on EC logging see e.g. SCHULMEISTER *et al*. (2003).

Figure 4 shows the EC-logs along profile A-A'. Values of electrical conductivity range in general between 30 to 70 mS/m. Lowest values are present in a depth of 3 to 7 m below land surface. Intervals with an increased electrical conductivity are present in a depth of 1 to 3 m in the northeast half of the profile and around 9 m - as indicated by circles in Figure 4. This layer of finer material can be interpreted as a confining clay layer that was found in the cores of adjacent drillings.

Cone Penetration Testing

From Cone Penetration Testing (CPT), geotechnical and lithological information can be gathered. Therefore, four CPT surveys were conducted at the Rho field site. During CPT measurements, the resistance at the tip of the probe and friction along the sleeve of the probe are measured while the probe is advanced with static pressure at a constant penetration rate. More information on CPT can be found in e.g. LUNNE *et al*. (1997), ROBERTSON (1990), and ROBERTSON & CAMPANELLA (1983a, b).

In Figure 5 the log at the location A120 on profile A-A' is shown. The sleeve friction and the resulting friction ratio show the subsurface at the Rho test site is quite high in silts and other fines throughout the subsurface which agrees with the results from the EC logging presented earlier. A clay layer is seen at a depth of 8.5 to 9.5 meters in this sounding.

Figure 6 presents the data from CPT log A120 in an interpretative diagram with point resistance (qc) versus friction ratio (Rf). This diagram shows that clean sands are mainly in the unsaturated zone and in the shallow water table aquifer above a layer of clay which is found in a depth of approx. 9 m. Below the clay layer, the CPT profile is indicating mainly silty sands to sandy clays.

Injection Logging

Injection logging is a method to characterize qualitatively hydraulic conductivity of an aquifer. For this purpose, water is injected through a screen at the tip of the rod string into the aquifer at a rate of approx. 200 - 400 l/h. Two injection logging profiles were conduct-

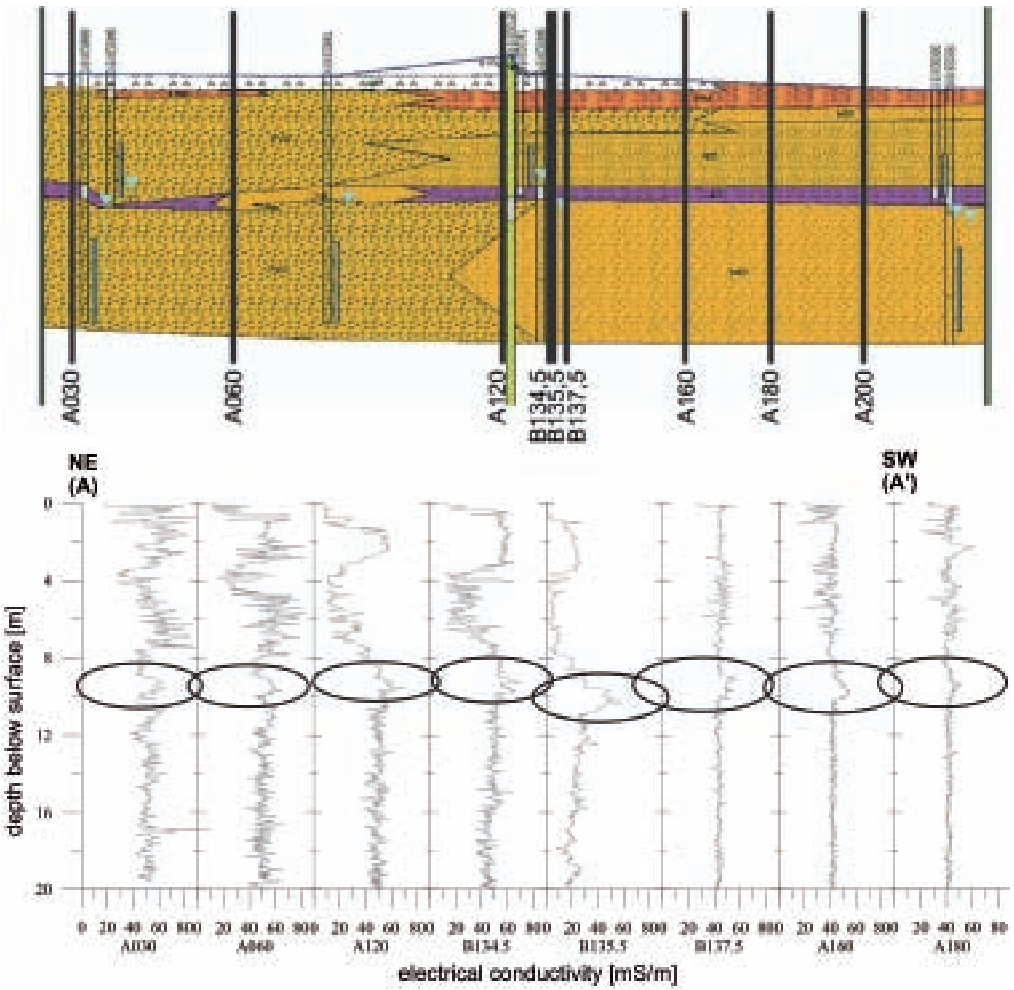

Fig. 4 - EC-logs along profile A-A'. Circles indicate the location of a confining clay layer at an approximate depth of 9 m BLS

ed during the Rho field campaign. To acquire depth profiles of relative hydraulic conductivity, the flow rate (Q) and injection (p) pressure is recorded simultaneously. As a result, a relative hydraulic conductance can be calculated which is a function of Q, p and system parameters, such a hose length, screen opening, depth of water level, etc.

Figure 7 shows the injection log at position B139.5. It is obvious that starting with a depth of 8.5 m down to 11.5 m, the formation is almost water tight. However, it can be assumed that due to clogging of the probe's screen the actual thickness of this layer is overestimated as clogging is only resolved during the further penetration through the aquifer. After the retrieval of the probe, parts of silty clay had to be removed from the screen. Further information on injection logging can be found in Dietrich & Leven (2006).

Water Sampling

For the purpose of estimating the hydrogeochemical quality of the groundwater at the site, a temporary Direct Push well was installed next to a conventional monitoring well that is equipped with a multi-level packer. Both methods - the Direct Push well and the multi-level

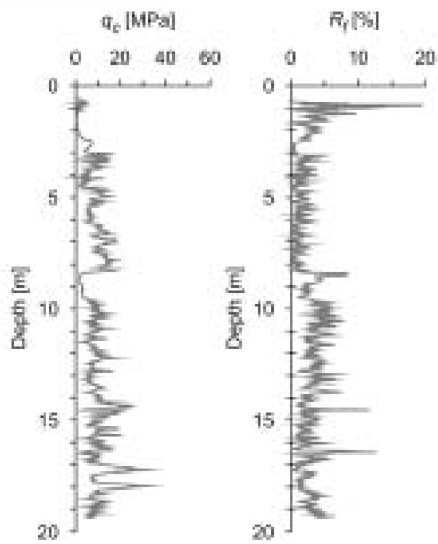

Fig. 5 - CPT log at A120 on profile A-A' (point resistance qc, friction ratio Rf = fs /qc x 100; with fs - sleeve friction)

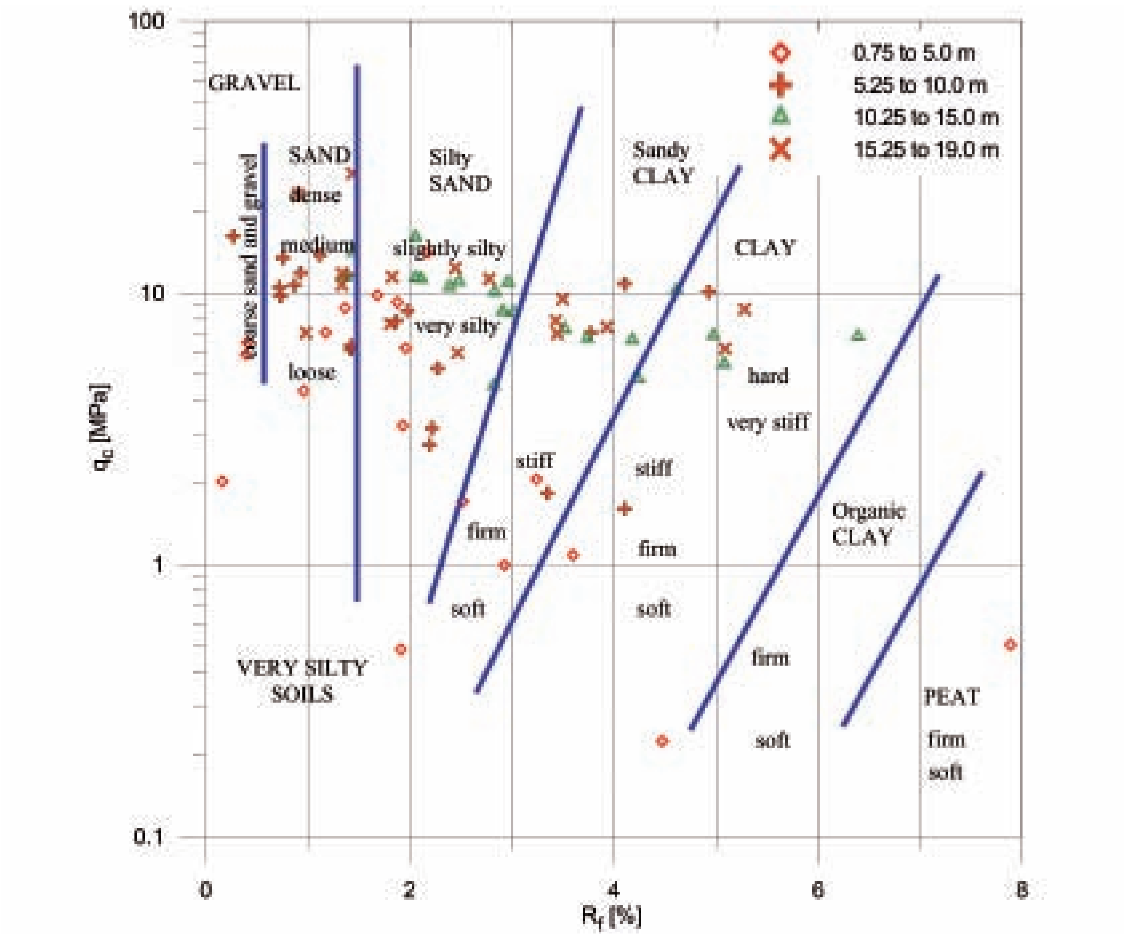

Fig. 6 - Interpretative diagram after Lunne et al. (1997) with data from CPT log A120 (Figure 5). A 3 cm average has been posted for every 25 cm of the CPT profile

packer well - allow for a depth-oriented sampling of groundwater. The temporary Direct Push well was installed using the Geoprobe "Sampling Point 16) which has an outer diameter of 1.6" (40,64 mm) and a screen length of approx. 1.1 m. Samples were taken every 2 m starting at an initial depth of 30 m up to a depth of 10 m (samples from 11 depths). I.e. with this method it is possible to sample groundwater from different depths with a comparably high accuracy at a comparably short time (less than 3 hours for the entire temporary well including installation and sampling). A detailed description of Direct Push methods for depth-oriented groundwater sampling can be found e.g. in DIETRICH & LEVEN (2006) or EPA (2005).

A second temporary Direct Push well was installed down gradient of the first sampling location with a starting depth of 30 m, samples were taken at 3m intervals (samples from 7 depths).

Figure 8 shows the results from the analysis of the direct push groundwater sampling at the two temporary Direct Push wells. It is obvious that it is possible to acquire high resolved concentration distributions along vertical profiles. At sampling location B120 (Figure 8a), highest concentrations of DCA and TCE where detected in a

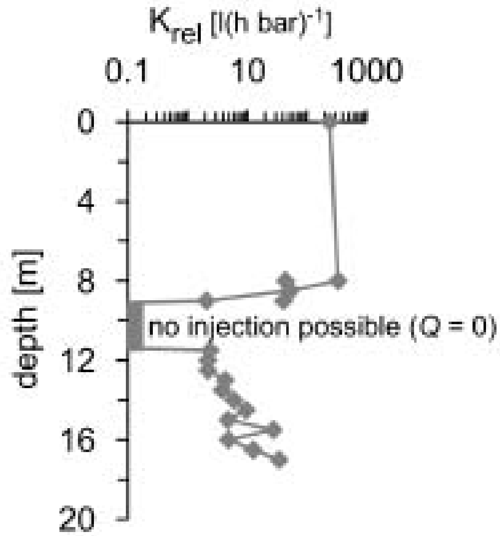

Fig. 7 - Injection log at location B139.5 (Krel - relative hydraulic conductivity)

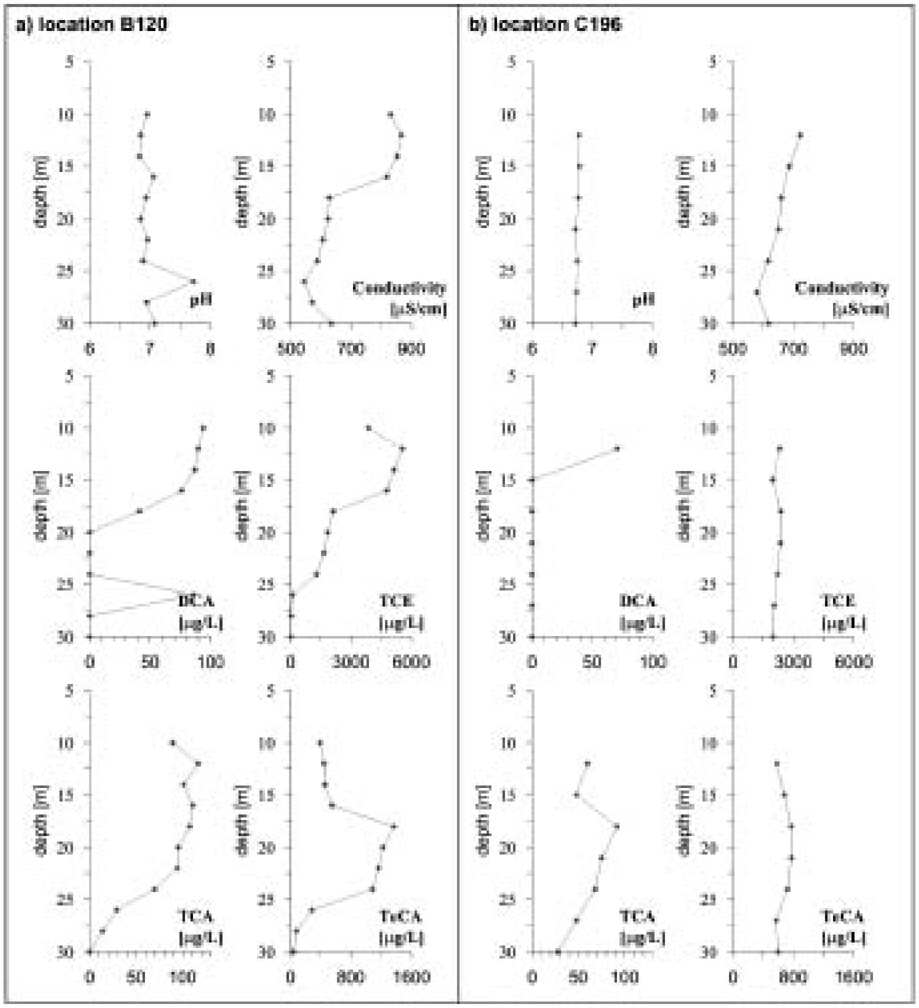

Fig. 8 - Results from sampling temporary Direct Push wells

depth between 10 and ca. 15 m, while highest concentrations of TeCA where found in a depth range of 17-25 m. TCA-concentrations of > 50 µg /l were detected over a depth of 10-25 m. In comparison, concentrations of all analyzed chlorinated organic compounds were lower in the down gradient Direct Push well C196 (Figure 8b). The distance between the two wells was approximately 60 m.

SUMMARY

The field site in Milano-Rho, Italy provided the opportunity to demonstrate the usefulness and suitability of geophysical and direct-push methods for an efficient and effective site characterization in terms of structure, hydrogeological and chemical parameters. In Table 1 the measurements are listed that were conducted during the course of the demonstration project within a period of seven working days.

First at the Milano-Rho field site the hydrogeological situation and subsurface heterogeneities were mapped using DC-geoelectrics. The DC-geoelectric surveys were able to see penetration depths on the order of 15 meters. However, backfill layers rendered the GPR

Method		**N° of profiles**	
Geophysics	DC-geoelectrics	4	profile lengths 50 - 300 m
	GPR	2	profile lengths 300 m
	Ohm Mapper	5	profile lengths 50 - 300 m
Method		**N° of probing locations**	
Direct Push	EC logging	13	max. probing depth 20 m
	Cone Penetration Testing	4	max. probing depth 20 m
	Injection logging	2	max. probing depth 15 m
	Groundwater Sampling	2	max. probing depth 30m number of samples 18
	1"-observation wells	3	max. probing depth 15 m

Tab. 1 - Overview of measurements conducted in the course of the demonstration project surveys relatively ineffective for penetration at this site due to the high dielectric properties of the fill material (i.e. clay with some construction materials present). These investigations were followed by several direct push techniques providing point information for a detailed vertical characterization. The direct-push methods were successful in being able to penetrate the subsurface rather easily once past the upper backfill layer down to depths of 30 m. CPT, EC-logging, and injection logging show similar results concerning the clay layer at a depth of 8.50 m to 9 m. With the Direct Push based groundwater sampling it was furthermore possible to acquire highly resolved depth-oriented information on groundwater contamination and on its hydrogeochemical properties.

In the course of the seven field demonstration days it was possible to gather data of high quality and resolution which helps in an improvement of the conceptual model of the site. By applying the introduced technologies, it is possible to increase the reliability and resolution of field data for an improvement of the derived site models and for an optimization of clean-up strategies.

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