CPT and other Direct Push methods

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ABSTRACT: The knowledge of the subsurface structure and composition is the precondition for the understanding and modelling of geohydraulic processes. A wide variety of in-situ and laboratory methods for subsurface characterization exist, with resolutions ranging from centimetre to field scale. As most of these methods are excellent tools for the characterization of homogenous aquifers, the exploration of heterogeneous aquifers is far more complex.
This paper presents initial results from a project using cone penetration tests and recently developed Direct Push methods for subsurface characterization at a field site in Bitterfeld, Germany. At this site, soil specific properties change over a range of several magnitudes within short horizontal and vertical distances. This study gives an overview of the results and a qualitative correlation of the tested methods.

1 INTRODUCTION

In this case study, different Direct Push (DP) methods for hydraulic and compositional subsurface characterization were applied at a site with a heterogeneous aquifer. In addition, extensive grain size analyses on soil samples in close proximity to the DP logs were performed. Sediment deposits at the tested sequence of the Bitterfeld site in Germany indicate a quaternary glaciofluvial channel fill. Within the tested aquifer, changes in soil specific properties are within a range of several orders of magnitudes and occur within short horizontal and vertical distances. To characterize the subsurface composition, cone penetration tests with pore pressure measurements (CPTU) in combination with a newly developed soil moisture probe extension were performed. The CPTU results were interpreted applying common interpretation models and compared to logs of different high resolution Direct Push tools that are used for the hydraulic characterization of sediment deposits. Core and grain size data helped to evaluate the capability of each method.

2 DIRECT PUSH-TOOLS

In the following section, a short description of the employed DP tools is given. McCall et al. (2006), Dietrich & Leven (2006), and Butler (2005) give a comprehensive overview of the state of the art and recent developments in the field of Direct Push and provide a broad record on related literature.

2.1 CPTU-SMP

A heavy duty subtraction-type piezocone with a projected tip area of 15 cm^2 and a projected sleeve area of 225 cm^2 was used for the CPTU profiling. This cone was chosen because of its robustness, as the tested aquifer consists of gravelly layers and is covered by backfill material. To avoid instrument loss, the upper 3 m were pre-pushed with a solid dummy tip.
While the piezocone is advanced at a constant speed of 2 cm/s into the ground the probe measures the tip resistance (q_c), sleeve friction (f_s), and the pore pressure at the u_2 position behind the cone. In this case, the piezocone was used in combination with a newly developed Soil Moisture Probe (SMP) extension that additionally measured the electrical conductivity and the relative permittivity of the soil. The relative permittivity is measured using a technique that Hilhorst (1998) describes as Frequency Domain technique (FD). As the relative permittivity is closely related to the volumetric water content in the soil, e.g. as expressed by Topp et al. (1980), the relative permittivity can be used to calculate the total porosity in the saturated zone.

2.2 Direct Push Injection Logger (DPIL)

The DPIL was developed to derive vertical profiles of the relative distribution of the hydraulic conductivity in the soil. This tool is used for discontinuous measurements and is installed using a percussion hammer. At desired depth intervals, the advancement of the probe is stopped and the water pressure in the injection tubing is measured at different injection rates using a pressure transducer and flow controller on the surface. The relative hydraulic conductivity (K_{DPIL}) can then be calculated after Dietrich et al. (2008):

$$K_{DPIL} = \frac{1}{R_{total} - R_{tube}} \quad (1)$$

where R_{tube}= Resistance of the tube; R_{total} = total resistance, both depending on the flow rate, back pressure and system parameters.

As the tool is advanced, water is continually injected through the screen behind the drive tip at relatively high flow rates to prevent the screen from clogging. To derive vertical K_{DPIL} distribution profiles, test intervals of 30 cm were chosen and, in a later step, reduced to 10 cm to increase resolution. Due to the resulting robustness of the system, a wide range of water pressure can be used for the hydraulic characterization.

2.3 Hydraulic Profiling Tool (HPT)

A Hydraulic Profiling Tool is used to evaluate the hydraulic properties of the subsurface using a similar approach as the DPIL. The probe is advanced into the soil at a constant speed of 2 cm/s either by pushing and/or using a percussion hammer. While the probe is advanced, water is injected into the ground through a screen on the side of the probe. A build-in transducer measures the pressure response of the soil to the water injection. High back pressure and low flow rates are normally corresponding to less permeable sediments, low backpressure and high flow rates indicate highly permeable sediments. In addition, this tool is equipped with an array of electrodes to measure the electrical conductivity of the soil as electrical conductivity may also be used for sediment characterization. An increase of the electrical conductivity can be an indicator for an increased abundance of fine material in the soil. Based on the combination of these in-situ methods, the HPT provides valuable information that can be used to estimate a relative vertical distribution of the hydraulic conductivity (K_{HPT}):

$$K_{HPT} \cong Q / P \qquad (2)$$

where Q= flow rate; P= pressure response data corrected for atmospheric and hydrostatic pressure.

For the calculation of K_{HPT}, system parameters are not considered. Flow rates of approximately 300 ml/min (18 l/h) were used.
There are currently no methods available to correlate K_{DPIL} or K_{HPT} to absolute values of the hydraulic conductivity (K).

2.4 Direct Push Slug Test (DPST)

The Slug Test is used to derive absolute K-values. Butler (1998) describes the slug test as measuring the recovery of head in a well after a near-instantaneous change in head at the well. At the test site, a pneumatic Direct Push slug test assembly was used. This test is performed in a temporary Direct Push monitoring well with a screened interval of 50 cm or 100 cm at the end of the rod string. The DPST uses compressed air to generate the head change within the well. For these experiments, a newly developed automated pneumatic slug test was employed. The K-values were determined based on Springer and Gelhar (1991).

2.5 Sonic Sampling and grains size analysis

To collect the soil samples for grain size analyses, Sonic sampling was employed. Thereby the rods are set into high frequency vibration causing the soil in contact with the rods to “liquefy”. This technique allows the retrieval of continuous and minimally disturbed 2 m soil cores. The cores were visually classified after sedimentological criteria and samples were taken for every observable change of color, texture and/or composition. Grain size analyses included the coarse grain and fine grain fraction.

3 CPTU DATA ANALYSIS AND SOIL INTERPRETATION

The CPTU-SMP data were first checked for outliers caused by load charge and discharge during probing. Also, unreasonably high values of f_s and q_c measured over a distance less than the cone diameter were discarded. The CPTU data are presented in Figure 1. Five distinct zones can be identified based on the friction ratio (R_f) which is defined by

$$R_f = \frac{f_s}{q_t} \times 100 \quad (3)$$

Different methods for the interpretation of CPT/CPTU-data exist. Six standard interpretation approaches were used, results applying the CPT soil behavior type classification system from CPTU data after Robertson et al. (1986) which uses q_t and R_f are shown in Figure 2, with

$$q_t = q_c + (1-a)u_2 \quad (4)$$

where a= area ratio of the cone (cone specific).

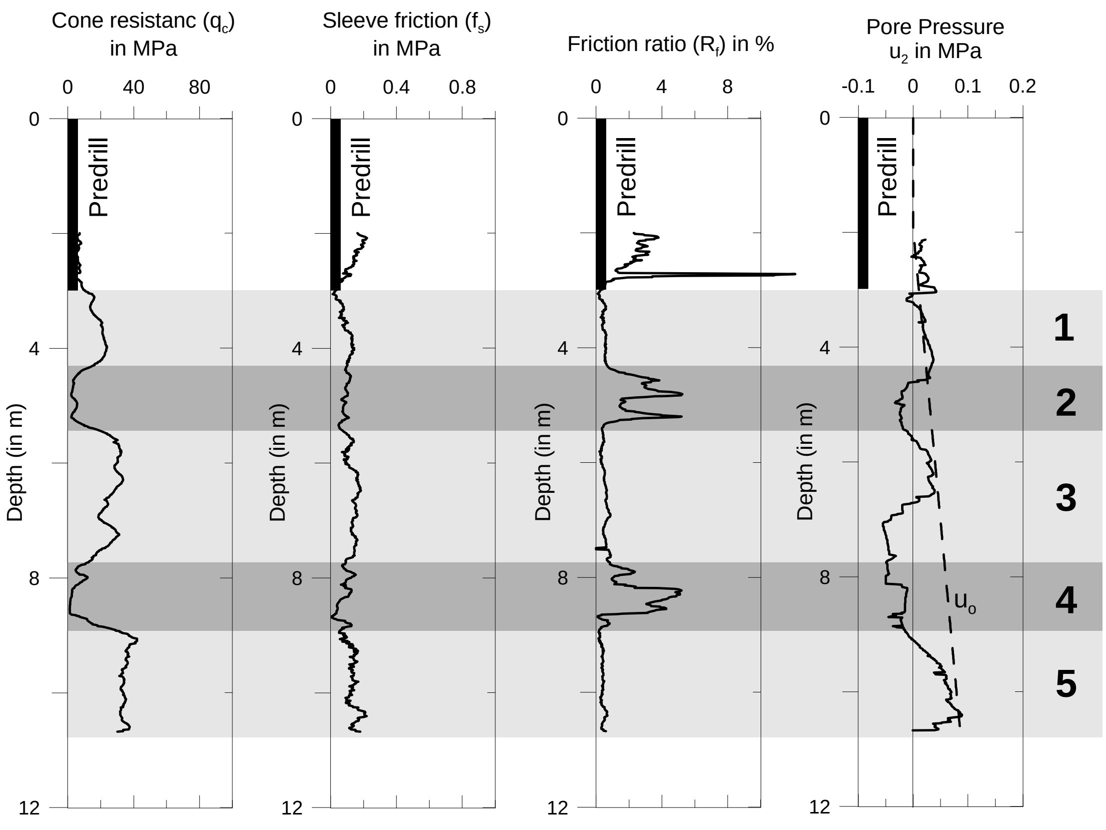

Figure 1: CPTU data showing q_c, f_s, R_f and u_2 and the layering based on the R_f.

When plotted in the interpretation chart, layers of lower friction ratios (layer 1, 3, and 5) fall mainly within a small range of zone 9 and 10 in the chart that correspond to sand, respectively gravelly sand to sand. Layers of higher friction ratio (layer 2 and 4)

plot over a wide range from zone 8 to 3, corresponding to sand respectively silty sand to clay. Considering the CPT data, the compositional heterogeneity of the aquifer is clearly indicated by the layers of higher friction ratio.
The dynamic pore pressure shows a high variability, changing between positive and negative values. Negative domains are interpreted as overconsolidated fine grained layers - a typical phenomenon for glacially impacted deposits. Nevertheless, when comparing the dynamic pore pressure to the hydrostatic pressure, the tested aquifer sequence can be described as connected and unconfined. The results of the interpretation show very good consistency throughout the different interpretation methods.

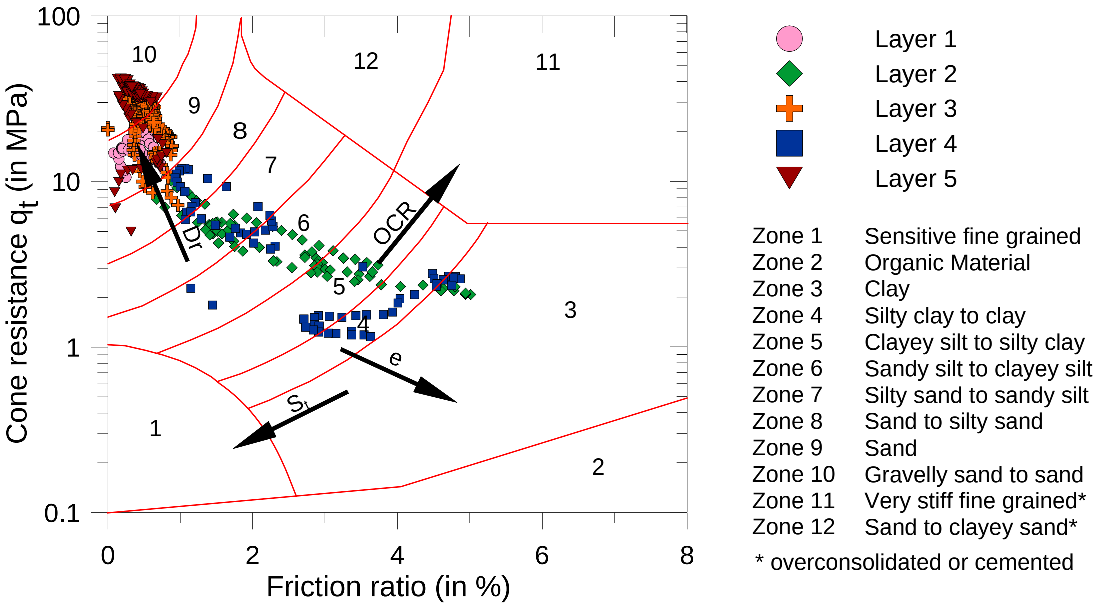

Figure 2: Soil Interpretation after Robertson et al. (1986).

4 COMPARISON OF DP DATA AND GRAIN SIZE ANALYSES

In addition supplemental DPIL and HPT profiles in close proximity to the CPT log were compiled. Results show differentiations in performance and resolution for the applied methods.
The electrical conductivity profile (Fig. 3) depicts the main compositional structures as the CPT profiles - however with less distinction. This may be caused either by changes in sediment composition (e.g. varying content of fine grained materials) or instrument dependent noise.
In contrast, the hydraulic characterization using the HPT and DPIL systems does not show a distinct sedimentological layering. Only when several HPT or DPIL logs that were taken along a 150 m long profile are combined, a tendency for the *K*-value distribution within the aquifer can be estimated, marked by the broad solid line in Figure 3. For the HPT, considering the pressure response and electrical conductivity data, this tendency can be correlated to the identified structures. The DPIL seems to describe a more general tendency of an increase in hydraulic conductivity starting at

about 9 m depth. The DPIL resolution stays within this general tendency even though the spacing of the test intervals was reduced to 10 cm. The lithologic profile that was generated from the geological characterization of the sediment cores shows the intensive layering of the profile especially in zones that were characterized by a low friction ratio. In this aspect, the geotechnical and hydraulic characterization show major differences.

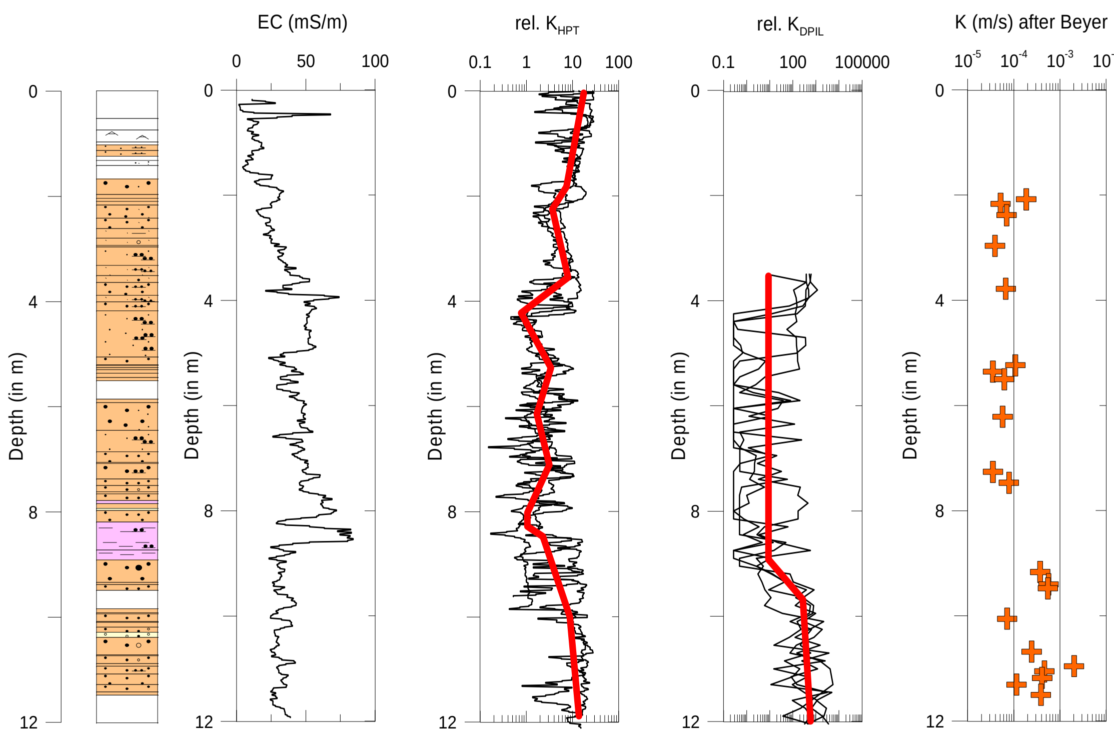

Figure 3: Comparison of the lithological profile; HPT and DPIL logs taken along a 150 m long profile, and preliminary results of calculated *K*-values after Beyer (1964) from grain size analyses.

Using the Sonic sampling technology, sediment cores of 2 m length were taken to a depth of 12 m. For every apparent change in color, texture or sediment composition soil samples were taken and grain size analyses performed. Preliminary results of 40 grain size distribution analyses support the results of the Direct Push campaign. The grain size distributions were used to calculate *K*-values after Beyer (1964):

$$K = c(U) \times (d_{10})^2 \tag{5}$$

where c = is an empirical factor; U = unconformity coefficient (*d60*/*d10*); *d10* and *d60* are the diameter of grains in the 10th and 60th percentile, respectively, expressed in millimeters.

From the 40 samples, a total of 21 samples were in good accordance to the limitation of the Beyer equation (U < 20; 0.06 < *d10* < 0.6mm). All of these 21 samples fall within the layers characterized by low friction ratios, showing the heterogenic composition of the high friction ratio layers. The *K*-value distribution for the 21 samples shows a clear partition of the aquifer, consisting of an upper and a lower part as identified by the DPIL. Eleven *K*-values from 2 to 7.5 meters average at a 7.19 x10^{-5} m/s with a standard deviation of 4.15 x10^{-5}. Ten samples for the depth interval of 9 to 11.50 m show an average *K*-value of 5.20 x10^{-4} m/s with a standard deviation of 5.25 x10^{-4}. For reference values a number of DPST were performed.

5 CONCLUSIONS

In this study, examples of a variety of methods for the in-situ characterization of the subsurface are presented. Amongst these, CPTU is the most established method and a standard application for the geotechnical praxis. From the CPTU data the main compositional structures within the upper 12 m of the tested aquifer can be identified. When the CPTU data are interpreted using soil behaviour type diagrams, results indicate a higher degree of heterogeneity in the layer of higher friction ratio. The sediment cores reflect the same main structures but show a higher level of heterogeneity, expressed by the number of distinguishable layers over the vertical distance, in the layers that are characterized in CPTU profile by a lower friction ratio.

HPT and DPIL are used for the hydraulic subsurface characterization. These methods depict a general tendency of the *K*-distribution in this study, even though the HPT data shows a better correlation to the main structures. The preliminary results of calculated *K*-distribution of 21 soil samples confirm the results of the DPIL and HPT.

It can be shown that the presented Direct Push tools are an efficient and reliable alternative for the compositional and hydraulic subsurface characterization.

6 REFERENCES

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