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Systematic description of direct push sensor systems: A conceptual framework for system decomposition as a basis for the optimal sensor system design

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ABSTRACT

Systematic decomposition and evaluation of existing sensor systems as well as the optimal design of future generations of direct push probes are of high importance for optimized geophysical experiments since the employed equipment is a constrain on the data space. Direct push technologies became established methods in the field of geophysical, geotechnical, hydrogeological, and environmental sciences for the investigation of the near subsurface. By using direct push sensor systems it is possible to measure in-situ parameters with high vertical resolution. Such information is frequently used for quantitative geophysical model calibration of interpretation of geotechnical and hydrological subsurface conditions. Most of the available direct push sensor systems are largely based on empirical testing and consecutively evaluated under field conditions. Approaches suitable to identify specific characteristics and problems of direct push sensor systems have not been established, yet. We develop a general systematic approach for the classification, analysis, and optimization of direct push sensor systems. First, a classification is presented for different existing sensor systems. The following systematic description, which is based on the conceptual decomposition of an existing sensor system into subsystems, is a suitable way to analyze and explore the transfer behavior of the system components and therefore of the complete system. Also, this approach may serve as guideline for the synthesis and the design of new and optimized direct push sensor systems.

1. Introduction

High-resolution exploration of near-surface sediments is essential when striving to answer environmental or geotechnical issues. A wide variety of non-invasive geophysical exploration techniques exist, which are suitable to gather information about variations of physical parameters in the ground with spatial resolutions ranging from a meter up to tenth or hundreds of meters (e.g., Rubin and Hubbard, 2005; Butler, 2005). Invasive exploration techniques, such as borehole or direct push logging, excel by offering a unique depth resolution ranging from a few centimeters to decimeters (Dietrich and Leven, 2006). Such high resolution data are usually considered a significant informational value and are fundamentally required when results of non-invasive or tomographic exploration techniques shall be validated by ground-truth. In addition to borehole and direct push sensor systems allowing for logging of physical parameter variations, also geotechnical, geochemical or hydrological probes have been developed. Such tools are used to log non-physical target parameters, e.g., hydraulic permittivity, tip resistance, or contamination content, which are frequently used to calibrate the hydrological, geotechnical or chemical interpretation of geophysical models (Paasche et al., 2006, 2009; Hachmöller and Paasche, 2013).

Traditionally, the collection of geophysical logging data requires the installation of boreholes. In near surface environments the borehole installation procedure results in highly disturbed sedimentary settings, since drill diameters usually exceed those of the later installed casings holding the borehole open. Considering the limited size and the small sample volume of near surface borehole probes, doubts remain whether traditional borehole logging results in physical parameter values representing realistic formation properties. Direct push technology is usually considered more attractive when invasively exploring near surface sediments, since sensors can be installed at the spit of a steel rod which is then pushed, hammered or vibrated into the ground (Dietrich and Leven, 2006). Employed steel rods are hollow and necessary communication cables between probe and control unit can run inside the steel rods while pushing the probe into the ground. Since no prior drilling with larger diameter than those of the probe is required, formation disturbance is reduced to a minimum when using direct push technology. This resulted in increasing popularity of direct push technologies. Fields of application include for example electrical resistivity logging (Campanella and Weemees, 1990), determination of contamination profiles, based on a volatile organic compound (VOC) pollution (Kram et al., 2001; Bumberger et al., 2012), measurements of

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Table 1
Classification and second-level classification of direct-push sensor systems (examples).

Method	System	Parameter measured	Interpretation skills	Quality measured	Input Energy	Conversion of matter	Inserting or extraction of matter	Measuring influence zone	References
Geotechnical	Cone Penetration Test (CPT)	Mechanical tip resistance, sleeve friction	Variations in consistency and bulk density, sediment type	Physical	Mechanical	No	–	10E-2–10E-1 m	Robertson et al. (1986a), Robertson (1990), Lunne et al. (1997), Robertson (2009)
Geotechnical	Video Imaging Probe (GeoVIS, VisCPT)	Image signal	Sediment type	Physical	Electromagnetic	No	–	10E-4–10E-3 m	Raschke and Hryciw (1997), Lieberman and Knowles (1998)
Geophysical	Electrical Conductivity Probe (EC)	Electrical conductivity	Clay mineral content, variations in sediment types	Physical	Electrical	No	–	10E-2–10E-1 m	Campanella and Weemees (1990), Christy et al. (1996), Schulmeister et al. (2003), Sellwood et al. (2005)
Geophysical	Soil Moisture Probe (SMP)	Electrical conductivity, relative permittivity	Volumetric moisture content, variations in sediment types	Physical	Electromagnetic, electrical	No	–	10E-1–10E0 m	Shinn et al. (1998)
Geophysical	Seismic Cone Penetration Test (SCPT)	Compressible-wave velocities, shear-wave velocities	Sediment type and there elasticity characteristics	Physical	Mechanical	No	–	10E0–10E1 m	Robertson et al. (1986b), Terry et al. (1996)
Hydrogeological	Direct Push Injection Logging (DPIL)	Water-injection rate, water-injection pressure	Variations in relative hydraulic conductivity	Physical	Mechanical	No	Inserting	10E-1 m	Pitkin et al. (1998), Butler and Dietrich (2004), Dietrich et al. (2008)
Hydrogeological	Permeameter	Water-injection rate, water-injection pressure	Variations in hydraulic conductivity	Physical	Mechanical	No	Inserting	10E-1 m	Lowry et al. (1999), Butler et al. (2007)
Geochemical	Membrane Interface Probe (MIP)	Ionisations intensities	Relative concentration of volatile organic compounds	Chemical	Thermal, Electromagnetic	Yes	Extraction	10E-3–10E-2 m	Christy (1996), Kram et al. (2001), Bumberger et al. (2012)
Geochemical	UV Laser-Induced Fluorescence Probe (LIF Probe)	Wavelength specific intensities	Relative concentration of petroleum hydrocarbons	Chemical	Electromagnetic	No	–	10E-4–10E-3 m	Bujewski and Rutherford (1997), Kram et al. (2001), Grundl et al. (2003)
Geochemical	X-ray Fluorescence Probe (XRF Probe)	Fluorescence quantum	Relative concentration of metals and nutrient profiling	Chemical	Electromagnetic	No	–	10E-4–10E-3 m	Elam et al. (1998), Unsell (1998)
Geochemical	Laser Induced Breakdown Spectroscopy Probe (LIBS)	Wavelength specific intensities	Relative concentration of metals	Chemical	Electromagnetic	Yes	–	10E-4–10E-3 m	Theriault et al. (1998), Lieberman et al. (2001), Fichet et al. (2001), Mosier-Boss et al. (2002)
Geochemical	Raman Probe	Wavelength specific intensities	Relative concentration of volatile organic compounds, radioactive substances	Chemical	Electromagnetic	No	–	10E-4–10E-3 m	Marquardt et al. (2001), Brown et al. (1999), Rossabi et al. (2000)
Geochemical	Visible and IR Reflectance Probe	Wavelength specific intensities	Variations in sediment type, organic and moisture content	Chemical/ physical	Electromagnetic	No	–	10E-4–10E-3 m	Gregory et al. (1995), Kweon et al. (2009), Dalan et al. (2011), Hausmann (2014)