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New Multilevel Groundwater Monitoring Systems for Use in Heterogeneous Rock and Soils

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ABSTRACT: A new multi-level groundwater monitoring system has been developed as part of a ground investigation for a proposed station on the Crossrail railway project in east London. The application of the system is described in the scope of the project outline. System properties, installation procedure and preliminary data are presented.

1 INTRODUCTION

Multilevel groundwater systems enable discrete hydraulic head monitoring, sampling and testing at several depth-specific horizons in a single exploratory well. This allows an evaluation of the vertical distribution of hydraulic parameters such as transmissivity, conductivity, hydraulic head as well as the assessment of hydraulic geochemical parameter variation for a site-specific investigation. Should profiles of hydraulic parameters from three or more boreholes be available, then a 3D-picture of the groundwater regime can be derived.

1.1 *Available methods to install vertically distributed monitoring/response zones*

Various systems are available to allow installation of a monitoring arrangement of vertically distributed response zones. Generally, multilevel groundwater monitoring systems are used if the costs for a piezometer nest (i.e. drilling and equipping individual exploratory wells in order to access multiple monitoring horizons) are higher when compared to a single hole multi-installation. Within the scope of a contaminant site investigation, a limited number of boreholes may be recommended in order to reduce the potential risk of vertical flow paths being generated when perforating aquifer(s) and confining layers. In such a case, multi-level borehole installations may be preferred instead of single piezometers. If a decision is made in favor of multilevel installations, the system type is selected using criteria such as rock type, testing/sampling purposes and maximum installation depth. The anticipated long term use is another factor determining the shortlist of suitable system types. For bedrock applications, retrievable multi-packer systems may be advantageous, especially if it is planned to re-use the instrumentation for several projects.

In permeable overburden, a cost-saving multilevel single-hole installation option comprising several piezometers placed around each other and ending at varying depths (bundled piezometers) might be used. The annulus between borehole and piezometer is filled with sand to create a response zone at the location of the filter tips with a relatively impermeable sealing material between the response zones. However, the quality of the seal between response zones of the bundled installation is questionable in many cases. This is because the spaces between the individual pipes of a bundled arrangement are likely to remain unfilled during the grouting process, and so vertical flow water circulation may persist within the borehole, causing erroneous head measurements or water samples of poorly defined origin.

1.2 *Short introduction to Crossrail ground investigation*

The Crossrail project aims to provide improved east-west rail access into and across London from the East and South East regions. Ground investigations are ongoing in order to acquire the geotechnical information required for decision making on the final tunnel alignment and the design of stations. At the proposed station at Whitechapel, multilevel borehole installations have been installed to assess the hydraulic properties of the London Clay and Lambeth Group formations. Vertical profiles of head and both horizontal and vertical permeability distributions in adjacent formations are to be evaluated in order to gain a better understanding of the complex groundwater regime. Of particular concern is a gravelly sand stratum within the Lambeth Group where high ground water pressure could have a substantial impact on the construction of the underground station. In combination with data from a range of in-situ and laboratory testing the ground water regime investigation will provide information for the design of the station, including constructability issues, and for the assessment of both short and long term ground movements associated with the excavations.

1.3 *Monitoring/testing requirements for the Crossrail project*

A variety of testing and monitoring techniques in differing soil types was required from a single borehole installation, with the capability of carrying out pumping tests in permeable layers. In clay of low permeability, precise pressure monitoring was required, enabling instantaneous indication of formation pressure change. As monitoring will extend over several years, the installed pressure sensors needed to be retrievable and pumping equipment moveable between testing sections without the need of changing the pressure monitoring arrangement (Fig. 1).

2 DESCRIPTION OF THE INSTALLED MULTILEVEL SYSTEM

In view of the mid and long term low borehole stability in the London Clay, and short term poor hole stability in the Lambeth Group soils, a permanent installation (to be grouted) was preferred against a retrievable multi-packer system. Since no off-the-shelf system was available allowing both medium pumping rates and unhindered (simultaneous) access to the monitoring zones, a new system was developed.

2.1 *Basic concept and operational principle*

The system developed for this purpose, named Multi-Port Sampling System (MPSS), allows multi-level groundwater monitoring, sampling and even pumping tests to be carried out in a single borehole. The installation comprises a "central" 50 mm diameter PVC tube running the length of the borehole with pumping ports, surrounded by up to six small 21 mm diameter access ports (PVC standpipes), each terminating in a different response zone. Each response zone is separated by impermeable backfill such as clay-based cement-bentonite-grout.

Pumping tests and monitoring can be carried out in the same hole with the central tube as the pumping well and with water levels monitored in the standpipes. A range of removable instruments can be installed such as temperature and pressure sensors which may be linked to a remote data logger if necessary (Fig. 1).

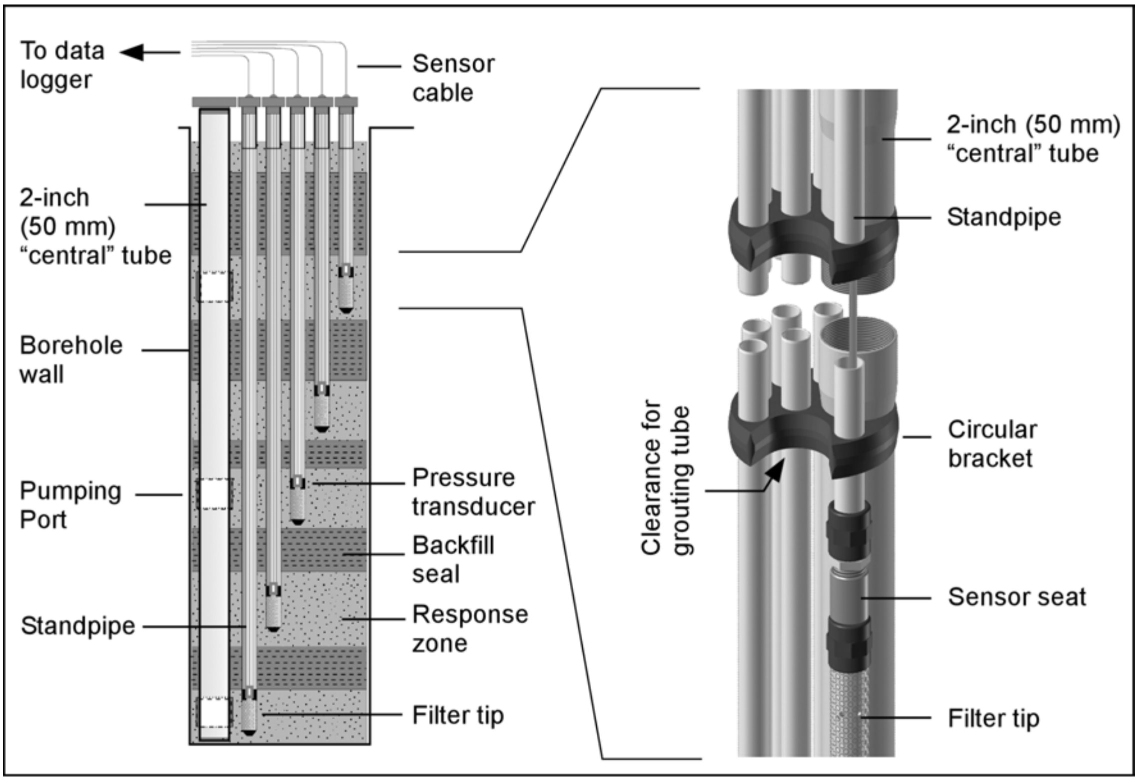

Figure 1: Concept (left, schematic) and the implementation (right) of the "Crossrail" borehole system. The monitoring zones are accessed by individual standpipes and instrumented with removable pressure sensors. Each sensor is placed in a retaining seat above the filter tip of the standpipe enabling closed-chamber type measurement. Relatively high pumping rates can be achieved at selected horizons where the large diameter tube is equipped with pumping ports (indicated by rectangles along the large diameter tube shown on the left).

The central tube and the standpipes are held together by circular brackets. The disc-shaped plastic elements ensure sufficient clearance between the standpipes, so that no cavities are formed during the grouting process. A semi-circular recess in one side of the discs allows the grouting tube to be inserted down the entire length of the borehole.

2.2 *Pumping port operation*

In a normal application, only one of several pumping ports is open at a time. The smallest diameter of the pumping port valve element is identical for both the closed and open valve position. The valve diameter is large enough for a commercial 2-inch submersible pump to pass through (Table 1). The pumping ports can be opened/closed using a combined tool consisting of a down-hole submersible pump with a packer mounted on its base (Fig 2). The tool is lowered to the desired pumping port. The packer is expanded and by hoisting the tool up the hole the port's valve is opened. The packer seals off the tube below, preventing formation water mixing with that in the pipe. Relatively high pumping rates up to 25 l/min are possible.

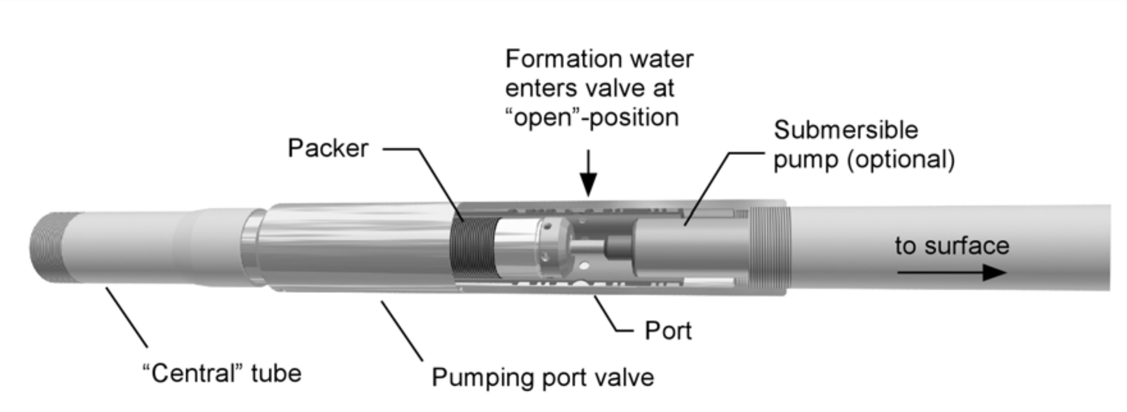

Figure 2: Pumping port valve in "central" tube shown with valve open/close packer.

2.3 *Standpipe instrumentation options*

Off-the-shelf or customized equipment can be lowered into the 21 mm diameter standpipes for various monitoring and sampling options. Pressure transducers may be installed for continuous monitoring of the hydraulic heads, and also for data-recording during sampling or during a pumping test. For tight formations, an O-ring sealed pressure sensor seat is recommended to decrease wellbore storage effects allowing faster response times. In case absolute pressure sensors are installed the barometric pressures fluctuations can be recorded at the surface. This gives the ability to correct for barometric pressure trends (see Section 4). The standpipes may also serve as conventional piezometers where water levels are measured manually using a dip meter.

Physic-chemical parameters can be monitored continuously using small diameter probes for temperature, electric conductivity, pH or other parameters.

For testing and sampling in low permeable zones, the 21 mm diameter standpipes can be used as an alternative to the "central" tube pumping ports. Small diameter double-valve pumps can be lowered into the standpipes to induce flow. The maximum flow rate using small diameter double-valve pumps is limited to 150-200 ml/min.

Table 1. MPSS specifications:

Maximum number of standpipes	6
Maximum number of pumping ports (theoretically *)	1 per meter
Maximum number of pumping ports (normal application *)	6
Maximum outer diameter of MPSS:	140 mm
Inner diameter of standpipes	21 mm
Inner diameter of "central tube"	51 mm
Smallest diameter of central tube pumping port (valve)	48 mm

*) Spacing and number of response zones are determined by borehole depth and minimum grout seal length

3 INSTALLATION PROCEDURE

At Whitechapel, a drilling rig with a 6 m high mast and working platform was used to aid the MPSS installation. A protective steel casing of 150 mm inner diameter was lowered into the borehole prior to installation. The MPSS-elements varying from 0.5 m to 2 m long were preassembled on site and installed in up to 4 m lengths. The central tube sections were threaded together and sealed, while the standpipes were joined using short collars with double O-ring seals that were slid into place over the pipes. The protective casing was progressively removed during the backfill procedure. A temporarily plastic tube was used to install the sand filter material direct to the response zones. Space for the temporary plastic tube is provided by the recess clearance as shown in Fig. 1. The backfill seal, a mixture of clay-based bentonite-cement grout, was installed in a similar way using a tremmie pipe lowered into the temporary plastic tube.

A drilling rig would not be required for MPSS installation where the borehole is stable and no protective casing is required.

4 PRELIMINARY RESULTS FROM MONITORING AT WHITECHAPEL

Pumping tests using two MPSS about 5 m apart are planned in the new future at Whitechapel. Pressure reactions at 6 vertically distributed response zones at similar depths in both MPSS are to be recorded and analysed in order to obtain horizontal and vertical conductivity estimates. Existing recorded pressure data show a distinct separation of the pressure curves of the six response zones, with the highest hydraulic head at the top response zone and the lowest head at the bottom response zone (Fig. 3, graph C). The difference in head between the top response zone (rz-6, 10.70 - 11.85 mbgl) and the bottom response zone (rz-1, 39.15 - 41.0 mbgl) is about 17.5 m, suggesting a strong hydraulic gradient in vertical direction. This coincides with the fact that a "low-head" but transmissive sandy layer is situated a few meters below the rz-1 zone (found by other exploratory wells near to the MPSS installation).

Well data showing atmospheric trends can be used for rough estimates of the poro-elastic properties of the soils using the theory of barometric effects on pore pressure (Van der Kamp & Gale 1983, Beavan et al. 1991). All response zones at Whitechapel show a strong susceptibility to barometric pressure variations (Fig. 3, graph A). A separate high precision pressure transducer is used at the surface allowing an evaluation of pore water pressure response to atmospheric pressure fluctuation. ΔP-values (pressure differences with respect to a corresponding value of an arbitrary reference date) of the response zone rz-1 within Lambeth Group are plotted versus the atmospheric pressure changes in Figure 3, graph B. Linear regression is conducted on a data set from a period where pore pressure data are not likely to be affected by other (artificial) trends. The example of response zone rz-1 shown in diagram B of Figure 3 suggests that atmospheric pressure change is transmitted to pore pressure change by factor 0.918. Since vertical hydraulic diffusion is assumed to be of minor importance within the overlying London Clay, the observed pore pressure variations are mainly ascribed to barometric loading effects acting on the compressible layers of the London Clay and the Lambeth Group. The observed high amplitudes of barometric-induced fluctuations suggest a low stiffness of the soils.

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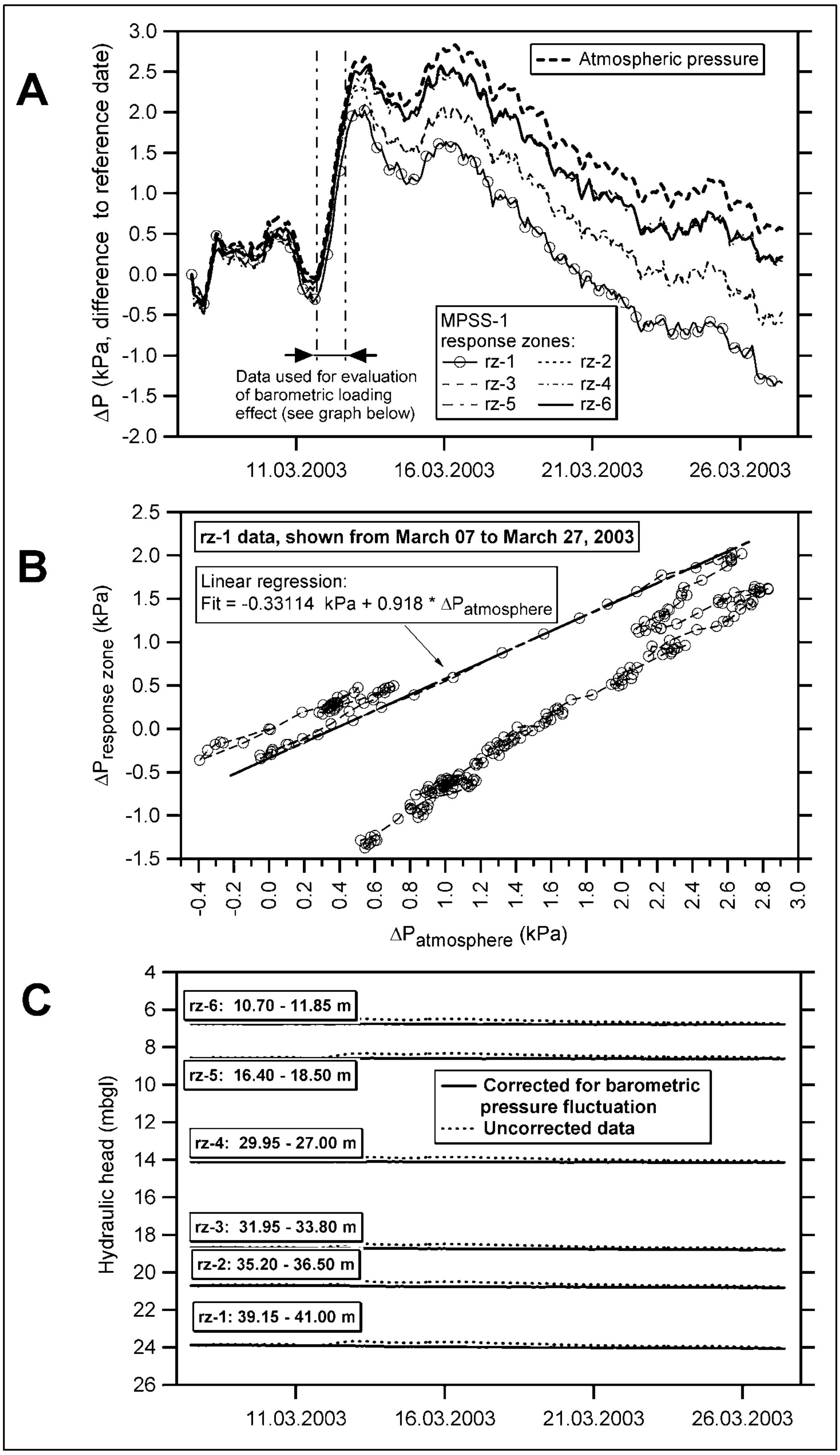

Figure 3: Pressure data and calculated heads from the MPSS-1 system, Whitechapel. The effects of barometric pressure fluctuations (A) are analyzed using a data set that is not disturbed by "artificial" activities (B). Calculated hydraulic heads are shown in graph C. The location of the response zones rz-1 to rz-6 are given in meters below ground level (mbgl) in graph C.