A New Method for Real-Time Monitoring of Grout Spread through Fractured Rocks

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ABSTRACT

Reducing water ingress into the Shaft at Dounreay is essential for the success of future intermediate level waste (ILW) recovery using the dry retrieval method. The reduction is being realised by forming an engineered barrier of ultrafine cementitious grout injected into the fractured rock surrounding the Shaft. Grout penetration of 6m in <50µm fractures is being reliably achieved, reducing rock mass permeability by up to three orders of magnitude.

An extensive field trials period, involving over 200 grout mix designs and the construction of a full scale demonstration barrier, has yielded several new field techniques that improve the quality and reliability of cementitious grout injection for engineered barriers.

In particular, a new method has been developed for tracking in real-time the spread of ultrafine cementitious grout through fractured rock and relating the injection characteristics to barrier design. Fieldwork by the multi-disciplinary international team included developing the injection and real-time monitoring techniques, pre- and post injection hydro-geological testing to quantify the magnitude and extent of changes in rock mass permeability, and correlation of grout spread with injection parameters to inform the main works grouting programme.

INTRODUCTION

The D1225 Shaft at Dounreay Nuclear Establishment on the north coast of Scotland was an authorised disposal facility for ILW from 1959 until the last deposition in 1971. The shaft was constructed entirely in rock with a nominal diameter of 4.6m and is lined only over the upper 8.0m of its 65m depth. In addition to the 620m^3 of recorded ILW disposals, the shaft space is flooded by groundwater. As part of the ongoing decommissioning programme at Dounreay, the contents of the shaft are to be retrieved, sorted and consigned to alternative storage and the contaminated groundwater removed and treated.

The shaft contents will be recovered using the dry retrieval method: the shaft water level will be reduced until an item of solid waste is visible, then remote handling equipment will retrieve and sort the solid waste and the process will repeat until the shaft has been emptied. For this gradual dewatering method to be successful the groundwater ingress rate must be limited to a value capable of being dealt with by the existing site liquid effluent treatment plant.

To accomplish this, an engineered barrier is being constructed around the Shaft by the controlled injection of stable ultrafine cementitious grouts into the bedded and jointed rock

surrounding the shaft. The grout is injected via drilled boreholes using an ascending stage sequence. The barrier design relies on grout spread from each stage treating a volume of surrounding rock. Using a split-spacing borehole technique with several series of injections, a multiple overlap between treated volumes is achieved and beneficial redundancy introduced.

Injections are controlled using the Grout Intensity Number (GIN) method proposed by Lombardi and Deere [1, 2] where the stop criterion is described by a pressure/volume curve of equal energy (a 'GIN' in units of bar.litres/metre) truncated by conventional pressure and volume limits. The method allows all parts of a given volume of homogenous rock to be grouted at the same intensity i.e. the same amount of work is done whether an injection terminates at high pressure/low volume, low pressure/high volume or at a point on the GIN curve between these extremes. The GIN method allows appropriate pressure to be applied to increase grout penetration, but prevents the combination of high pressure and high volume injections, thereby limiting the risk of ground heave.

Understanding the nature and range of the grout spread in the discontinuities within the rock mass is therefore a fundamental aspect of the design of the injection point layout and definition of the controlling GIN for each homogenous zone and thus the grout penetration experiment described here formed an important element of the early grouting site trials phase of the D1225 Shaft Isolation Project.

SITE GEOLOGY

The pre-works site trials, of which the P1 grout penetration experiment formed an early part, were undertaken in an area lying 65m to the north east of the D1225 Shaft and approximately along geological strike. Stratigraphically, the sequence is generally at the same level as the Shaft and as both the D1225 Shaft and the trials area lie on the foreshore line, they share a topographic similarity. Faulting is present at both areas and is characterised by steep dips (75° to 82°) and throws of between 3 and 20m.

The Caithness Flags at Dounreay generally comprise a cyclic sequence of silty limestones (A horizons), bituminous siltstones (B horizons), siltstones (C horizons) and sandstones (D horizons) with a typical upward sequence of A, B, C, D, C, B, A. The cycles repeat at 6 to 10m intervals numerous times, allowing successive A or A/B units to be numbered as marker beds up the sequence. The C and D horizons demonstrate more developed jointing, predominantly along bedding planes and are associated with the flowing features identified during hydrogeological site characterisation work. The beds dip at approximately 10° to the north west.

Extensive site characterisation work [3, 4] was undertaken in advance of the grouting trials to locate accurately known and suspected faults, confirm the geological model and to establish a hydrogeological baseline.

PENETRATION FIELD EXPERIMENT

Concept

Lombardi [2] describes an experimental method where a trial borehole is injected with grout while the injection pressure, injected volume and grout penetration are continuously monitored. Assuming reasonably uniform radial spread from the injection point, a 'test GIN' can

be determined for a given penetration. The GIN for the spacing required by the design can then be estimated using the expression:

$$R = R_t \sqrt[3]{(GIN/GIN_t)} \qquad (1)$$

where:

      R - penetration required in the prototype (design)
      R_t - penetration estimated from the test
      GIN - the GIN to be applied to the prototype
      GIN_t - the test GIN corresponding to the test penetration

Capturing injection pressure and volume data is straightforward with modern grouting equipment and is discussed briefly later. However, the practicality of determining the penetration distance and corresponding grout injection volume is a fundamental difficulty and explains in part why the experimental derivation of the GIN is rarely used in conventional grouting work.

An option study undertaken to look at the practical aspects of detecting grout concluded that the most cost effective and practicable solution to assessing the form of the grout flow would be to use sensors to detect grout arrival in real time at a number of observation holes located around the injection borehole. For this to work, it was recognised that fluid grout detection must be performed in a sealed section of observation hole to prevent the hole becoming a preferential sink for the injection grout and adversely affecting the development of the grout front from the injection point. Laboratory trials of various forms of detection probe (pressure, temperature, conductivity and pH) were undertaken and showed that the down-hole pH transducer was the most effective at detecting grout and that a change in pH could detect and distinguish grout both at dilute concentrations (imminent arrival) and at full concentration (fluid grout arrival).

Experimental Layout

The field experiment was arranged as a 75m deep central injection borehole (P1) with 3no. 75m observation bores (PO11 – PO13) arrayed equally on a 4m radius and a further 3no. observation holes (PO14 – PO16) arrayed equally on a 6m radius with a 60° offset from the inner observation bores – Figure 1. Boreholes P1 and PO11 – PO13 were geophysically logged using wireline tools (televiewer, gamma log, flow log) and based on the stratigraphy and hydrogeology inferred from the logs the strata was subdivided into a number of contiguous 3m sections that were accurately referenced to the stratigraphical position within the sequence. These 3m sections were then hydrogeologically tested to estimate the hydraulic conductivity and character of the ground around the boreholes prior to grout injection. This characterisation was expressed in terms of borehole 'zones' (Table 1), analogous to Lombardi's 'homogeneous zones', with an experimental GIN being sought for each.

Borehole P1 was then grouted in ascending stages that matched the stratigraphic positions of the hydrotesting. After the grout penetration experiment, a further 2no. boreholes (PO17, PO18) were drilled 1.5m and 4.5m respectively from P1 and hydrogeologically tested, again in continuous 3m intervals located at the same stratigraphic position within the sequence as the pre-grouting tests. The purpose of the post-grouting hydrotests was to quantify the change in rock mass transmissivity caused by a single grout injection. As noted previously, the completed

barrier used a split splacing technique and therefore each piece of ground will experience multiple grout injections

All boreholes were of a similar depth to those anticipated for the main Shaft Isolation works and passed through several cycles of the stratigraphical sequence ensuring that penetration trials were undertaken in all types of ground. In total, the borehole depth allowed 25no. stages to be injected and monitored.
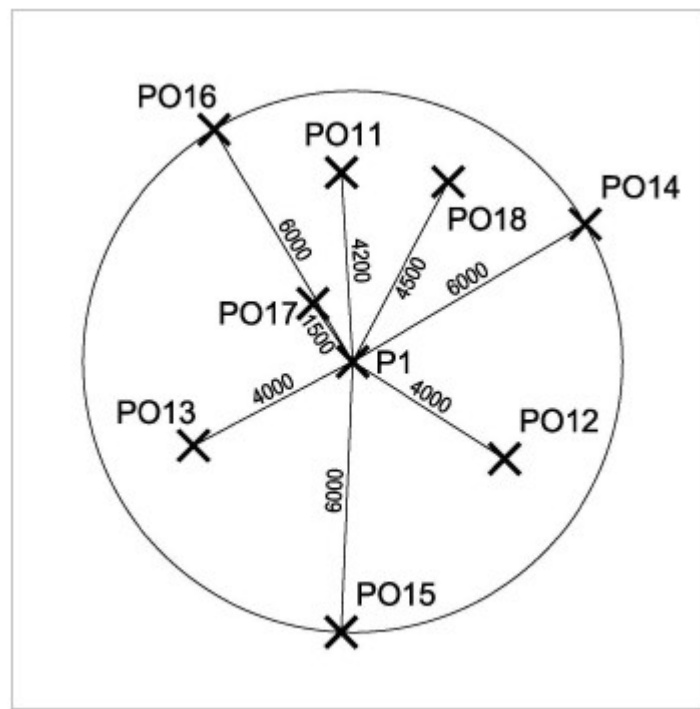
Figure 1 – Plan View on Field Experiment

Zone	Name	Description	Anticipated Grouting Properties
W	Weathered Zone	Closely spaced discontinuities, High or very high permeability.	Low pressure/high take. Likely to stop on volume limit.
F	Fault or Joint Zone	Clusters of SV joints or zone of broken ground. Moderate or high permeability	Low pressure/high take. Likely to stop on volume limit.
1	Major Bedding Planes	Clusters of SH discontinuities, identified as continuous across the site. Moderate or high permeability.	Low to medium pressure/high take. Require high GIN to ensure saturation.
2	Minor Bedding Planes	Multiple SH fissures with range of low permeabilities, low or moderate permeability.	High pressure/low take. High GIN and split spacing required to ensure full saturation.
3	Intact Rock	Very few fractures (0 or 1 per 5m) Very low or low permeability.	High pressure/low take. High GIN and multiple split spacing required to ensure full saturation.

Table 1 – Borehole Zoning Definitions

Drilling

The boreholes for the field experiment were drilled using Boart Longyear DB520 hydraulic rotary drilling rigs employing an HQ wireline coring system (producing a 96mm bore diameter) and a clean water flushing medium. Wireline coring was selected as the preferred drilling method for reasons of radiological waste minimisation and, whilst relatively slow compared with percussive methods, provided a stiff drill string and good bore verticality.

During earlier drilling trials, various polymeric flushing media were assessed. However, these were not used during the penetration experiment nor in subsequent works, primarily due to concerns about clogging of discontinuity apertures and the development of borehole wall 'skin' effects, but also because clean water worked adequately as a flushing medium and was found to make solids control more manageable.

Hydrogeological Testing

Hydrotesting in each of the boreholes was undertaken by the constant head injection method. The test interval was 3m, with each stage being isolated using a double packer straddle with a down-hole shut-in tool. Test pressures of 1 – 3bar were used from 5m to 20mbgl while differential pressures of 3 – 6bar were used for intervals deeper than 20mbgl. The decline of the flow rate was recorded as a function of time, with the test duration being determined by the time necessary to record sufficient data of the transient formation response to be analysed in a semi-log plot (typically 20 – 30minutes per interval). Analyses of the test results were based on the conventional steady-state approximation equation or straight line analysis as appropriate. The results provided estimates of hydraulic conductivity (transmissivity/interval length) for ungrouted ground ranging over 6 orders of magnitude between 3×10^{-4}m/s and 2×10^{-10}m/s.

Grouting

The primary grout used in the penetration field trials was developed during an earlier phase of grout material trials and comprised an ultrafine ($d_{95}=16\mu$) cement colloidally mixed with water, a superplasticiser and a silica fume stabilising agent.

Down-hole equipment comprised air-inflated double packers mounted on a steel mandrel with a variable (1 – 3m) straddle. Grout was delivered through Kevlar grout lines, with injection commencing near the base of the borehole and progressing in 3m ascending stages.

The grout mixing and injection plant comprised a pair of Colcrete SD200 high shear colloidal mixers fitted with automatic batching control. Batched grout was held in an agitator tank prior to being injected using paired opposing phase single acting 0-100bar piston pumps. Each pumpset was equipped with an in-line electro-magnetic flow meter and 0-100bar pressure transducer with signals being returned to the control system in a separate grouting control module.

The grout injection was controlled using bespoke software operating on a desktop computer, capable of controlling and datalogging up to 6no. simultaneous injections with different parameters for each. For a given injection, stage information (borehole number, depth) was entered along with the defining injection parameters (GIN, maximum pressure, maximum volume, pressure corrections for stage depth). Flow rate for each pump was selected using ABB controllers and was generally held constant for each injection at between 3 to 5 litres/minute. For

the purposes of the penetration experiment, the GIN parameter and volume limit were set at an artificially high level to allow injection to continue until grout detection occurred.

Down-Hole Monitoring

Each of the observation bores PO11 – PO16 was fitted with a double packer set with a 5.5m straddle. Hach Lange pH and pressure/temperature transducers were fitted to the centre of the straddles and hard-wired back to a datalogger at the surface.

Water flushing lines were included in the observation bore packer sets to counteract the effect of pH buffering from earlier injections. By this method, the pH in the test interval could be reduced sufficiently between vertically adjacent injections to allow fresh grout arrival to be detected.

Experimental Method

Each injection commenced with seating of the injection and observation packer sets at the test stage, with the 5.5m observation interval being centred vertically opposite the shorter 3m grout injection interval. Datalogging of the down-hole transducers in bores PO11 – PO16 was commenced some time in advance of grout injection to establish a pre-injection baseline. Where necessary, water flushing of the observation bores to re-establish neutral pH was undertaken until the packer sets where inflated. The injection lines and interval were filled with primary grout and injection commenced at a constant flow. Logged data from the grout control system and observation transducers was graphed and displayed in real-time to alert the operators to grout arrivals. Post analysis of the combined data allowed each fresh grout arrival, signified by a pH of 12.7, to be correlated with an injection pressure and volume, thereby providing the experimental GIN for that penetration distance from the following expression:

$$GIN = p_t.V_t/L \qquad\qquad (2)$$

where,

p_t - the injection pressure at time of grout arrival (bar)
V_t - the injected volume at time of grout arrival (litres)
L   - the injection interval length (m)

The pattern of grout arrival over the 6no. observation bores together with known arrival times permitted assessment of the penetration form and directional bias where present, and for these data to be related to the stratigrpahy and joint orientation using the results from the pre-grouting televiewer and gamma logs.

RESULTS

25no. grout injections were undertaken during the experiment, comprising 1no. zone F, 1no. zone W, 11no. zone 1, 8no. zone 2 and 4no. zone 3 intervals. Practical difficulties during grouting near the base of the borehole and packer bypass through subvertical joints is thought to have led to some fissure clogging that may have affected grout acceptance in lower stages.
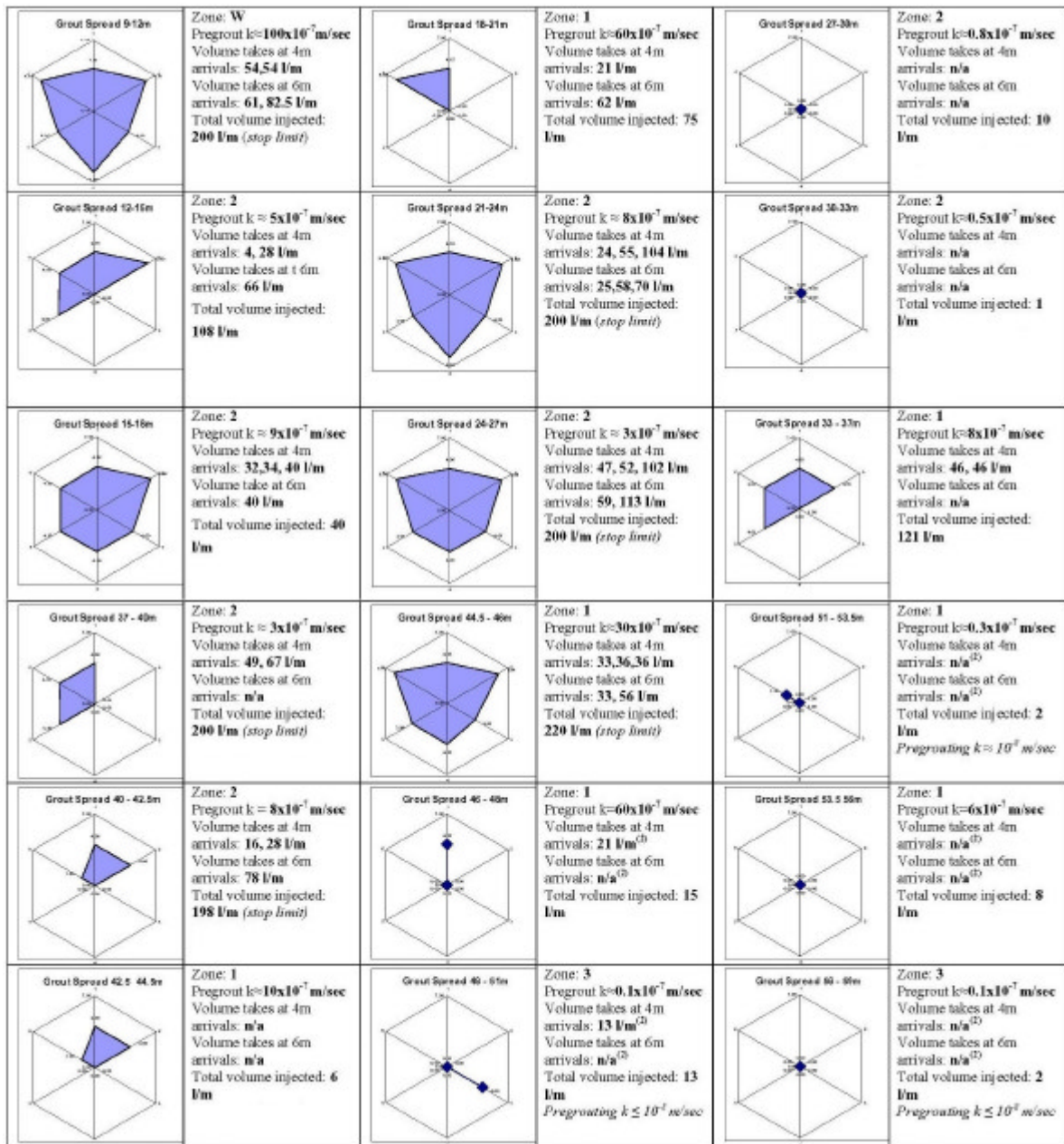
Figure 2 – Schematic Grout Injection Results

Grout Spread	Details	Grout Spread	Details	Grout Spread	Details
Grout Spread 9-12m	Zone: W; Pregrout $k\approx100\times10^{-7}$ m/sec; Volume takes at 4m arrivals: 54,54 l/m; Volume takes at 6m arrivals: 61, 82.5 l/m; Total volume injected: 200 l/m (*stop limit*)	Grout Spread 18-21m	Zone: 1; Pregrout $k\approx60\times10^{-7}$ m/sec; Volume takes at 4m arrivals: 21 l/m; Volume takes at 6m arrivals: 62 l/m; Total volume injected: 75 l/m	Grout Spread 27-30m	Zone: 2; Pregrout $k\approx0.8\times10^{-7}$ m/sec; Volume takes at 4m arrivals: n/a; Volume takes at 6m arrivals: n/a; Total volume injected: 10 l/m
Grout Spread 12-15m	Zone: 2; Pregrout $k\approx5\times10^{-7}$ m/sec; Volume takes at 4m arrivals: 4, 28 l/m; Volume takes at 6m arrivals: 66 l/m; Total volume injected: 108 l/m	Grout Spread 21-24m	Zone: 2; Pregrout $k\approx8\times10^{-7}$ m/sec; Volume takes at 4m arrivals: 24, 55, 104 l/m; Volume takes at 6m arrivals: 25,58,70 l/m; Total volume injected: 200 l/m (*stop limit*)	Grout Spread 30-33m	Zone: 2; Pregrout $k\approx0.5\times10^{-7}$ m/sec; Volume takes at 4m arrivals: n/a; Volume takes at 6m arrivals: n/a; Total volume injected: 1 l/m
Grout Spread 15-18m	Zone: 2; Pregrout $k\approx9\times10^{-7}$ m/sec; Volume takes at 4m arrivals: 32,34, 40 l/m; Volume take at 6m arrivals: 40 l/m; Total volume injected: 40 l/m	Grout Spread 24-27m	Zone: 2; Pregrout $k\approx3\times10^{-7}$ m/sec; Volume takes at 4m arrivals: 47, 52, 102 l/m; Volume takes at 6m arrivals: 59, 113 l/m; Total volume injected: 200 l/m (*stop limit*)	Grout Spread 33 - 33m	Zone: 1; Pregrout $k\approx8\times10^{-7}$ m/sec; Volume takes at 4m arrivals: 46, 46 l/m; Volume takes at 6m arrivals: n/a; Total volume injected: 121 l/m
Grout Spread 37 - 40m	Zone: 2; Pregrout $k\approx3\times10^{-7}$ m/sec; Volume takes at 4m arrivals: 49, 67 l/m; Volume takes at 6m arrivals: n/a; Total volume injected: 200 l/m (*stop limit*)	Grout Spread 44.5 - 46m	Zone: 1; Pregrout $k\approx30\times10^{-7}$ m/sec; Volume takes at 4m arrivals: 33,36,36 l/m; Volume takes at 6m arrivals: 33, 56 l/m; Total volume injected: 220 l/m (*stop limit*)	Grout Spread 51 - 53.5m	Zone: 1; Pregrout $k\approx0.3\times10^{-7}$ m/sec; Volume takes at 4m arrivals: n/a[1]; Volume takes at 6m arrivals: n/a[2]; Total volume injected: 2 l/m; *Pregrouting $k\approx10^{-8}$ m/sec*
Grout Spread 40 - 42.5m	Zone: 2; Pregrout $k=8\times10^{-7}$ m/sec; Volume takes at 4m arrivals: 16, 28 l/m; Volume takes at 6m arrivals: 78 l/m; Total volume injected: 198 l/m (*stop limit*)	Grout Spread 46 - 48m	Zone: 1; Pregrout $k=60\times10^{-7}$ m/sec; Volume takes at 4m arrivals: 21 l/m[1]; Volume takes at 6m arrivals: n/a[2]; Total volume injected: 15 l/m	Grout Spread 53.5 56m	Zone: 1; Pregrout $k=6\times10^{-7}$ m/sec; Volume takes at 4m arrivals: n/a[1]; Volume takes at 6m arrivals: n/a[2]; Total volume injected: 8 l/m
Grout Spread 42.5 44.5m	Zone: 1; Pregrout $k\approx10\times10^{-7}$ m/sec; Volume takes at 4m arrivals: n/a; Volume takes at 6m arrivals: n/a; Total volume injected: 6 l/m	Grout Spread 49 - 51m	Zone: 3; Pregrout $k\approx0.1\times10^{-7}$ m/sec; Volume takes at 4m arrivals: 13 l/m^{2}; Volume takes at 6m arrivals: n/a[2]; Total volume injected: 13 l/m; *Pregrouting $k\leq10^{-8}$ m/sec*	Grout Spread 60 - 6?m	Zone: 3; Pregrout $k\approx0.1\times10^{-7}$ m/sec; Volume takes at 4m arrivals: n/a[1]; Volume takes at 6m arrivals: n/a[1]; Total volume injected: 2 l/m; *Pregrouting $k\leq10^{-8}$ m/sec*

The temperature probes in the observation bores generally showed no response at any point during grout injection. Given the extensive clean water flushing that was necessary to reduce pH after each stage, it is likely than any grout-driven temperature response was masked by the water/ground temperature gradient. The pressure transducers often showed some response, both to start of injection and grout arrival. However, the responses were highly variable in form and scale and, coupled with their unreliable nature, were not a credible indicator of grout arrival. The pH transducers were found to be unaffected by the start of injection or any resulting groundwater motion, but showed a distinct and pronounced response to grout approach and arrival. The absolute pH values recorded during perceived grout approach corresponded

closely with those measured in the laboratory for various grout dilutions, whilst the peak pH readings for perceived arrival matched the laboratory values for neat grout. In many cases, physical grout arrival was definitively confirmed by the presence of liquid grout found coating observation instruments that had been withdrawn for cleaning and maintenance after the end of injection.

Schematic plots of grout spread are shown in Figure 2. The stages below 59m recorded no grout arrival at 4m or 6m and for reasons of space are therefore not shown. The radial distribution of the grout has been plotted by joining the grout arrivals for each hole at the appropriate distance from P1. Where grout was detected in two adjacent 4m holes, grout is assumed to have travelled 4m towards the intermediate 6m hole. Otherwise, no grout is assumed to have travelled towards the 6m holes (except for PO16 in the case where PO17 shows that flow has occurred). In recognition of the proportionality of the pH response to grout front proximity, the Figure 2 results have been plotted using a less conservative definition of grout arrival: a sudden and rapid rise in pH or a pH of above 11.5.

DISCUSSION AND CONCLUSIONS

The GIN Experimental Method is recognised to be theoretically attractive, but extremely difficult to implement. However, the innovative development of the pH probes on this project to detect grout arrivals in observation holes made the method a feasible option for the study of both penetration and for the estimation of GIN values. In addition to detection of grout arrivals, the clear and proportional response of the pH probes allowed credible quantitative assessments to be made of the grout penetration and hence the form of radial spread at each stage. The stages below 37mbgl show a strong directional bias in the direction of PO11 and PO16. However, the site characterisation work revealed a sub-vertical fault passing through the periphery of the penetration trial and intersecting observation holes PO12 and PO15 immediately beneath the 37mbgl level. The fractured rock associated with the fault appears to have taken grout preferentially and effectively isolated PO12 and PO15 from the P1 injection.

Overall, the extensive body of results show that a significant reduction in permeability was achieved by the injection of primary grout in this single borehole, typically an order of magnitude or greater in the more permeable strata. Further reduction of the permeability would be expected in a complete grout barrier as a result of injection in subsequent series of boreholes following the split-spacing principle.

ACKNOWLEDGEMENTS

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