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Could magnetic properties be used to image a grouted rock volume?

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ABSTRACT

In this study, we show that development of a detectable permeation grouting system is feasible, based on the addition of magnetic materials to the grout, specifically, magnetite. A magnetic-based detection system is selected for development because unlike other previously trialled detection methods, magnetic fields are detectable over large distances within the subsurface, and importantly, attenuation of the magnetic field is not strongly dependent on the material properties of the surrounding rock. To test the conceptual feasibility of such a system, a finite element based numerical model is developed to simulate the magnetic field anomaly that can be achieved by the addition of magnetic materials to a cement grout. The model is verified against an analytical solution and then used to predict the magnetic field generated by a grouted cylinder of rock, assuming a fixed percentage of uniformly distributed magnetic minerals, and a central injection borehole. Two field trials are conducted to verify the detectable grouting concept, the first using a walkover survey that allowed mapping of the magnetic signal in 2D. The second is designed to mimic magnetic field measurements from a borehole monitoring array, with a single central magnetic grout block (representing the grout close to the injection point). Results of the two field trials show that the magnetic cement is detectable, even when the background magnetic noise within the surrounding soils/rocks is significant. A good agreement is obtained between the measured and the modelled magnetic anomaly. This research opens the door to the development of a 'detectable' magnetic grouting system, that can increase confidence in the integrity of grouted rock volumes and reduce the inefficiencies currently present in the grouting industry, enabling in-situ real-time optimisation of grouting campaigns.

1. Introduction

Cement grouting of rocks is widely used for reducing the hydraulic conductivity of underground structures (Li et al., 2016), of founding layers below dams and their interface with the dam core (e.g. Rastegarnia et al., 2017), for hydraulic containment of underground storage and disposal sites (e.g. Tsuda et al., 2012) and for the filling of underground shafts and cavities prior to construction of major infrastructure (Meier and Hoffmann, 1999). The most popular method within Europe for design and control of grouting campaigns is the empirical Grouting Intensity Number (GIN) method (Lombardi, 1996; Brantberger et al., 2000). The GIN method combines observations of pressure and injected volume to calculate a grouting intensity number. When kept below a user defined threshold, the GIN controls the energy applied to the fractures, thus avoiding fracture jacking and uplift. El Tani (2012) reformulated both the GIN and North American grout refusal criteria to calculate grout penetration based on an analytical model of radial flow of a Bingham fluid into a planar fracture. However Rafi and Stille (2015) demonstrated via a case study that the GIN value should be defined based on knowledge of grout spread, particularly for fractures at shallow depths or fractures requiring a high level of sealing. They presented an analytical solution for estimating grout penetration that includes the deformation of fractures during grouting.

The common assumption in the control of all permeation grouting campaigns is that grout penetrates radially from an injection borehole. This assumption is necessary, but invalid; in a rock with varying fracture apertures, individual fractures cross-cutting the injection borehole will have varying principal grout flow directions and variable penetration distances. The need to assume radial flow derives from an inability to detect the extent of grout penetration during and after injection. The definition of the GIN value without knowledge of grout penetration can result in the application of overly high injection pressures, with the result that grout penetrates beyond the target zone (waste of grout material), and unwanted uplifting occurs. On the other hand too low injection pressures can result in incomplete filling, with the result that grouting campaigns tend to be overly conservative relying on split-spacing boreholes. This results in grout wastage, drilling of unnecessary boreholes and a lack of data for true design optimization. In some circumstances, gaps in grout curtains may remain unknown. This is of

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particular concern where hydraulic containment is critical. Without knowledge of grout penetration it is not possible to optimize design of the grout injection.

Several methods for detecting grout penetration have been previously proposed within the research literature; all have significant drawbacks and none are widely used within the construction industry. Chen et al. (2000) added fluorescent particles to grout to visualise grout spread. However, this is an intrusive approach which required penetration of the grouted rock using inspection boreholes and a downhole television logging system. This approach would ultimately compromise the integrity of a grout curtain by the drilling of inspection boreholes in the grouted rock volume. Majer (1989) proposed that high frequency seismic monitoring could be used a potential real-time monitoring system of grout penetration. However, the author was unable to correlate the location of the grout with the seismic activity recorded, in fact, the only seismic events that could be located occurred after the injection of grout had ceased. Ground penetrating radar has also been investigated as a potential method for the detection of different grouts behind tunnel linings (Zhang et al., 2010). However grout was only detected at distances less than 1 m and not in the presence of utilities within the tunnel. Detection of GPR signals is only expected to be possible over several meters as the signal is strongly attenuated by the ground. Furthermore detailed knowledge of the electrical properties of the material at the particular site where monitoring is to take place would be required. pH monitoring was used to infer grout spread in the design of the grouting campaign at Dounreay (UK) to hydraulically isolate a vertical shaft containing nuclear waste (Henderson et al., 2008). Grout penetration distances were estimated using the pH as an indication of grout breakthrough (Henderson et al., 2008) with some success. However, relying on pH measurements has drawbacks: it is not possible to locate the penetration front of the grout itself (as bleed water in advance of the grout front also exhibits a high pH) and it is generally not permissible for invasive observation boreholes to be located within the rock volume that is to be grouted.

In this paper, we test the feasibility of a new approach to detect grout penetration, through the addition, and subsequent detection, of magnetic minerals to cement grout. We develop a numerical model to demonstrate the feasibility of a magnetically detectable grouting system and compare our model with the results from two surface-based field trials. The key objectives of this study are to determine whether, and over what distance, cement grout containing magnetite particles is detectable in the subsurface, and whether different shaped magnetic grout blocks (volumes) produce detectably different magnetic fields.

2. Theoretical concept

To-date, no researchers have investigated the use of magnetic properties for grout detection. When compared to other geophysical approaches, a magnetic-based detection system could have significant advantages: (1) magnetic materials can be detected over large distances within the subsurface, (2) attenuation of the magnetic signal strength is not dependent on the properties of the surrounding material (i.e. rock, water or air), and (3) at any one location, the magnitude and direction of a magnetic field generated by a magnetic body is dependent on the shape and location of the magnetic body. Hence, theoretically, the shape and location of an injected magnetic grout within the ground may be accurately determined without requiring a priori knowledge of the in-situ rock/soil properties.

To determine the theoretical feasibility of developing a magnetically detectable grout, a numerical model was developed to simulate the 3D magnetic field produced by a known volume of magnetic material within the ground, subject to the Earth's magnetic field. There are many different types of magnetic materials; their magnetic properties differ based on their composition and crystal structure, and in the response of their electrons to an externally-applied magnetic field. Amongst naturally occurring magnetic minerals, magnetite (Fe_3O_4) has the largest magnetic susceptibility (up to $\chi = 650$) and the strongest remnant magnetization (up to 5000 A m^{-1}) (Kletetschka et al., 2000). Therefore, in the presence of an external magnetic field, such as that produced by the Earth, magnetite can produce a large magnetic anomaly.

2.1. Theoretical model

To model the magnetic field produced by the presence of a body containing magnetite within the ground, we use Maxwell's magnetostatic equations with the assumption that the region of interest is current free (Griffiths, 1999):

$$\nabla \times \mathbf{H} = 0 \tag{1}$$

$$\nabla \cdot \mathbf{B} = 0 \tag{2}$$

Here, $\mathbf{H}$ is the magnetic field (units: A m^{-1}), and $\mathbf{B}$ is the magnetic flux density (units: T). From Eq. (1), a scalar magnetic potential ψ can be defined such that

$$\mathbf{H} = -\nabla\psi \tag{3}$$

and hence we are only required to solve Eq. (2). The magnetic field $\mathbf{H}$ and the magnetic flux density $\mathbf{B}$ are related via the constitutive equation

$$\mathrm{B} = \mu\mathbf{H} + \mathbf{B}_r \tag{4}$$

where μ is the magnetic permeability and $\mathbf{B}_r$ is the remanent magnetic flux density. The magnetic permeability can be written as $\mu = \mu_0(1+\chi)$, where $\mu_0 = 4\pi \times 10^{-7}$ NA^{-2} is the permeability of free space, and χ is the magnetic susceptibility of the magnetic body.

The total magnetic field can be split into a background field, $\mathbf{H}_b$, and an anomalous part, $-\nabla\psi_a$, that represents the magnetic field which arises from the presence of the magnetic body, such that $\mathbf{H} = \mathbf{H}_b - \nabla\psi_a$. Eq. (2) then becomes

$$\nabla \cdot (\mu(\mathbf{H}_b - \nabla\psi_a) + \mathbf{B}_r) = 0 \tag{5}$$

This equation represents the governing equation for determining the magnetic field due to a body of magnetically-susceptible material within the Earth's magnetic field. To solve this equation for ψ_a, appropriate boundary conditions must be defined. On the boundary of the magnetic material, continuity of the magnetic field and continuity of the normal component of the magnetic flux density can be assumed, i.e.

$$[\psi_a]_1^2 = 0 \tag{6}$$

$$[\mathbf{n}\cdot\mathbf{B}]_1^2 = 0 \tag{7}$$

where the notation $[\ ]_1^2 = [\ ]_2 - [\ ]_1$ is used for the difference in a quantity across the boundary, and $\mathbf{n}$ is the outward unit normal of the magnetic body. On the exterior boundaries of the model, we impose

$$\psi_a = 0 \tag{8}$$

i.e. the field induced due to the presence of the magnetic grout is set to zero. This is a valid assumption if the boundaries are sufficiently far away.

A numerical model was developed to solve Eq. (5) with boundary conditions (6)–(8) within the finite element software platform, FreeFem++ (Hecht, 2012). After solving, the magnetic anomaly is given by

$$B_a = |\mu(\mathbf{H}_b - \nabla\psi_a) + \mathbf{B}_r| - |\mu\mathbf{H}_b| \tag{9}$$