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On using the thin fluid-layer approach at ultrasonic frequencies for characterising grout propagation in an artificial fracture

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ABSTRACT

Grouting the fractures encountered when constructing underground facilities is of primary importance for environmental, safety and economic reasons. The success of grouting operation, however, depends upon several parameters governing the grout propagation. Experimental benches replicating fractures have therefore been designed to study processes related to grout propagation. In this paper, we investigate the ultrasonic transport properties of such an idealized fracture whose 100 μm aperture is about 0.02 the wavelength, and filled with various fluids flowing under external forcing. As the artificial fracture is made of two solid and parallel walls separated by a thin fluid layer, we use the thin fluid layer concept to study the compressional (P-) wavefield transmitted across and reflected off the fracture, with no mode-conversion considered. We demonstrate that air and various fluids (water, grouts of varied w/c – water to cement ratio) can be distinguished when injected into the fracture, both at atmospheric pressure or under over-pressure as done in real grouting cases in the field. Then, using an analytical solution, we verify our experimental data and predict the results that can be obtained with a different fracture aperture. Our results illustrate that replicating such ultrasonic measurements both in space and time would allow to monitor successfully the grout propagation within an artificial fracture. The detection of the filtration of the suspended cement-particles of the grout, the formation and erosion of filter-cakes, are also in the scope of the method.

1. Introduction

Fractures occur naturally in rock masses and generally represent preferential pathways for groundwater, as well as zone of weakness within the rock mass. When excavating for the construction of underground facilities, it is therefore often chosen to seal the most problematic fractures, and more generally deformation zones, encountered by injecting cementitious grouts. This increases the safety of the underground facility, both during its construction and future usage, including the protection of natural groundwater and the biosphere in the vicinity of the facility [e.g. [1–4]].

It has been observed that sealing fractures with cement grouting can be improved by optimising several parameters, such as the rheology of the grouting fluid, and the pressure of injection.[2,5–10] The complexity of the rock mass is also of great importance, as for example the connectivity of the fracture network and the variation in fracture aperture have a major impact on the success of grouting operations.[11] Especially, the bigger the fracture aperture, the better the grout propagation, and therefore the more effective the sealing.[12]

As the geometry of natural-fracture networks in a rock mass is complex and poorly constrained, experimental benches have been developed in laboratories to study grout propagation into fractures with a much better control of experimental conditions. This way, the grout propagation can be studied within replicated fractures [e.g. [13]] or idealised fractures of a much simpler geometry [e.g. [5,14,15]]. In the latter case, the assembly typically consists of two plates of non-porous material separated by a thin void. The geometry of the problem is therefore simple but fully constrained, allowing an accurate and reproducible study of the grout propagation as a function of several parameters, for example the properties of the cement, the pressure of injection and the aperture of the fracture [e.g. [5,14,15]]. Such experiments have shown that one critical factor controlling the grout propagation is the size of the particles with respect to the aperture of the fracture (in complex interactions with other parameters such as the concentration of particles, the pressure [see for example Refs. [14,15]]). Solid particles of the cement may arch over the constrictions, forming plugs or filter-cakes. The grout may propagate further, but in the form of filtered cement with a lesser density, whose sealing property is poorer than that of the original mixture.[14,15]

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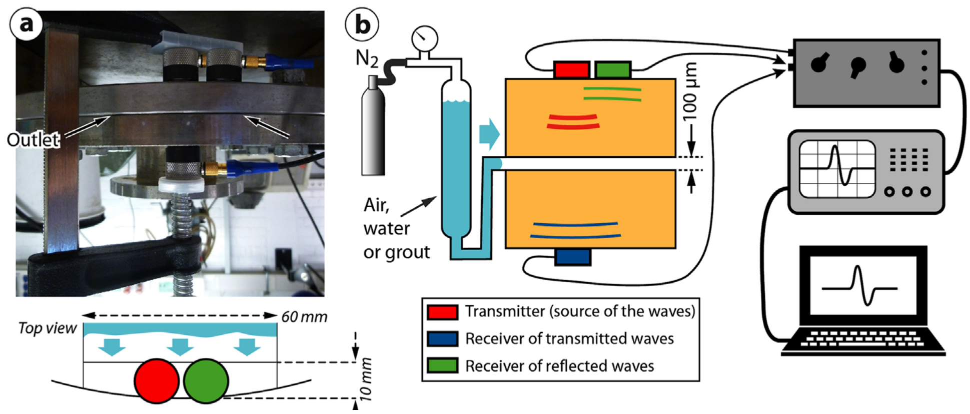

Fig. 1. (a) Transducers equipping an artificial fracture. (b) Sketch of the ultrasonic setup used in this study showing the fracture to be filled with air, water or grout. Schematic wave fronts generated by the source are indicated in red; wave fronts transmitted across or reflected off the fracture are represented in blue and green, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Experimental benches may be made of transparent material to visually follow the propagation of grouts[5]. In some other setups, the platens are made of thick steel in order for the fracture geometry to not change when applying an injection pressure as high as that typically used in the field (e.g. around 15 bars[14,15]). Even in the cases where a visual inspection is possible, it is challenging to relate optical and other physical properties of the grout such as viscosity and density. Rheological and elastic properties of cements pastes are tied, which is the reason for cement pastes to have extensively been studied using elastic waves at ultrasonic frequencies (see amongst others[16–20]). However, to our knowledge, only one study applied ultrasonic measurements to a laboratory experiment where a fracture was grouted[13]. Reflections off the fracture, acoustic emissions as well as travel time tomography were tested, and proved that ultrasonic measurements are effective in monitoring the grout propagation in a fracture.

The study of Saleh et al.[13] did not however consider the detection of rheological changes of the grout during the experiment, and the geometry of the fracture (a crack affecting a slab made of concrete) was irregular. Our study focusses on discerning changing fluid properties in a fracture successively filled with air, water, and grouts, using ultrasonic waves and the thin fluid layer concept [e.g. [21,22]]. The thin fluid layer concept considers (i) a fluid layer of constant thickness embedded between two non-porous solid bodies and (ii) illuminated with elastic waves whose wavelengths are greater than the thickness of the fluid layer. Therefore, this model can be seen as a simplified fracture whose major limitations to replicate a real case are the absence of roughness of the walls (hence no contact of the walls is allowed) and the non-transfer of fluids between the matrix and the fluid layer. Early theoretical developments have shown that the response of a fluid layer to a normally incident compressional wave (P-wave) depends on (i) the ratio of the bulk modulus to effective shear modulus of the fluid, (ii) the ratio of elastic impedance of the solid to the shear impedance of the fluid and (iii) the energy loss of converted shear wave (S-wave) in the fluid.[23] Therefore, when the properties of the fracture walls are constant, there is scope for repeated elastic-wave measurements to characterise changing properties of the fluid. As the shear modulus, shear impedance and attenuation of S-waves in cement pastes/grouts span over broad ranges as a function of the cement concentration and the presence of superplasticizer,[24–27] the use of elastic waves has potential for characterising changing properties of the fluid. In other words, the working hypothesis of our study is that an increase in concentration in cement in the fluid, resulting amongst other things in higher viscosity and density, can be detected by an increase in the amplitude of the elastic waves transmitted across the fracture, and conversely a decrease in the amplitude of the reflected waves.

The thin fluid layer concept has been used in previous laboratory experiments by Groenenboom and Kokkema.[21] However, this study was focussed on monitoring the variations of the hydraulic aperture of a crack as water (of constant properties) was injected at varying pressure. Moreover, this study considered signals transmitted across the fracture.[21] This means that ultrasonic transducers need to be located on both sides of the fracture, which aside to extra equipment costs makes it more complicated or not feasible when upscaling the method to field cases. Recent laboratory experiments have illustrated that changes in pore pressure at a single interface could be detected using the reflected ultrasonic wavefield,[28] which encourage to test a similar approach in the case of the thin fluid layer. Therefore, in this study we examine the information contained in signals transmitted across and reflected off a fracture when the properties of its filling vary in time. We demonstrate that reflected P-waves carry sufficient information about the fluid properties, implying that full benefit can be taken from reducing the equipment to only one side of the fracture.

2. Experimental setup

2.1. Fracture apparatus

The setup used to replicate a fracture is represented in Fig. 1 and is one of the short slots used by Draganovic et Stille[14]. The experimental bench consists of two ca. 15 mm thick steel platens. Their thickness has been reduced locally to form an artificial idealised fracture, which in this paper will be referred to as “fracture” for simplicity. The fracture aperture is 100 µm and extends over ca. 10 × 60 mm at the termination of a 60 mm wide conduit (Fig. 1a). This fracture was saturated with various fluids (Fig. 1b). A system fully described in Ref.[14] also allows to put the fluids under pressure for injection. In the following, “static” indicates conditions of measurements where the fracture is saturated by fluids with a slight overpressure of approximately 900 Pa due to gravity forces. Given the viscosity of the fluids and the fracture aperture, only a negligible flow rate was observed. “Flowing” denotes conditions where a pressure of 1.5 MPa was applied to the tank where the fluid was stored (Fig. 1b). Depending on the viscosity of the fluid, the 2.6 l content of the tank was flushed within a few seconds. It is worth emphasising that the thickness of the platens was designed to ensure that changes in the fracture aperture under the effect of pressure is negligible.

2.2. Ultrasonic apparatus

Ultrasonic waves were generated and recorded using a two-channel ultrasonic apparatus presented in Malehmir et al. 29.