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Research papers

Cross-hole fracture connectivity assessed using hydraulic responses during liner installations in crystalline bedrock boreholes

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ABSTRACT

In order to continually improve the current understanding of flow and transport in crystalline bedrock environments, developing and improving fracture system characterization techniques is an important area of study. The presented research examines the installation of flexible, impermeable FLUTe™ liners as a means for assessing cross-hole fracture connectivity. FLUTe™ liners are used to generate a new style of hydraulic pulse, with pressure response monitored in a nearby network of open boreholes drilled in gneissic rock of the Canadian Shield in eastern Ontario, Canada. Borehole liners were installed in six existing 10–15 cm diameter boreholes located 10–35 m apart and drilled to depths ranging between 25–45 m. Liner installation tests were completed consecutively with the number of observation wells available for each test ranging between one and six. The collected pressure response data have been analyzed to identify significant groundwater flow paths between source and observation boreholes as well as to estimate inter-well transmissivity and storativity using a conventional type-curve analysis. While the applied solution relies on a number of general assumptions, it has been found that reasonable comparison can be made to previously completed pulse interference and pumping tests. Results of this research indicate areas where method refinement is necessary, but, nonetheless, highlight the potential for use in crystalline bedrock environments. This method may provide value to future site characterization efforts given that it is complementary to, and can be used in conjunction with, other currently employed borehole liner applications, such as the removal of cross-connection at contaminated sites and the assessment of discrete fracture distributions when boreholes are sealed, recreating natural hydraulic gradient conditions.

1. Introduction

Crystalline bedrock aquifers occur in many regions of the world and are exposed in vast areas, such as the Precambrian rocks of the Canadian Shield, Baltic Shield, and Brazilian Shield. While wells drilled in crystalline rock may be associated with limited yield in some locations, they are nonetheless important for water supply, especially in many developing countries where surface water is often inadequate (Howard and Karundu, 1992; Chilton and Foster, 1995; Adekunle et al., 2007; Kulabako et al., 2007; Neves and Morales, 2007; Holland and Witthüser, 2011; Foster, 2012; Boisson et al., 2015). Unfortunately, these aquifers can be particularly vulnerable to contamination (e.g. Kim et al., 2016; Vitale et al., 2017). Crystalline bedrock aquifers generally contain negligible matrix porosity and as a result, groundwater flow is transmitted nearly exclusively through fractures within a largely impervious rock matrix. Although the effective porosity of these pathways is quite small (in the order of 10^{-4}–10^{-5}), average linear groundwater velocities can be significant, creating the potential for rapid contaminant transport and widespread contaminant migration (Allen and Morrison, 1973; Singhal and Gupta, 1999; Conboy and Goss, 2000; Levison and Novakowski, 2009). These conditions may be enhanced by minimal matrix diffusion, storage and associated solute degradation, as well as rapid recharge of groundwater and associated contaminants in areas with thin overburden, which is common in crystalline bedrock environments (Grisak and Pickens, 1981; Gerhart, 1986; Bodin et al., 2003; Gleeson et al., 2009; Levison and Novakowski, 2012; Levison et al., 2012; Praamsma, 2016).

Given this inherent vulnerability, characterization of crystalline bedrock aquifers, to gain an enhanced understanding of groundwater flow and contaminant transport, is a necessary task. However,

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fully understanding this vulnerability is complicated by inherent fracture network complexity (Berkowitz, 2002). In crystalline bedrock environments, past investigations undertaken to better understand groundwater flow and solute transport, for applications including the development of nuclear waste repositories, reveal the potential for highly heterogeneous fracture networks and highlight the difficulties in understanding network characteristics, such as flow path length and geometry, at various spatial scales (e.g. Smith et al., 2001; Hodgkinson et al., 2009; Cvetkovic and Frampton, 2010; Henkel et al., 2010; Follin et al., 2014; Cuss et al., 2015).

A number of systematic characterization methods and approaches have been developed for fractured bedrock site characterization (e.g. Raven, 1986; Karasaki et al., 2000; Vilks et al., 2003; Day-Lewis et al., 2006; Parker et al., 2012). Of the many parameters available for describing a fracture network (e.g. orientation, density, aperture etc.), fracture connectivity plays an important role in governing subsurface recharge, flow, and transport (e.g. Guihéneuf et al., 2014; Becker et al., 2016). Characterizing fracture network connectivity can be a challenging and resource-demanding task, given that a seemingly dense network of fractures (e.g. interpreted from rock core or borehole geophysics) is not necessarily hydraulically connected, due to factors such as constrictions in fracture aperture. To specifically assess the hydraulic properties and fracture connections between boreholes, a number of hydraulic testing methods are available, such as cross-borehole flowmeter tests and commonly used pumping tests and pulse interference tests (e.g. Gernand and Heidtman, 1997; Paillet, 1998; Andersson et al., 2004; Nakao et al., 2005; Stephenson et al., 2006; Worley, 2012, Elmhirst and Novakowski, 2012; Klepikova et al., 2013; Roubinet et al., 2015).

In fractured bedrock environments, extraction or injection stimulus in a pumping test can be associated with significant fluid displacement given minimal effective porosity. This may be undesirable at a contaminated site given the additional costs associated with water storage and treatment following fluid removal. Furthermore, long duration pumping tests are often influenced by external boundary conditions (Raven, 1986) that may confound results where inter-well formation properties are of greatest interest. Pulse interference tests serve as a potential alternative to pumping tests (e.g. Novakowski, 1989; Elmhirst and Novakowski, 2012). These tests involve monitoring the response in one or more observation wells to a change in head in a source well. The high diffusivity of fractured bedrock enables the generation of a detectable pressure perturbation over greater distances than that which could be observed in porous media (Novakowski, 1989). The source of this perturbation may take the form of a slug (Sageev, 1986; Novakowski, 1989) or a sequence of flow rate changes (McKinley et al. 1968), as is commonly applied in the oil and gas industry. Pulse interference tests may be completed under open-hole conditions or with isolated test sections (He et al., 2006; Illman and Tartakovsky, 2006; Stephenson et al., 2006; Cheng et al., 2009; Elmhirst and Novakowski, 2012). The isolated form of a pulse interference test is generally more desirable than open-hole testing because it allows for the examination of targeted vertical borehole intervals and/or discrete fractures; however, this testing approach is both time and resource demanding.

Given the potential drawbacks associated with both pumping tests and pulse interference tests, benefits stand to be gained from the exploration of novel cross-hole testing methods. In this study we examine a unique hydraulic pulse generated by the downhole installation of FLUTe™ blank liners, as a new method of cross-hole hydraulic testing. FLUTe™ liners are impermeable, urethane-coated nylon fabric sleeves closed at the bottom end, designed by Flexible Liner Underground Technologies, LLC, with the original purpose of providing a complete seal along the borehole wall (Keller et al., 2013). Accordingly, these liners can be used at contaminated sites to seal boreholes immediately after they are drilled to prevent hydraulic cross-connection between fractures intersected by the borehole (e.g. Parker et al., 2012; Meyer et al., 2014). FLUTe™ liners are also currently used to facilitate the identification of hydraulically active fractures using temperature (Pehme et al. 2007, 2010, 2013) and may also be used to create temporary sensor deployments for the design of multi-level systems (Pehme et al., 2014).

During the installation of a liner, water is forced outward from the borehole into the surrounding aquifer. The generated hydraulic pulse can be considered a form of progressive, large-scale slug test where the rate of liner descent (and discharge of water exiting the source well) is dependent on the transmissivity of the remaining open borehole interval and fracture intersections (Cherry et al., 2007; Keller et al., 2013). As the liner descends, progressively deeper fractures are cut off from flow, generating a pulse that should be detectable in surrounding observation holes. Through measurements of liner descent velocity and driving head, FLUTe™ Transmissivity Profiling (Keller et al., 2013) can be used to identify the location of permeable fracture features along the borehole wall as well as estimate the transmissivity of these features. This profiling method is an efficient approach for examining a borehole's transmissivity distribution, especially when used in combination with short interval straddle packer testing (Quinn et al., 2015). However, the procedure is still under refinement and is limited to the scale of a single borehole. To date, analysis of the potential pulse interference component has not been conducted.

The objective of this study is to investigate the use of liner installations to assess cross-hole fracture connectivity and inter-well hydraulic properties, and to do so in a manner that is complementary to, and can be used in conjunction with, other currently employed borehole liner applications. The proposed method takes advantage of a pre-existing hydrogeological tool to generate a new style of hydraulic pulse. We hypothesize that pressure responses generated during liner installation can be used to identify hydraulic connections between boreholes. Furthermore, the pressure responses generated during installation can be analyzed with type-curve fitting methods used in pumping test analysis to approximate values of transmissivity and storativity for the inter-well connections examined. This method may be valuable in future characterization of crystalline bedrock aquifers by providing a means of cross-hole data collection that is rapid, convenient, and relatively inexpensive. Knowledge gained from this approach, regarding fracture connectivity and hydraulic parameters across a given site, has potential to guide wellhead protection studies and groundwater remediation strategies.

2. Methods

Six borehole liner installation tests were conducted at a fractured bedrock field site in eastern Ontario, Canada. The following section describes the research site and past aquifer characterization activities, and also presents the applied methodology for site structural analysis, liner installation testing, and analysis of the collected pressure response data.

2.1. Site Description and characterization

Field investigations were completed during 2015–2016 at a research site located near Tamworth, Ontario, Canada. This site is underlain by Precambrian bedrock of the Canadian Shield below less than 1.5 m of sandy loam overburden (Dillon Consulting Ltd. 2004; Gao et al., 2006). Bedrock in this area consists predominantly of heterogeneous, thinly layered, metasedimentary, gneissic rocks