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Lessons learned from hydraulic and pneumatic tomography in fractured rocks

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Abstract

Difficulty in characterizing the fracture-rock matrix system, its hydraulic properties and connectivity at resolutions have led to the development of different conceptual models of fractured rocks. Over the last several decades, considerable effort has gone into creating maps of subsurface heterogeneity in hydraulic conductivity (K) and specific storage (S_s) of fractured rocks. In the unsaturated zone, maps of permeability (k) and porosity (ϕ) may also be obtained with pneumatic tests. Traditionally, numerous single-hole tests are conducted at successive intervals along boreholes to obtain information on such variability. If data from multiple test intervals in several boreholes are available, then they are amenable to geostatistical analysis. However, at some field sites, boreholes are sufficiently far apart that could lead to difficulties in conducting traditional geostatistical analysis as single-hole tests do not directly provide information on connectivity between boreholes. Recent research in the characterization of both unconsolidated and fractured rocks through synthetic, laboratory and field studies has shown that hydraulic tomography (HT) and pneumatic tomography (PT) are very promising approaches in characterizing subsurface heterogeneity. This is due to the fact that both HT and PT rely on multiple pumping or injection tests to generate signals that are detected in neighbouring monitoring intervals. In this paper, I discuss lessons learned from the various studies published in the literature on HT and PT in fractured rocks. In particular, some lessons learned include that: 1) both techniques allow for the mapping of heterogeneity between boreholes; 2) they are applicable at large scales as long as reliable drawdown signals can be detected; 3) PT has shown that improved mapping of heterogeneity leads to the suppression of scale effect in flow properties; 4) both techniques can map the connectivity of flow properties; and 5) improved mapping of heterogeneity and connectivity may lead to improved transport predictions. Overall, HT and PT both appear to provide the most reliable maps of subsurface heterogeneity in fractured rocks, but improvements can be made. Future research needs resulting from these lessons are also briefly discussed.

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Keywords: Fractured rock hydrogeology, site characterization, hydraulic tomography, pneumatic tomography, heterogeneity.

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1. Introduction

Over the last several decades, considerable effort has gone into mapping the heterogeneity of hydraulic parameters such as the hydraulic conductivity (K) and specific storage (S_s) of fractured rocks. Traditional methods include kriging and stochastic simulation that utilize numerous small-scale data from slug and single-hole tests. More recently, efforts have gone into stochastic inverse modeling of ambient hydraulic head information and/or individual pumping tests.

Despite the considerable effort, the accurate mapping of K and S_s heterogeneity is still elusive. A promising alternative to traditional methods of mapping heterogeneity is hydraulic tomography (HT), which relies on the sequential or simultaneous inverse modeling of multiple cross-hole pumping or injection tests conducted at different locations. Over the last decade, the technique has been tested primarily in unconsolidated deposits [1-8], but also in fractured rocks [9-13] yielding promising results. Pneumatic tomography (PT) has also been developed to map the heterogeneity of airflow parameters of the unsaturated zone [14-17].

Based on the work by various research groups, it was suggested [18] that both HT and PT are superior to traditional methods of mapping heterogeneity. This is because both rely on the inverse modeling of not just one pumping or injection test, but multiple tests conducted at different locations. It relies on multiple pressure signals sent across the fractured rock, hence yields information on heterogeneity and connectivity of flow parameters. While geophysical methods have also been used to map fractured rocks, they do not provide direct information on flow parameters. Therefore, this paper focuses on mapping methods that rely on hydraulic or pneumatic tests conducted in single and/or multiple boreholes.

While HT and PT are promising techniques, there are a number of issues that remain unresolved. The purpose of this paper is to outline lessons learned from various studies and to discuss research needs.

2. Lessons learned from previous research

2.1. Mapping of heterogeneity between boreholes is possible

The most straightforward way of mapping heterogeneity is to collect a sufficient number of small-scale estimates of flow parameters and interpolating those values. It is difficult to specify a sufficient number of samples for interpolation, as this quantity depends on project objectives and the desired resolution of mapped heterogeneity. For example, 844 K data were collected at the Äspö Island in Sweden [19], while 227 air permeability (k) data [20] were obtained at the Apache Leap Research Site (ALRS) in USA for geostatistical analyses.

In particular, the heterogeneity in air k was mapped at the ALRS by kriging [20] k estimates from 1- and 3-m scale single-hole pneumatic injection tests conducted in shallow boreholes in unsaturated fractured tuff. The geostatistical analysis at the ALRS revealed that k data are amenable to continuum geostatistical analysis and exhibited distinct spatial correlation structures. This suggested that the data can be viewed as a sample from a random field, or stochastic continuum [21] despite the fact that the rock contains discontinuous fractures across the site.

Kriging of small-scale data may not be as effective in mapping the connectivity of features that could be important to groundwater flow and contaminant transport processes, especially when the data sets are sparse, clustered or the distances between boreholes are large. This shortcoming of kriging was revealed by the geostatistical analysis of 844 single-hole hydraulic injection tests at 3-m injection intervals at the Äspö Island [19]. In particular, the variograms displayed almost a pure nugget behavior with very short correlation lengths despite the fact that other site data suggested extensive fractures or fracture zones that could have long-range correlation structures. Therefore, a dense data set is needed to obtain sufficient detail in heterogeneity and their connectivity that are important to groundwater flow and transport modeling.

Recently, hydraulic tomography (HT) and pneumatic tomography (PT) have been developed as alternative site characterization methods to obtain heterogeneous distributions (or tomograms) of flow parameters between boreholes. The method relies on the sequential or simultaneous inverse modeling of two or more hydraulic or pneumatic cross-hole pumping or injection tests conducted in geologic media [15-16, 22-31]. During a HT survey, water is sequentially extracted from or injected into different areas of an aquifer and the corresponding pressure responses are monitored at other intervals to obtain drawdown or buildup data sets. PT is analogous, but the pumped or injected fluid is air and the investigation takes place in the unsaturated zone.

A PT analysis [15-16] of cross-hole pneumatic injection tests conducted at the ALRS [32-34] revealed detailed tomograms of k and porosity (ϕ) heterogeneity. In particular, those authors conducted geostatistical inverse modeling of multiple pressure records from three tests simultaneously, while treating the rock as being randomly heterogeneous, to obtain a high resolution kriged maps over grid blocks with 1-m scale resolution. The k tomogram was found to be consistent with those obtained earlier [20] from single-hole pneumatic injection tests at the site.

In another example, a geostatistical inverse algorithm was applied to a synthetically generated fractured medium to investigate the feasibility of HT to detect fracture zones and their connectivity in two dimensions [35]. The hypothetical fractured rock aquifer was a 2D vertical square domain consisting of five orthogonal vertical and two horizontal fracture zones embedded in a rock matrix. Results revealed that the high K zones imaged from the observation data collected from multiple pumping tests reflected the fracture pattern and its connectivity in the synthetic fractured aquifer quite well. However, estimated values of K and S_s fields were smoother than the true values perhaps due to a consequence of using a code that treats the fractured rock as a single continuum. They found that the fracture pattern and connectivity became more vivid and the estimated hydraulic properties approached true values as the number of wells and monitoring ports increased.

There are several other examples that show that both HT and PT are able to map the heterogeneity in flow parameters between boreholes with quite good accuracy. Obviously, the level of detail mapped decreases with the boreholes being farther apart and as the sensor density decreases. In particular, it was recommended that a monitoring device should be placed at a minimum distance of one correlation length to capture the heterogeneity pattern of interest [22]. In order to obtain higher resolution tomograms, sensors should ideally be placed at distances smaller than the "rule of thumb" of one correlation length.

2.2. Hydraulic and pneumatic tomography surveys can be conducted over large volumes

One significant advantage of HT and PT over kriging is that it may be more efficient hence, cost effective at characterizing large volumes of fractured rock, as it relies on cross-hole pumping or injection tests. Theoretically speaking, there is no limit to the size of the domain in which HT or PT is applicable as long as drawdown (or buildup) signals can be detected at monitoring locations. However, practically speaking, there are limits in which drawdown can be detected due to: 1) the limitation to the size of the signal that can be generated; 2) the limitation to the pumping or injection test duration; 3) flow properties of the rock, and 4) the presence of background noise as well as sources and sinks that can corrupt drawdown signals [18].

A recent summary of various HT and PT experiments [18] in fractured rocks revealed that the technique can be used to characterize large volumes of fractured rocks. In particular, the interpretation [12] of two, large-scale, cross-hole pumping tests at the Mizunami Underground Research Laboratory (MIU) construction site in central Japan with a geostatistical inverse algorithm [23] allowed for the mapping of three-dimensional distribution of K and S_s, their connectivity, as well as their uncertainty at the kilometer scale. At that time, this was perhaps the largest application of HT at a field site. Those authors were able to identify two fast flow pathways or conductive fault zones as well as low K zones, despite the availability of only two cross-hole pumping tests. The authors assessed the soundness of the estimated K and S_s tomograms using three different approaches: 1) by comparing the calibrated and observed drawdown records as well as predicting the drawdown responses at monitoring intervals that were not used in the construction of the K and S_s tomograms; 2) by comparing the estimated K and S_s tomograms to previously known fault locations, and 3) by utilizing coseismic groundwater pressure changes recorded during several large earthquakes as a means to evaluate the K and S_s tomograms. While the results were encouraging, there were only two pumping tests available for inverse modeling, which precluded them from investigating whether HT could be utilized to map finer details of hydraulic heterogeneity in fractured rocks. The desire to test the capabilities of HT with more cross-hole tests led to a detailed laboratory rock block study [36], which revealed more details to heterogeneity and connective pathways with the availability of additional pumping tests and a denser pattern of monitoring locations.

Another issue with the application of HT at very large scales is computational cost. To circumvent this issue, adaptive mesh generation [37] was utilized to construct a significantly larger grid to improve the HT study at the MIU site [12] through the inclusion of additional drawdown inducing events in the analysis.

2.3. Improved mapping of heterogeneity leads to suppression of scale effects in flow properties

The scale effect in flow parameters such as K (and k) has been observed by numerous investigators [15-16, 32-34, 38-42]. The recognition of the presence of the scale effect is important as the use of an inflated estimate of flow parameter can significantly impact groundwater flow and transport predictions.

Explanations for the scale effect include: (1) formation of skin around injection boreholes causing K (and k) obtained at the injection interval to be smaller than those determined in monitoring intervals; (2) interpretation error arising from the use of inconsistent theory; (3) dual nature of fractured rocks; (4) use of data resulting from different measurement techniques; (5) use of data from tests conducted over several formations; and (6) directional effects.

A number of causes have been cited, but the improved mapping of heterogeneity and in particular, the connective pathways may be the key piece to the puzzle in explaining the scale effect [42] observed by a number of researchers worldwide. In particular, it was shown that the scale effect observed by comparing single- and cross-hole estimates of air k and air-filled ϕ became suppressed when more details to the heterogeneity were provided by pneumatic tomography [15-16]. This suggests that the scale effect may be an artifact of treating the fractured rock as a homogeneous medium.

2.4. Both techniques can map the connectivity of flow properties

A significant advantage of HT and PT over other methods of characterization is that the information on connectivity of flow parameters, which leads to channeling and significant reduction of travel times may be directly provided [42]. This is because HT and PT rely on multiple cross-hole tests that are conducted by sending pressure waves across the fractured rock, which are then detected in monitoring zones. In contrast, a lack of drawdown responses in monitoring intervals is an indication of lack of connectivity, although this depends on the duration of the well test and the diffusivity of the rock mass. For example, the connectivity of high and low K zones was imaged in the large scale HT study [12], albeit at a lower resolution due to the availability of only two cross-hole tests. It is of interest to note that these authors

[12] noticed a moderate negative correlation between K and S_s, suggesting that a larger diffusivity is obtained along connective pathways.

In the literature, the connectivity of high K feature seems to be the focus, but the connectivity of low K features can also be important for contaminant storage and its delayed release. Likewise, the connectivity of high and low S_s features can be important as they can have impacts on fluid storage and pressure signal propagation.

2.5. Improved mapping of heterogeneity and connectivity may lead to improved transport predictions

Perhaps one of the most important reasons for mapping heterogeneity is to obtain improved predictions of solute and contaminant transport. There is a scarcity of studies in which the fractured rock is characterized with either HT or PT and the computed tomograms are used for solute transport predictions. In one example [9] that I am aware of, multiple cross-hole pumping tests were interpreted simultaneously in 2D within a sub-vertical shear zone in granite using a geostatistical inverse approach to map flow channels that influence tracer experiments. Because the spatial correlation structure of transmissivity (T) was unknown, 40 T fields were mapped that equally matched the pumping tests, the static head measurements and the point T data. Storativity was treated to be a constant. These authors found that the geostatistical inverse modeling of abundant hydraulic measurements can be useful in revealing a coarse heterogeneity structure, even when data are insufficient to identify the geostatistical structure. While the estimated T fields were found to reproduce hydraulic test data, the fields did not necessarily lead to successful transport predictions.

Solute transport may be more difficult to predict with a low resolution K tomogram, but laboratory sandbox experiments in heterogeneous porous media [43] suggested that better predictions can be obtained. In particular, the study showed that a K tomogram from HT, when compared to results from effective parameters [44] and a K distribution from kriging, yielded superior transport predictions. It is of interest to note that ϕ heterogeneity was not found to be significant in transport predictions. However, this is not likely the case in fractured rocks, where heterogeneity in ϕ is expected to be significantly larger.

Moreover, as solute transport is affected by fine scale heterogeneities and chemical processes, accurate predictions of solute transport could be more difficult to attain. In fractured rocks, dead-end fractures, fracture-matrix interaction, mixing at fracture intersections and other factors can also impact solute transport. Therefore, the accurate prediction of tracer transport may require the inclusion of concentration data in inverse modeling [45].

There is clearly a need for more studies to assess tomograms obtained from HT and PT in predicting solute transport.

3. Implications for future research

A number of studies have shown that HT and PT are very effective in mapping heterogeneity and their connectivity of fractured rocks. However, studies are needed to compare HT and PT against more established methods of mapping heterogeneity. Studies published for heterogeneous porous media based on laboratory sandbox experiments [46-47] and field studies [48] have shown the superior performance of HT over traditional methods of characterizing heterogeneity, but studies in fractured rocks are lacking.

It is clear from an earlier study [9] that attaining accurate transport predictions is still difficult. This may partially be due to the coarse resolution of K and S_s tomograms obtained through existing experimental configurations. Therefore, one could ask how the resolution of tomograms can be improved. A straightforward answer would be to increase the density of measurements and the number of pumped locations. Current technologies allow for multiple sections of the borehole to be monitored with straddle packer systems. More recently, flexible liner technology has increased the number of monitoring points along a borehole. The resolution of the tomograms can also be improved by placing additional monitoring devices where the uncertainty estimates are high. However, the drilling of additional boreholes, installing additional equipment, and conducting multiple cross-hole pumping tests may not be an option for some investigations due to financial and time constraints. Therefore, one may have to rely on additional data types to improve tomogram resolution.

In general, this author shares the sentiments of other researchers, that the integration of additional data types may improve tomogram resolution and may be a promising research topic for the future. However, we should exercise caution in integrating various data because each type of test (i.e., cores, slug/single-hole tests, pumping tests, borehole flow meters, tracer tests, thermal, and geophysical surveys, etc.) interrogates different parts of the fracture-rock matrix system and carries different types of information. For example, geophysical techniques may be useful in mapping fractures or fractured zones, but the approach may not be useful in accurately quantifying K or S_s of the fractured rock. On the other hand, geophysical techniques have been found to be useful in mapping tracer clouds as they are transported in fractured rocks [49]. Recent work has also shown that the resolution of the K tomogram can be increased quite substantially through the integration of flux information with HT [50].

4. Concluding remarks

HT and PT are both very promising in mapping heterogeneity in flow parameters. As the CAT scan technology has revolutionized the medical industry, there is potential for HT and PT to significantly improve our capabilities in mapping the subsurface. With improved images of flow properties, predictions of groundwater flow and solute transport should become more accurate. It is evident that there are many applications which can benefit from more accurate tomograms.

In this paper, we discussed a number of lessons from different studies of HT and PT conducted with synthetic, laboratory, and field experiments. While HT and PT have been shown to be quite robust through several demonstrations, much work is needed to improve tomogram accuracy and its resolution.

Finally, an increasing number of studies on the tomographic interpretation of hydraulic and pneumatic tests have been published. While these computed tomograms may be pleasing to the eye and reveal details to heterogeneity in flow properties, more effort should go into their validation as I believe that this is a very important issue which is often overlooked. In the end, calculated tomograms are only useful when they can be used to improve the accuracy of groundwater flow and solute transport predictions.

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