Estimation of Fracture Transmissivities from Borehole Data Collected in the Laxemar Area, Oskarshamn, Sweden

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ABSTRACT
The statistical distribution of fracture transmissivities are estimated across a range of fracture-set scales using a previously developed method, from borehole hydraulic test data collected in the Laxemar area, Oskarshamn, Sweden. The resultant fracture transmissivity parameter estimates are subject to some error due to interconnectivity of fractures, which is unaccounted for in the statistical model. The results do provide a general description of the fracture environment, especially in comparison to results from borehole hydraulic testing programs set in other geologic settings. It is hoped that this will prove a useful application of the method.

RÉSUMÉ
La distribution statistique des transmissivitées de fractures dans le roc a été réalisé sur une plage d'échelles de fractures utilisant une métode préalablement développée, à partir d'essais de conductivité hydrauliques réalisés dans des trous de forage, dans la région de Laxemar, Oskarshamn en Suède. Les estimés des paramètres de transmissivité des fractures sont sujets à erreures causées par l'interconnectivité des fractures, un phénomène qui n'est pas considéré dans le modèle statistique. Les résultats décrivent le milieu fracturé de façon générale, particulièrement lorsque comparé aux résultats d'essais hydrauliques réalisés sur d'autres types de roche. Il est espéré que les résultats représentent une application utile de la méthode.

1 INTRODUCTION

This paper is concerned with the estimation of the statistical distribution of fracture transmissivities from borehole measurements of transmissivity made in test intervals of constant length. To avoid confusion associated with over use of the word transmissivity, the latter measurements will generally be referred to in this article as “data”. In practice, the data is collected via the injection of water into intervals, isolated from the remainder of the borehole by packers. The spacing between the packers can be arbitrarily chosen, and in this article is referred to as the “scale” of the testing.

The parameter estimation problem is most easily considered for a set of parallel fractures embedded in bedrock. The separation between fractures is random in nature, and is described in this article using the term fracture-set scale. (In this article and in those referenced below, the fracture-set scale is in fact the inverse of a Poisson point process density parameter). Snow (1970) estimated the scale of a set of fractures he termed “flowing” from the fraction of non-flowing tests, and estimated their transmissivities from the remainder of the data (i.e. from the transmissivities calculated from the flowing tests). Osnes (1994) estimated the (gamma distributed) transmissivities of a similarly-defined fracture set using a maximum likelihood method. Both methods are limited by the fact that the scale of the fracture set whose transmissivities are to be estimated is fixed relative to the fraction of no-flow tests and to the scale of the hydraulic testing program. West et al. (2006b) estimated log-normal parameters for fracture transmissivities across a range of fracture-set scales. The range was dictated by the data and by the scale of the testing program, while the transmissivities were estimated using the maximum likelihood method.

In general, it is difficult to verify estimated statistical parameters directly since field work offers limited ability to sample adequately. For this reason, it is important that statistical models are tested using stochastic theory or Monte Carlo methods (based on random number generation). The method of West et al. (2006b) was tested using the Monte Carlo method from simulated data generated from known fracture population statistics. It was found that the estimated transmissivity distribution approximates the distribution of a similarly-scaled fracture set made up of the most transmissive fractures from among a specified population. Estimation accuracy was shown to be most sensitive to the variance in the transmissivities of the fracture population, and less sensitive to test interval length. Estimation accuracy was shown to decrease with increasing fracture-set scale.

West et al. (2006b) applied their method to transmissivities measured in 2 m, 0.5 m, and 0.1 m long test intervals in Smithville, Ontario. This was a natural choice since the fractures in the flat-lying dolostone aquifer are parallel and seemingly hydraulically independent, which are two important assumptions of the method.

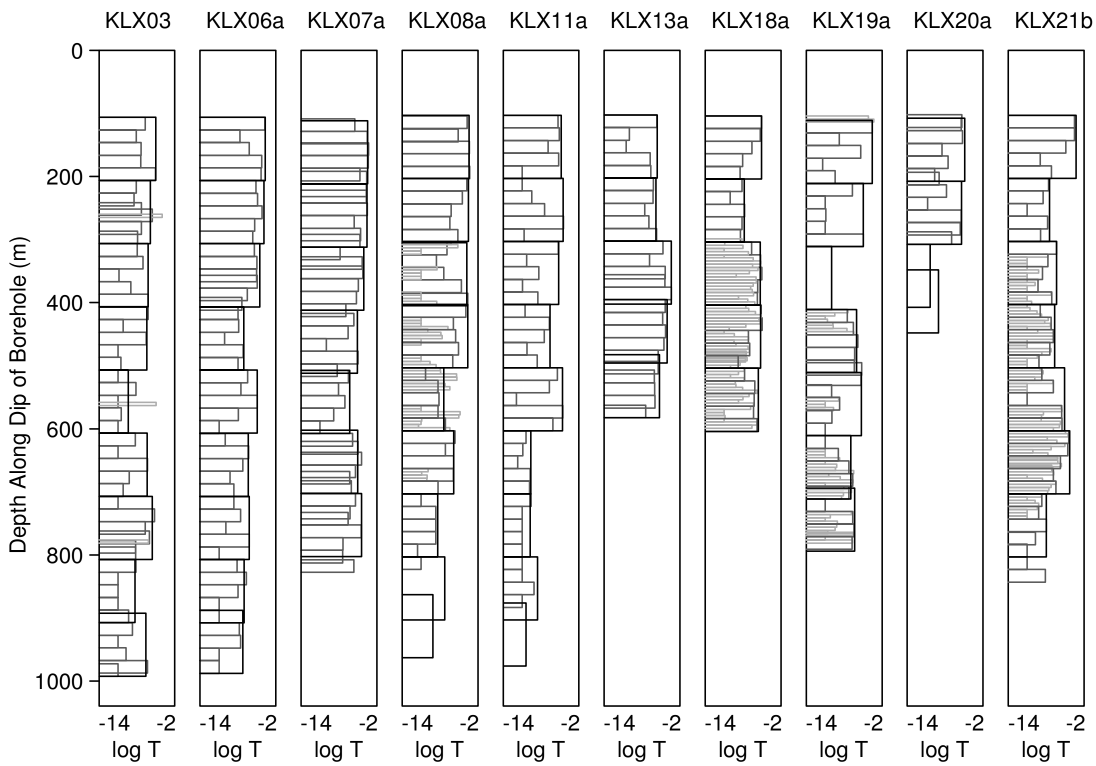

Figure 1 Test interval transmissivities measured in ten boreholes in the Laxemar area, Oskarshamn, Sweden

In this paper, the method is applied to data collected in the Laxemar area, Oskarshamn, Sweden. The data were collected as part of a borehole hydraulic testing program performed by Svensk Kärnbränslehantering (Swedish Nuclear Fuel and Waste Management Company, or SKB) as part of a site investigation for the evaluation of siting alternatives for the final disposal of spent nuclear fuel. The geology of this area is very different from that of the Smithville area, with the almost kilometre long boreholes being drilled mainly through the Ävrö granite. Detailed fracture mapping has identified multiple sets of randomly-oriented fractures (Svensk Kärnbränslehantering, 2006).

2 METHODS

2.1 Hydraulic Testing

The testing program consisted of pulse injection and constant head injection tests performed in intervals isolated from the remainder of the borehole using straddle packers. The boreholes were tested with 100 m, 20m, and 5m test interval lengths, and the shorter test intervals length tests were only performed within those of the larger intervals whose transmissivity exceeded a specified threshold. The testing results were analysed using a variety of methods, and the data used in the current work are those recommended as the most representative (e.g., Enachescu et al., 2006). The hydraulic testing and data analysis was performed by Golder Associates AB and Golder Associated GmbH.

2.2 Parameter Estimation

The Laxemar data were plotted and inspected in order to choose sets for statistical estimation (see Figure 1, and note that all transmissivities referred to in this article have units of metres squared per second). Data chosen for statistical analysis should ideally exhibit no trends or correlations along the borehole, and should form a continuous sample. Based on a visual inspection, it was decided to use the 5 m and 20 m data from each of boreholes KLX18a and KLX21b. Application of the method to sets of transmissivity data measured in the same borehole at different scales provides an opportunity to verify the results. Similarly the 100 m data and the contained 20 m data from all ten of the considered boreholes were selected for parameter estimation.

The method of West et al. (2006b) was applied to estimate the scale and shape parameters of the log normal distribution for fracture transmissivities as a function of fracture-set scale. An associated parameter estimation method (West et al., 2006a) was also applied in order that the bedrock hydraulic conductivity and groundwater velocity per unit hydraulic gradient might also be estimated.

3 RESULTS AND DISCUSSIONS

Figure 2 shows the results of the parameter estimation method as applied to the 20m and 100m data from each of the boreholes KLX18a and KLX21b. The scale and shape parameters of the log normal distribution describing the fracture transmissivities are shown as a function of fracture-set scale. All the results indicate that the transmissivity scale parameter increases while the transmissivity shape parameter decreases with increasing fracture-set scale, from left to right across the plot. This indicates that the method has distinguishing a progressively sparser, more transmissive and less hydraulically diverse set of fractures from among the population. The hydraulic conductivity and groundwater velocity per unit hydraulic gradient, in contrast appear independent of the mean spacing. This is as it should be since these values are representative of the bulk rock mass.

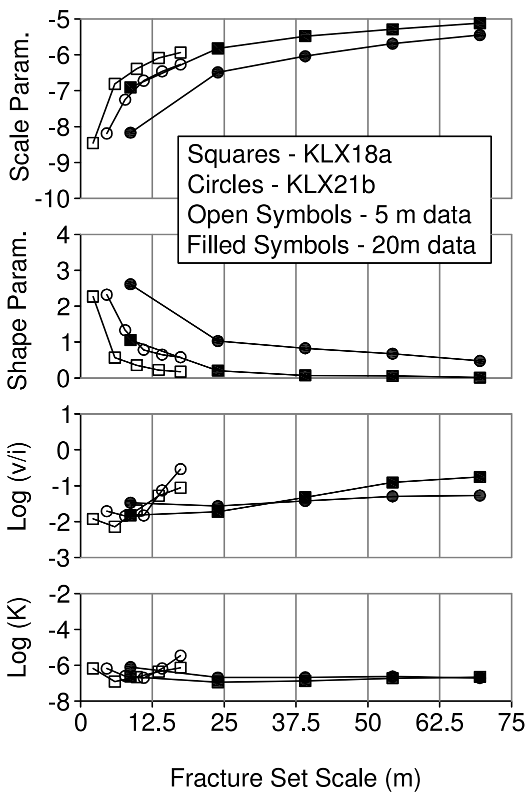

Figure 2 Fracture transmissivity and bulk rock parameter estimates plotted as a function of fracture-set scale

The corollary to the article of West et al. (2006) is that the transmissivities of a fracture set at any particular scale may be estimated using data measured across a range of scales. This is, so long as the allowable ranges in fracture-set scale overlap, the transmissivity parameters estimated from two sets of data collected at two different scales should form a single curve. This situation is shown in Figure 2 to be more true of estimates from KLX18a than from KLX21b. For example, at the 10 m fracture-set scale for borehole KLX18a, the transmissivity shape parameters estimated from the 20m and 100m test interval data are 0.5 and 1.0, respectively. At the same fracture-set scale, the corresponding values from the KLX21b data are 1.0 and 2.7.

Figure 3 shows results of the parameter estimation method as applied to the 20m and 100m data aggregated together from the ten considered boreholes. Of note in this plot is the fact that, again, alignment of the 20m and 100m test interval results is not achieved.

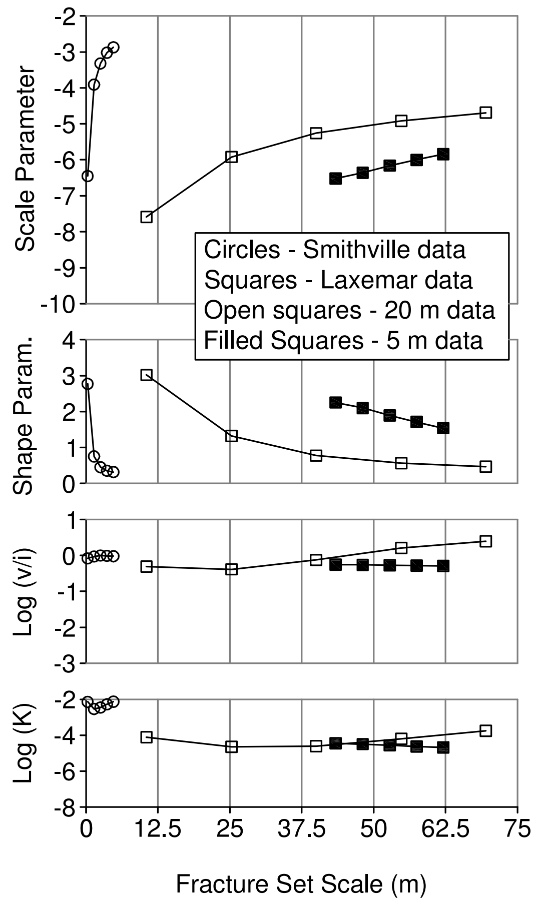

Figure 3 Fracture transmissivity parameters and bulk rock parameters estimated from the Laxemar data and from the Smithville data

One reason for the discrepancies in results from analysis of hydraulic test data made at two differing scales is that the flows within the fractures in the granite do not meet the necessary criteria of statistical independence, and this is due largely to fracture interconnectivity resulting from non-parallel fracture orientations. In perfectly parallel flow systems, transmissivities measured in smaller test intervals sum to the transmissivity of the larger test interval which contains them. The results presented in Figure 4, show that, in this case, the sums of the 20 m data are almost invariably larger than their respective 100m values. This provides very strong evidence of the strength of the connection of fractures from within the 20 m test intervals to outside them.

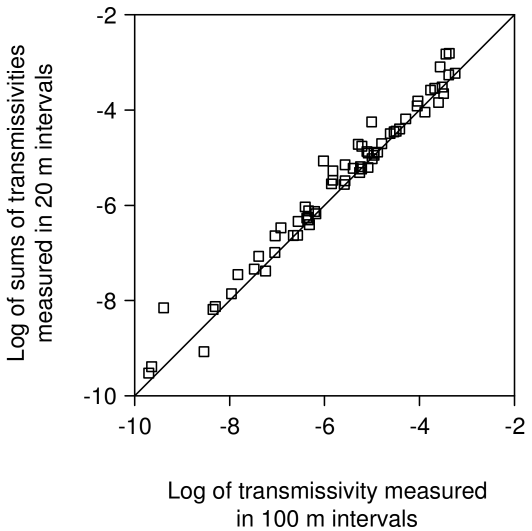

Figure 4 Illustration of the discrepancy between the sums of the 20 m data and the corresponding 100 m data

The second reason for the discrepancy in results from analysis of hydraulic test data made at two differing scales is simply that the variability in fracture transmissivity in the overall population is just too large for this type of analysis to be able to distinguish among them. As noted in the introduction, in numerical experiments performed assuming known systems of perfectly parallel fractures, this was found to be the most important factor affecting estimation accuracy.

The transmissivity scale and shape parameters from the Smithville study are plotted on Figure 3, for comparison, and to put the previously-discussed estimation error in context. While the estimated transmissivity parameters fall across a smaller range of fracture-set scale, they indicate a similar range in transmissivity variability (shape parameter). Given that the properties of the thinly-bedded dolostone are so very different from those of the massive randomly-fractured granite, it is appealing to see these statistics plotted on the same page. It is the author's idea that a library of such curves from a variety of geological settings might prove useful both to designers of hydraulic testing programs and to discrete fracture network modellers.

4 CONCLUSIONS

The availability of transmissivity data collected in boreholes in the Laxemar area, Oskarshamn has provided an excellent opportunity for the use and testing of the method of West et al. (2006b) for the estimation of fracture transmissivities as a function of fracture-set scale. Despite the fact that the fracture sets under investigation in Sweden are far from the parallel system that is assumed by the method, the results are instructive and meaningful when compared to estimates from the Smithville site, in Ontario. It is hoped that since the method is easy to use (it requires little more than input of the minimum measurable transmissivity, the test interval length, and the measured data themselves) it will be applied to data in a variety of geological settings in order that a library of fracture transmissivity parameter curves might be developed for public use.

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