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Conceptual uncertainty in crystalline bedrock: is simple evaluation the only practical approach?

JOEL GEIER
Geosciences Department, Oregon State University, Corvallis, Oregon 97331, USA
jgeier@attglobal.net

CLIFFORD I. VOSS
Water Resources Division, US Geological Survey, Reston, Virginia 20192, USA

BJÖRN DVERSTORP
Department of Waste Management & Environmental Protection,
Swedish Radiation Protection Authority, SE-171 16 Stockholm, Sweden

Abstract A simple evaluation can be used to characterize the capacity of crystalline bedrock to act as a barrier to release radionuclides from a nuclear waste repository. Physically plausible bounds on groundwater flow and an effective transport-resistance parameter are estimated based on fundamental principles and idealized models of pore geometry. Application to an intensively characterized site in Sweden shows that, due to high spatial variability and uncertainty regarding properties of transport paths, the uncertainty associated with the geological barrier is too high to allow meaningful discrimination between good and poor performance. Application of more complex (stochastic-continuum and discrete-fracture-network) models does not yield a significant improvement in the resolution of geological barrier performance. Comparison with seven other less intensively characterized crystalline study sites in Sweden leads to similar results, raising a question as to what extent the geological barrier function can be characterized by state-of-the art site investigation methods prior to repository construction. A simple evaluation provides a simple and robust practical approach for inclusion in performance assessment.

Key words crystalline rock; nuclear waste; performance assessment; radionuclide transport

INTRODUCTION

In crystalline rock, it is probably impossible to characterize sites well enough to ensure that all significant hydrological features have been discovered. The fracture system is too complex to define, even by intensive field measurements. Even with sophisticated tools, the correctness of the interpretation and mathematical implementation cannot be guaranteed. How should practical evaluation of such sites be carried out: use complex models and as much detailed data as possible, or generalize and simplify?

This paper presents a simple approach for assessing geological barrier performance in fractured crystalline rock. The approach uses elementary hydrological principles and very simple models that can readily be verified and reproduced. The objective is to determine bounds on the physically plausible ranges of hydrological parameters affecting geological barrier performance, and to identify critical sources of uncertainty in these parameters.

APPROACH

The simple evaluation is aimed at predicting a few characteristic hydrogeological parameters that control radionuclide release from a repository and transport to the biosphere, based upon an understanding of the key physical processes, and based on extensive consequence calculations (predictions of the radiation dose that is delivered to the biosphere, for a given set of assumptions) that were carried out within the SITE-94 performance-assessment study (SKI, 1996). This approach is restricted to a consideration of groundwater flow and the geological barrier potential. The influence of site-specific hydrochemistry and mineralogy on transport is not directly accounted for, but their effects on sorption parameters were accounted for in the consequence calculations used to determine acceptable ranges of the transport resistance parameter, F (SKI, 1996).

Evaluation of groundwater flux and geological barrier potential

Groundwater flux q [L T^{-1}] is arguably the most important hydrological parameter for determining safety. High q implies a greater potential for exposure of engineered barriers to changing geochemical conditions, and for rapid transport of radionuclides from leaking engineered barriers to the biosphere.

Flux is evaluated from site data including: maximum potential head differentials (from local and regional topography), location and orientation of major fracture zones (from structural geologic models of each site), estimates of hydraulic conductivity K [L T^{-1}] for the rock mass, and estimates of transmissivity for major fracture zones, which are drawn from prior interpretations of hydrological tests in boreholes. The flux is estimated by a simple application of Darcy's law for one-dimensional (1-D) flow:

$$q = K\Delta h / L \tag{1}$$

where Δh [L] is the maximum potential hydraulic head differential, and L [L] is the transport distance from the radionuclide source to the discharge point. Radionuclide transport in the far field depends upon both q and the configuration of the fracture-system pore space. The evaluation of geological barrier potential is based on flux through a variety of simple, idealized models for pore geometry. The results are summarized in terms of an effective transport resistance parameter:

$$F = a_w L / u \tag{2}$$

where a_w [L^{-1}] is fracture surface area per unit volume of mobile water, and u [L T^{-1}] is the fluid velocity of the water through the pore space (equal to q divided by the porosity). High values of F imply high surface areas available for sorption and matrix diffusion, in relation to advection of solute, and hence the possibility for high retardation of sorbing species.

The controlling influence of F for geological barrier performance was suggested by theoretical considerations and confirmed by parameter studies (SKI, 1996) using a 1-D model of radionuclide transport that accounts for advection, dispersion, sorption, matrix diffusion, and radioactive decay (Worgan & Robinson, 1995). For the range of conditions that are relevant for a repository in Swedish granitic rock, F is by far the most important retardation factor.

Table 1 Summary of pore-geometry models used to evaluate geologic barrier function.

Model	Description	Interpretation
Simple planar fracture	Single fracture with smooth faces separated by a constant aperture	Classical "parallel-plate" model
Simple tubular channels	Set of co-planar, cylindrical tubes spaced a uniform distance apart	May be viewed as an extreme case of channelized flow
Multiple planar fractures	Set of *n* parallel-plate fractures, each having the same aperture	Idealised fracture zone with multiple fractures conducting flow in parallel
Stepped fracture, flow parallel to steps.	Stepped fracture, aperture varies in the direction perpendicular to the direction of flow	Represents an intermediate degree of channelling within the fracture plane
Stepped fracture, flow transverse to steps.	Stepped fracture, aperture varies along the direction of flow	Represents a case of increased pore volume relative to net fracture transmissivity
Breccia zone	Tabular zone filled with spherical grains of uniform radius	Breccia zones may account for many of the highest-flow zones in boreholes at Äspö

Alternative simple models for pore geometry

F depends on q and a_r (or equivalently u and a_w), which are functions of both local pore geometry and network effects (Dverstorp *et al.*, 1992; Moreno & Neretnieks, 1993; Nordqvist *et al.*, 1995), and are difficult to measure directly in the field. These must either be estimated from field data such as tracer tests, or extrapolated from network models. Either approach requires idealizations about flow and transport geometry within the fracture pore space, the implications of which are seldom clear.

In this simple evaluation, idealized pore-geometry models (Table 1) are used to scope the variety of possible relationships between q and F. These models lead to algebraic formulae for F, which were developed by Dverstorp *et al.* (1996) in terms of models that are constrained to yield the same Darcy velocity for a given hydraulic gradient. The formulae express differences among models solely as a function of assumptions regarding pore geometry, the factor for which field data are lacking.

APPLICATION

Simple evaluation of groundwater flux and potential for radionuclide transport

The simple evaluation was applied for hypothetical repositories located in crystalline bedrock at Äspö and seven other study sites in Sweden, based on surface and borehole investigations conducted by the Swedish Nuclear Fuel and Waste Management Co. (SKB). The level of detail in site characterization varies among sites (Dverstorp *et al.*, 1996). The most intensive characterization was for the Äspö HRL site (Stanfors *et al.*, 1991). Finnsjön was the next most intensively characterized site.

Each site is assumed to contain a repository through which groundwater flows and eventually discharges at a point on the ground surface. Groundwater passes through the host rock of the repository, which includes fractured rock mass, fracture zones, and a disturbed-rock zone around repository tunnels due to excavation and operation of the repository. The geometry of flow paths from the repository to the discharge point is based on prior interpretations of the configuration of fracture zones at the sites. A plausible set of transport pathways is postulated to scope the range of q that could occur within the constraints of the interpreted structural models.

Gradients at repository depth are selected as either: (a) the regional gradient applies; or (b) the maximum local head occurs undiminished in the repository, and minimum local head occurs at the repository discharge point (the ground surface or a high-transmissivity fracture zone). The former is the simplest and most reasonable assumption, which would not require anomalous configurations of fractures and surface conditions. The latter assumption results in the maximum possible gradient through the repository, under present climatic and surface conditions.

Hydraulic conductivities for flow from the repository are chosen in either of two ways: (a) for flow via only the rock mass, K along the flow path is equal to that of the rock mass at repository depth; or (b) for flow via the disturbed-rock zone and/or fracture zones connecting in series to a surface discharge point, the fracture zone K at repository depth applies along the entire flow path. The former assumption gives a minimal estimate of q for a given gradient. The resulting q ranges are shown in Fig. 1(a). For Äspö, all calculations that assume transport through less than 100 m of undisturbed rock result in q greater than 10^{-4} m year^{-1}. Only an unlikely case of flow through 600 m of undisturbed rock mass (without fracture zones) gives low q.

For Finnsjön, although K is higher, the calculated q values are intermediate to the range determined at Äspö. The absence of very high q values for Finnsjön is largely because there are no fracture zones close to the repository, according to the assumed model of the geologic structure (SKB, 1992).

The simple evaluation of the geological barrier potential uses the q estimates plus the formulae for simple models of pore geometry. Parameters for the pore-geometry models are constrained by field measurements of transmissivity (from hydrological tests) and estimates of porosity from large-scale tracer tests. For specific models of pore geometry, the parameters can in some cases be constrained further by field observations. Figure 1(b) compares the resulting ranges of F for Äspö and the seven study sites. With the exception of Fjällveden and Gideå, all of the sites show a very

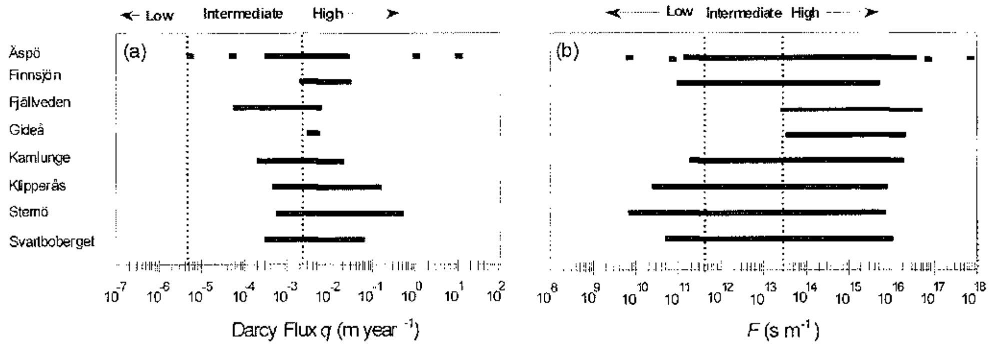

Fig. 1 Results of simple evaluation of: (a) groundwater flux q and (b) geological barrier potential F. For Äspö, extreme values resulting from special cases not comparable to cases evaluated for other sites are shown as distinct points to distinguish these from cases that are comparable for the other sites.

broad range of possible F values, from 10^{11} s m^{-1} or less, to 10^{16} s m^{-1} or more.

Consequence calculations for the SITE-94 Reference Case (SKI, 1996) yield the following approximate interpretations of the predicted F values:

(a) $F < 3 \times 10^{11}$ s m^{-1} poor performance: high peak radiation to biosphere results from negligible retardation of radionuclides.
(b) $3 \times 10^{11} < F < 2 \times 10^{13}$ s m^{-1} intermediate performance: the geological barrier moderately retards radionuclide transport.
(c) $F > 2 \times 10^{13}$ s m^{-1} good performance: most sorbing radionuclides retarded sufficiently that peak radiation releases are small.

These categories pertain specifically to performance assessment in terms of peak rates of release to the biosphere. Based on these criteria, the results of the simple evaluation show that geological barrier performance at all but two of the sites could range from negligible to very good. The exceptions, Fjällveden and Gideå, give more favourable predictions mainly because the structural models for these sites did not lead to consideration of pathways via fracture zones; less favourable results might be obtained if alternative structural interpretations were considered.

RESULTS AND DISCUSSION

The predicted range of F values for Äspö is roughly 10^{8}–10^{16} s m^{-1}. Values below 10^{11} s m^{-1} imply poor performance (negligible far-field barrier potential) and correspond to pessimistic assumptions about hydrological connections (e.g. direct connection to a fracture zone), or pore geometry (e.g. extreme channels), or both. However, even if these pessimistic cases are excluded, the predicted F span a very wide range, and poor performance cannot be excluded. The key factors affecting these predictions are: (a) the wide range of possible q due to variability of K and uncertainty as to how conductive elements connect, and (b) high uncertainty regarding the relationship between q and a_w along transport paths, a direct result of uncertain pore geometry.

The availability of much more detailed data for Äspö apparently has not led to a more narrowly defined range of q and F compared with other sites. Rather, the intensive characterization at Äspö appears to have resulted in identification of a comparatively high intensity of fracture zones, motivating more pessimistic calculation cases than were developed from the interpretations of the less intensively characterized sites. It can be speculated that the high intensity of observed structures at Äspö is largely a consequence of the more intensive site-characterization programme.

The results can be compared with the predictions of more detailed models of Äspö from the SKI SITE-94 project, which included a discrete-feature (DF) network model (Geier, 1996), and a stochastic-continuum (SC) model (Tsang *et al.*, 1996). These models made intensive use of site-characterization data and included analysis of many variants to estimate consequences of parameter uncertainty. Predictions of q for the full range of variants and canister locations within the DF and SC models are compared with the simple evaluation in Fig. 2. The simple evaluation predicted a higher upper bound on q due to consideration of a pessimistic case in which the repository connects directly to the surface via a high-transmissivity fracture zone. Excluding this case, the

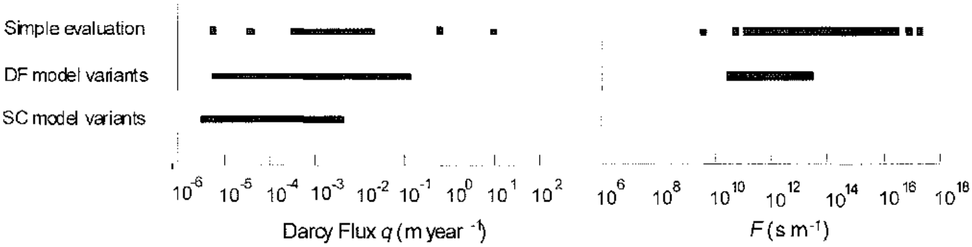

Fig. 2 Estimated ranges of q and F for the simple evaluation and detailed hydrological site models.

DF model and simple evaluation gave similar upper bounds of $q \not\subset 10^{-1}$ m year^{-1}, while the SC model gave a lower maximum.

The range of F predicted by the DF model for all variants and canister positions combined is 2×10^{10} to 5×10^{14} s m^{-1}. While this represents a reduction of several orders of magnitude relative to the range predicted by the simple analysis (Fig. 2), in terms of practical criteria both methods predict that far-field performance could range anywhere from marginally poor to very good far-field performance. Thus compared with the simple evaluation, the detailed models did not markedly improve on ability to say, in absolute terms, whether the performance of the far-field system as a barrier is excellent, marginal, or poor at the HRL site. The detailed models do distinguish between effects of spatial variability (e.g. variation between canister sites), and uncertainty, which represents imperfect understanding of the system. Detailed models also allow probabilistic evaluation of the consequences of parameter uncertainty; however, key aspects of uncertainty, such as regarding the choice of conceptual model or structural interpretation, often cannot be quantified.

CONCLUSIONS

A simple evaluation provides: (a) an essential bounding check on more complex models; (b) an inexpensive, comprehensible assessment in which the effects of specific assumptions are easily traced; and (c) identification of key sources of uncertainty. This application shows that, due to high spatial variability and uncertainty regarding pore geometry, it is not possible to confirm capacity of the bedrock at Äspö to retard radionuclides. Further, comparison among Swedish crystalline sites indicates difficulty in distinguishing their barrier potentials. Although investigations at Äspö were the most intensive, uncertainty in barrier performance there, is as great as at other sites. Comparison of the simple evaluation with the results of complex numerical modelling, based on stochastic continuum and discrete-feature network concepts, shows that while such modelling yields some reduction in the range of predicted performance, this reduction is not sufficient to make a clear distinction between good and poor geologic barrier performance. While complex models do provide a means of testing the significance of various types of uncertainty, and thus have a role in guiding site characterization efforts, a simple evaluation apparently predicts practical measures of site performance as well as can be accomplished based on surface data.

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