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Stochastic hydrogeological modelling of fractured rocks: a generic case study in the Mórágy Granite Formation (South Hungary)

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Abstract: In connection with the Hungarian radioactive waste disposal program a detailed study of the mass properties of the potential host rock (granite) has been carried out. Using the results of this study the various parameters (orientation, length, intensity, transmissivity, etc.) describing a fracture set were estimated on the basis of statistical considerations. These estimates served as basic input parameters for stochastic hydrogeological modelling of discrete fracture networks (DFN), which is a strongly developing area of hydrology, providing geologically realistic geometry for site investigations. The synthetic fracture systems generated were tested against some (but not all) field observations. The models built up on the basis of the statistical descriptions showed the same equivalent hydraulic conductivity for the modelled region as the field measurements. In addition, the models reproduce the observed hydraulic head-scattering along vertical boreholes. On the basis of the stochastic simulations of the fracture system some input parameters for the performance assessment of the planned repository were investigated. Calculation of flows into a planned disposal tunnel indicated that if the hydraulic conductivity of the material in the tunnel is the only variable parameter then there are two thresholds: under 1×10^{-9} m/s and above 1×10^{-5} m/s further change of the hydraulic conductivity does not dramatically affect the inflow.

Key words: Mecsek Mts, uncertainty, stochastic simulations, hydrogeological conditions, fractured rocks, granite.

Introduction

Fractured rock investigation often focuses mostly on discontinuities. One reason, from a hydrogeological point of view, is that fractures are usually more permeable than the surrounding rock. Consequently flow and transport processes are concentrated mainly in the fracture systems in the investigated rock mass. Fractures are also important in ore deposits, and petroleum, gas and geothermal reservoirs are frequently located in fractured rocks (Van Golf-Racht 1982).

After the publication of the pioneering study by Snow (1965), the hydrogeological approach to fractured rocks underwent a gradual change. Researchers realized that fractures behave as conducting features and often have a special role in flow and transport processes.

The development of discrete fracture network (DFN) modelling technologies was accelerated by underground research laboratories (URL) for radioactive waste (Sweden, Canada, United States, Japan, etc.). The aim was to characterize the fractures and to develop tools able to reproduce measured field data and to handle parameter uncertainties. These studies highlighted the need for proper integration of geological, hydrogeological, geochemical and geophysical data (Neuman 2005). In addition, the hydrogeological studies in URLs were able to provide some important input parameters for repository performance assessments.

In most cases fractured rocks must be characterized in situ. An advantage of in situ measurements is that the data include the effect of field stress conditions and of fracture connectivity. The most widely used method is the single borehole packer test and multi-borehole interference tests are also used (Neuman 2005) in order to gain information about the flow system on a larger scale. High-resolution flow-meters (Rouhiainen & Pöllanen 1999) can provide detailed information about the conductive fractures intersecting a borehole.

A key finding was that at some sites the fracture network is not continuous (Uchida et al. 1998; Sawada et al. 2000). This means that fractures or fracture clusters are not connected with each other, and thus that there is not hydraulic continuity between all points in a studied region. This feature is known as compartmentalization.

Almost all the studies in URLs have concluded that all fracture parameters (transmissivity, size, etc.) have a strong scale dependence (La Pointe & Outters 2000; Andersson et al. 2002). For example, cm-scale fractures cannot be investigated in regional scale mapping and, conversely, large tectonic lineations cannot be observed in thin sections, although both of them may belong to the same fracture system. These considerations emphasize the need for mathematical techniques that are able to integrate data measured at different scales.

Most approaches consider discontinuities in a fractured rock mass as a two or three dimensional network of polygons (Neuman 2005). These polygons are usually described by stochastic parameters for location, size, orientation, transmissivity, etc., since these data cannot be determined for each fracture deterministically (Dershowitz et al. 1998; M. Tóth et al. 2004). The results from field measurements and observations need some interpretation (conceptualization) and statistical processing before becoming input parameters for DFN modelling. The concept must be compatible with the general geological and hydrogeological conditions of the studied site.

The investigation of potential disposal sites for radioactive waste in Hungary started in 1992 (Balla 2000). After a screening process the interest has been focused on Mississippian granite (Mórágy Granite Formation) in the vicinity of the village of Bátaapáti (Fig. 1). The geological exploration of the area has been organized and financed by the Public Agency for Radioactive Waste Management (PURAM). Several boreholes have been drilled (Balla et al. 2003) in the studied area in order to obtain information about fracture orientation, fracture density, rock stability etc. and to assess the geological/hydrogeological suitability of the site (Balla et al. 2004). It is important to note that this study is mainly generic and utilized only data available from surface based investigations (Balla et al. 2003) and did not consider data from access tunnel excavations. The basis of this paper was originally presented by Benedek & Mező (2005).

The structural evolution of the granite and the mechanisms of different deformation phases are discussed by Maros et al. (2004). The authors suggested that the pluton underwent a complex tectonic evolution starting from the magmatic stage and then subsequently the Variscan and the Alpine orogenies. Two alternative theories were proposed to explain the present structural pattern of the site: 1) folding related evolution; and 2) strike-slip faulting.

In the first section of this study we intend to reproduce the geometry (orientation, length, density, etc.) of the fracture system observed in the Mississippian granite formation and additionally to estimate flow parameters of fractures (transmissivity). It is noteworthy that the up to date conceptual model developed for the site will not be presented, since the main aim of this paper is to demonstrate the capabilities of the DFN approach. In the second step fracture systems are built up stochastically (50 realizations) and we show different, but not all aspects of the model's applicability.

Site geology

The site discussed in this paper is located in the Mecsek Mts in southern Hungary (Fig. 1). On the basis of geological interpretations the system can be divided into two main segments: 1) overlying sediments and 2) the granite system (Balla et al. 2003). It is important to note that the granite can also be divided into subsystems: 1) weathered granite and 2) fresh granite. This paper focuses on the latter one.

Buda et al. (2000) distinguished four different types of crystalline rocks at the investigated site: 1) microcline granitoids containing megacrysts, 2) amphibole-rich enclaves, 3) microgranites, 4) pegmatites. They suggested, based on whole-rock major and trace element geochemistry, that partial melts were formed in a continental collision zone during the Variscan orogeny. In addition, basaltic melts could have been generated as a consequence of partial fusion of a mantle wedge above the subduction zone. The granite body underwent numerous secondary processes: K-metasomatism, mylonitization, cataclasis, hydrothermal alteration and mineralization. In addition, the granite was affected by multiphase metamorphic events (Koroknai 2003) which resulted in the formation of slate, mylonite, etc. The age of the granite formation is the subject of debate: Balogh et al. (1983) suggest a Carboniferous formation age, however Chernysev et al. (2002) argues for a metamorphic event at that time.

The granite was penetrated by swarms of Cretaceous basaltic (bostonite, trachyandesite) dykes (Harangi 2003). At

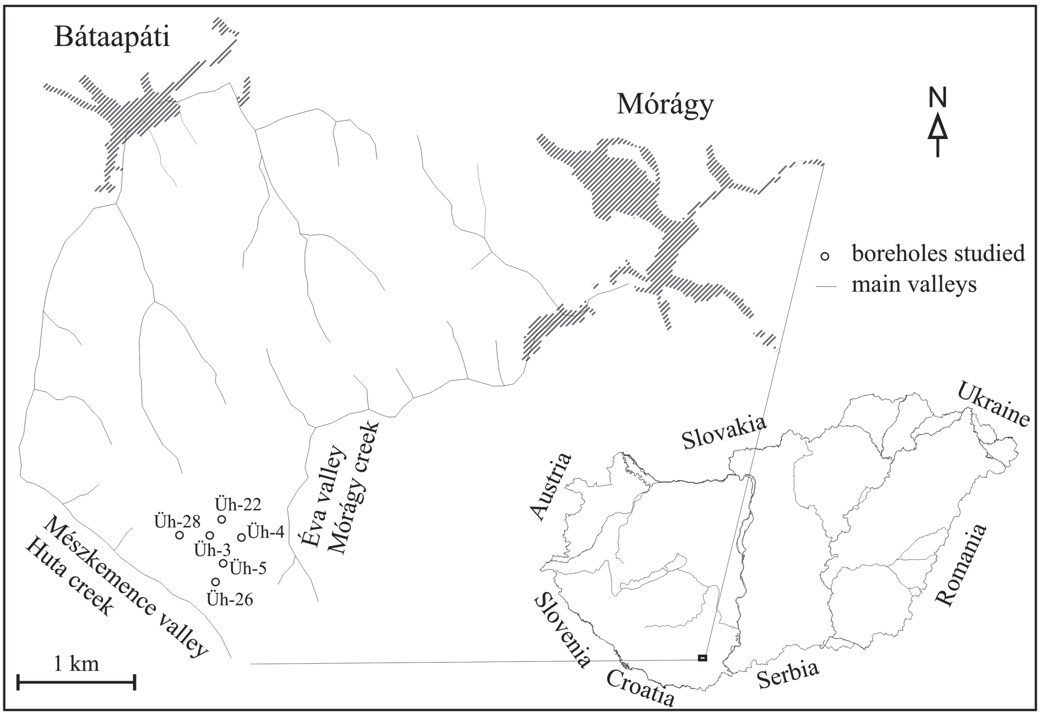

Fig. 1. Generalized map of the study area.

the interface between the granite and dykes a cooling margin can frequently be observed and this is usually associated with fractures. The dykes are strongly weathered and hydrothermally altered.

Hydrogeological conditions

At the site of the planned repository very detailed investigations have been carried out using various methods. The hydrogeological conditions of the entire investigated area is presented in the basic paper of Balla et al. (2004).

Among the features of the fresh granite, one of the most important is its strongly fractured and argillized character in local zones of tectonic displacements. It is also heterogeneous (Maros et al. 2003). Extensive single-hole packer testing, with an average test interval length of 10 m, found that packer interval transmissivities vary over six orders of magnitude without any spatial trends (Balla et al. 2004). The calculated transmissivity of the fresh granite is in the range between 10^{-12} and 10^{-6} m^2/s. The transmissivity of the main water conductive features varies between 8×10^{-6} and 2×10^{-5} m^2/s (Balla et al. 2004).

A typical hydraulic head profile along a borehole is displayed in Fig. 2. The variability of hydraulic head results from two different phenomena: 1) small scale (1 to 5 m) hydraulic head scattering and 2) large (5 to 20 m) hydraulic head jumps. The first is caused by the natural variability (fracture orientation, size, transmissivity and connectivity) and clustering of fracture systems. Balla et al. (2004) suggest that the large hydraulic head jumps are associated with the strongly altered, argillized fault core zones observed in the granite. It is frequently concluded that the boundary between compartments with different hydraulic heads must have a very low permeability (Dershowitz et al. 1998). In the case of the studied area Tóth et al. (2003) estimated the hydraulic conductivity of these zones to be 10^{-12} to 10^{-10} m/s by using inverse modelling technique. Cross-hole interference tests clearly demonstrated that borehole sections displaying only small scale hydraulic head-scattering are within a single compartment (Benedek et al. 2003a). At site scale the strongly compartmented character causes high complexity of the flow pattern. In this paper the effects of compartment boundaries and the general conceptualization of the site are not considered further. This paper studies conditions within a single compartment.

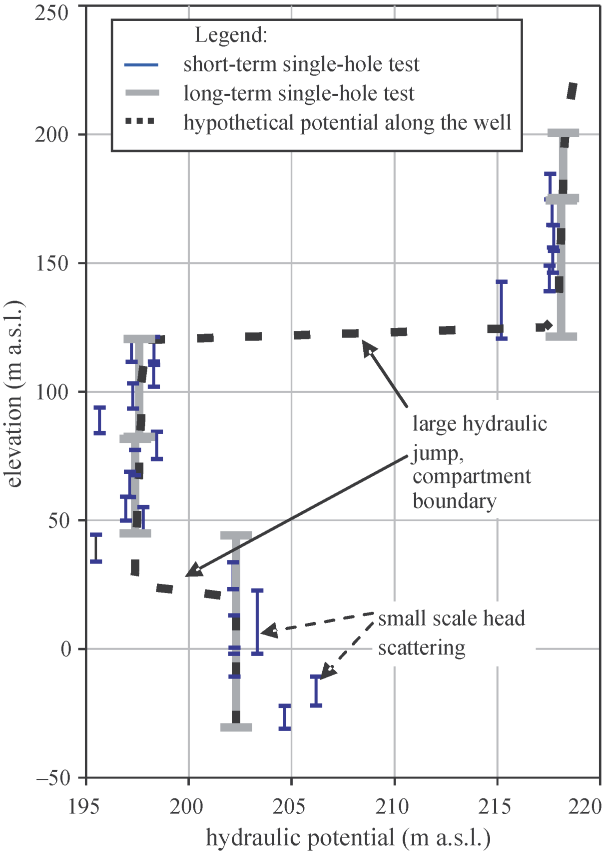

Fig. 2. Head profile along a borehole (Üh-28) at the site. Small scale head-scattering and larger jumps in head are indicated with arrows.

The chemistry of groundwater at the site has been studied in detail by Horváth et al. (2003). They suggested that in the northern area the vertical flow velocity component is larger than in the South. This is presumed to reflect differences in the compartmentalization of the granite. In this paper only boreholes located in the southern section were considered. In this part of the site 6 boreholes (Üh-3, Üh-4, Üh-5, Üh-22, Üh-26, Üh-28) have been drilled (Fig. 1).

Modelling tool applied

The modelling tool (FracMan software package) applied was developed by Golder Associates Inc. (Seattle) to model the geometry of discrete features, including faults, fractures, paleochannels, karstic elements and stratigraphic contacts (Dershowitz et al. 1998). This software is frequently used in nuclear projects and in the oil industry. The oil industry applies the software in up-scaling information from fractured rock reservoirs to equivalent continuum models, to predict well production and to provide information about the necessary well spacing.

FracMan simulates fractures as 3-D networks of triangular finite elements. The software represents individual fractures as 2-D elements defined stochastically based on probability distributions for orientation, length, transmissivity, aperture, storativity, etc. In addition, deterministic features can also be involved in the models. The solver for FracMan (MAFIC) uses a Galerkin finite element solution scheme to approximate the solution for the diffusivity equation (Bear 1972). FracMan is also able to model coexisting matrix (generic matrix block or fully discretized matrix elements) and fracture (DFN elements) systems. Solute transport modelling under steady-state or transient flow conditions, and stochastic emulation of convective dispersion, matrix diffusion, radioactive decay and mineral specific retardation are also supported. Boundary conditions are assigned in the traditional way (constant or transient hydraulic head and flux).

FracMan provides an integrated environment for the entire process of discrete feature data analysis and modelling. In the first step the user can analyse and transform raw field data (fracture orientation, packer interval transmissivity, fracture density, etc.) into the format required for discrete fracture modelling. In the next step, stochastic simulations of fracture patterns can be made. If the generated fracture systems meet the selection criteria they can be converted into a finite element mesh with the appropriate hydraulic parameters.

The software is also able to model fractures generated under specific geological and geodynamic conditions. For example, the software has the capability to reproduce fractures generated due to folding, faulting, hydrofracturing or resulting from a specific in situ stress field.

Model size, boundary conditions

The size and boundary conditions for the model were highly simplified, recognizing that for a specific location compartment boundaries may need to be considered. The model was a generic cube with 200 m sides. The boundary conditions were defined to result in a one directional flow of 1% gradient, from S to N. The other faces of the cube were defined as no-flow boundaries.

The model contained stochastic and deterministic elements. The stochastic elements represent the fractures in the granite and the deterministic elements the planned waste disposal tunnel.

Stochastic elements

Fracture orientation

The total set of fracture orientation data was measured in individual boreholes by BHTV (acoustic borehole televiewer; Zilahi-Sebess et al. 2003). For this study only the hydraulically active fractures have been considered, as other ones have only a limited role in the flow system. The selection was made using the results of high-sensitivity flow measurements (Heat-Pulse Flowmetry (HPF); Szongoth & Galsa 2003). These were carried out at 1 m scale, and provide data on inflow intensity and location. The combination of the two data sets (BHTV and HPF) allows the estimation of orientations and of the one-dimensional (along boreholes) fracture intensities of the hydraulically active fractures.

Visually two (or three) sets of fractures can be distinguished: 1) NE-SW strike, SE dip; 2) E-W strike, N dip; 3) N-S, NW-SE strike, W, SW dip (Fig. 3). For this study the probability distributions of the fracture orientation data were approximated using the univariate Fisher distribution (Mardia 1972). The probability distribution is defined as follows:

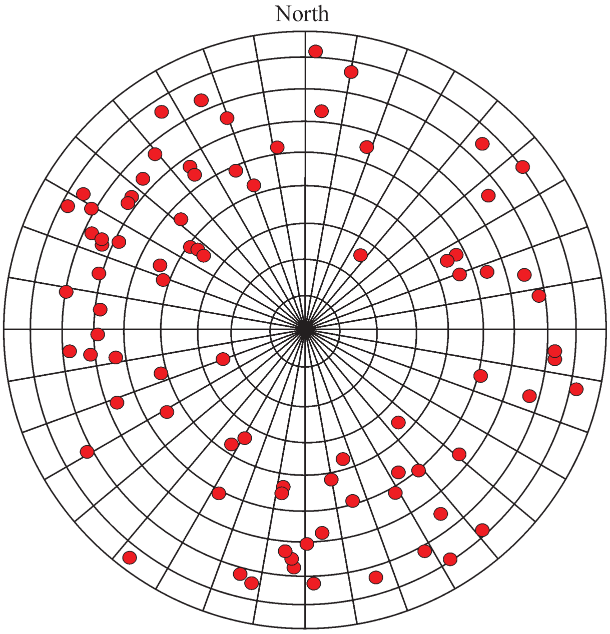

Fig. 3. Stereographic projection (lower hemisphere) of hydraulically active fractures in the boreholes investigated.

$$f(\varphi',\Theta') = \frac{\kappa \sin\varphi' \, e^{\kappa\cos\varphi'}}{2\pi(e^{\kappa}-1)}, 0 \le \Theta' \le 2\pi$$

where κ is the distribution parameter and φ', Θ' are the variations about the mean direction. The goodness of fit was demonstrated by Kolmogorov-Smirnov statistics. To reduce the overestimation of horizontal and sub-horizontal fractures due to the vertical orientation of the boreholes the Terzaghi (1965) correction was applied.

For the study described in this paper only two sets of fractures (NE-SW and N-S, NW-SE strike) were defined in order to simplify the system and to reduce computation time. The results are presented in Table 1.

Fracture size distribution

The 3-D size distribution of the fractures in the rock mass can be estimated by different methods: 1) size-number scaling plots at regional, outcrop, etc. scales; 2) censoring statistics; 3) trace length matching; 4) pressure transient analysis. In this study the size-number scaling plot approach was used.

At the site and in the vicinity of the site there are three independent trace length data sets: 1) artificial outcrops (Balla et al. 2003; Gyalog et al. 2003); 2) vertical seismic profiling (VSP) in boreholes (Prónay 2003); 3) seismic reflection surveys (Prónay et al. 2003).

Table 1: The statistical parameters (Fisher distribution) for the orientation of the two hydraulically active fracture sets.

Fracture system	Strength (%)	Fisher parameters			Kolmogorov-Smirnov statistics (%)
		Main dip direction (°)	Main dip angle (°)	Fisher K	
Set1	78.6	341.6	82.5	5.71	95.6
Set2	21.4	126.1	59.5	27.32	93.6

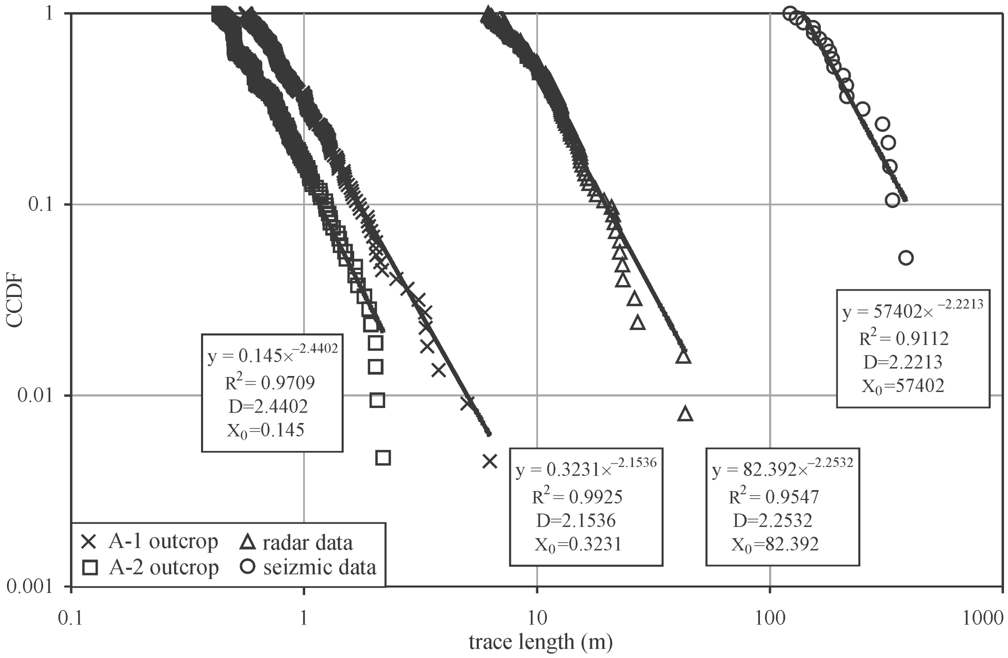

Fig. 4. The complementary cumulative density function (CCDF) of trace length for different scales.

These data sets are representative of different scales: outcrops provided information about the trace length up to ~6 m, VSP in the range of 2 to 40 m, and seismic surveys in the range of 50 to 380 m. Trace length distributions at any scale are truncated in two ways: 1) the lower one is selected by the operator; 2) the upper one results from the size of the sampling window.

The scaling properties of trace length have been estimated using the complementary cumulative density function (CCDF; Fig. 4) for each scale. Due to the truncations only the linear segments of these functions can be applied in the estimation of fracture size distributions (Andersson et al. 2002). At any scale the best-fit to the measured data was a power law function (Fig. 4). The data for different scales are very consistent, which suggests that the fractures at all scales belong to the same system.

Direct simulation of fractures in 3-D based on 2-D data sets is not reliable. For example, the probability that a large fracture intersects an outcrop is higher than is the case for small fractures, and consequently trace length is biased. In addition, the orientation of fractures and outcrops can also influence the trace length distribution. La Pointe & Outters (2000) argued for a relationship between the size distribution of trace length (2-D) and that of fractures (3-D) intersecting a trace plane (outcrop). The following equations can be applied to link the parameters of fracture size distribution and trace length distribution:

$$D_{3\text{-D, fractures}} = D_{2\text{-D, traces}} + 1,$$
$$x_{3\text{-D, fractures}} = x_{2\text{-D, traces}}$$

where $D_{3\text{-D, fractures}}$ and $x_{3\text{-D, fractures}}$ are the parameters of the power law function in 3-D and $D_{2\text{-D, traces}}$ and $x_{2\text{-D, traces}}$ are the parameters of a power law function in 2-D. D and x represent the exponent and minimum value of power law distribution, respectively. In this study D was calculated as an average of D values at different scales ($D = 3.26$) but x was determined as the smallest value among the different scales ($x = 0.145$).

The size distribution of fractures with different orientation was also compared. This complex data set (orientation, size) is only available for artificial outcrops (Balla et al. 2003; Gyalog et al. 2003). CCDF calculations suggested that there is no fundamental difference between the trace lengths of differently oriented fractures (Benedek & Mező 2005).

Fracture intensity

The intensity of fractures in 3-D can be described as a volumetric value, as fracture area per unit volume of rock (P_{32}, m^2/m^3). However this parameter cannot be estimated directly from field measurements and must be derived indirectly.

The number of fractures intersecting individual boreholes (linear intensity, fractures per meter, P_{10}) is only a function of the orientation of boreholes, fractures and the size of fractures (La Pointe et al. 1993). Dershowitz et al. (1998) suggested that volumetric and linear intensity can be linked through the following equation:

$$P_{32} = P_{10,\text{ obs}} \times (P_{32,\text{ sim}}/P_{10,\text{ sim}}) = C_{31} \times P_{10,\text{ obs}}$$
$$C_{31} = P_{32,\text{ sim}}/P_{10,\text{ sim}}$$

where $P_{32,\text{ sim}}$ is the volumetric intensity in the simulation, $P_{10,\text{ obs}}$ is the linear intensity measured in the boreholes (in this study BHTV data are used; Zilahi-Sebess et al. 2003) and $P_{10,\text{ sim}}$ is the linear intensity in the simulation. C_{31} is a proportional constant, which can be determined by using inverse modelling. Since the size distribution of the fractures and the orientation of the boreholes and the fractures are known, all the data required to calculate P_{32} are available. $P_{32,\text{ sim}}$ was changed gradually until an acceptable fit between

$P_{10,\ obs}$ and $P_{10,\ sim}$ was found. In the stochastic simulations with 50 realizations the average value of C_{31} in the individual realizations stabilized at around 1.35 for both fracture orientation sets (Benedek & Mező 2005).

In general only a portion of the entire fracture system is active hydraulically, since the majority are very small (background fracturing) or not connected to other fractures. For this reason, and to save computational time, the size distribution was truncated. The upper limit was determined on the basis of the cross-hole interference tests, which indicate that the largest distance between packer intervals in hydraulic connection is about ~400 m (Benedek et al. 2003b). The lower limit was estimated using inverse modelling: the lower limit for fracture size was changed until the modelled linear intensity of hydraulically active fractures was consistent with field measurements in boreholes (HPF measurements in Szongoth & Galsa 2003). Based on this the lower limit value was set to 10 m. The comparison of linear intensity indicated by HPF measurements and the simulated values in 50 individual realizations is shown in Fig. 5.

Spatial model

The spatial model is basically the definition of the relationship of the individual fracture centres in space, for which many models are available (Dershowitz et al. 1998). Benedek et al. (2003b) carried out a series of fractal dimension calculations for each borehole in order to evaluate the spatial relationships. On the basis of the location and the frequency of fracture-borehole intersections, box-fractal and mass-fractal dimensions were calculated. These calculations showed fractal dimensions (Mandelbrot 1985) in the range of 0.88 to 0.99, very close to one. A fractal dimension of 1 in a 1-D data source (borehole) represents a random fracture pattern in space. Therefore a Baecher model (Baecher et al. 1977), a randomly, but uniformly distributed fracture centre model was applied.

Transmissivity distribution of individual fractures

For a DFN flow simulation it is necessary to estimate the transmissivity distribution of individual fractures. For this study an approach adapted from Osnes et al. (1988) was used. This method assumes that the transmissivity of a packer test interval can be regarded as the sum of the transmissivities of the conductive fractures intersecting the test interval:

$$T_i = \sum_{j=1}^{n_j} T_{i,j}$$

where T_i is the transmissivity of the packer interval, n_j is the number of conductive fractures intersecting the test interval and $T_{i,j}$ are the transmissivities of the conductive fractures. The approach used was the following: 1) conductive fractures with an intensity approximated by a Poisson distribution are generated stochastically for the test zone, 2) to the conductive fractures transmissivities are assigned stochastically by Monte-Carlo simulation based on an initial estimate of the fracture transmissivity distribution (in this study a lognormal distribution), and thus the interval transmissivity can be calculated, 3) stochastic simulation terminates when a good fit is found between observed packer interval transmissivities and simulated transmissivities. The goodness-of-fit is tested using Kolmogorov-Smirnov statistics.

Test interval transmissivities are available from three independent sources: short-term single-hole tests (Molnár et al. 2000, 2003a,b), 2) long-term single-hole tests (Molnár et al. 2000, 2003a,b) and 3) cross-hole interference tests (Bradley et al. 2000; Ács et al. 2003a,b,c). The relatively small number of interference tests precludes a reliable estimate of the transmissivities and therefore only the single-hole tests were used. In the simulations the following assumptions were applied: 1) the P_{10} value (linear intensity) of conductive fractures is close to 0.08 based on HPF measurements (Szongoth & Galsa 2003), 2) the detection limit of HPF measurements

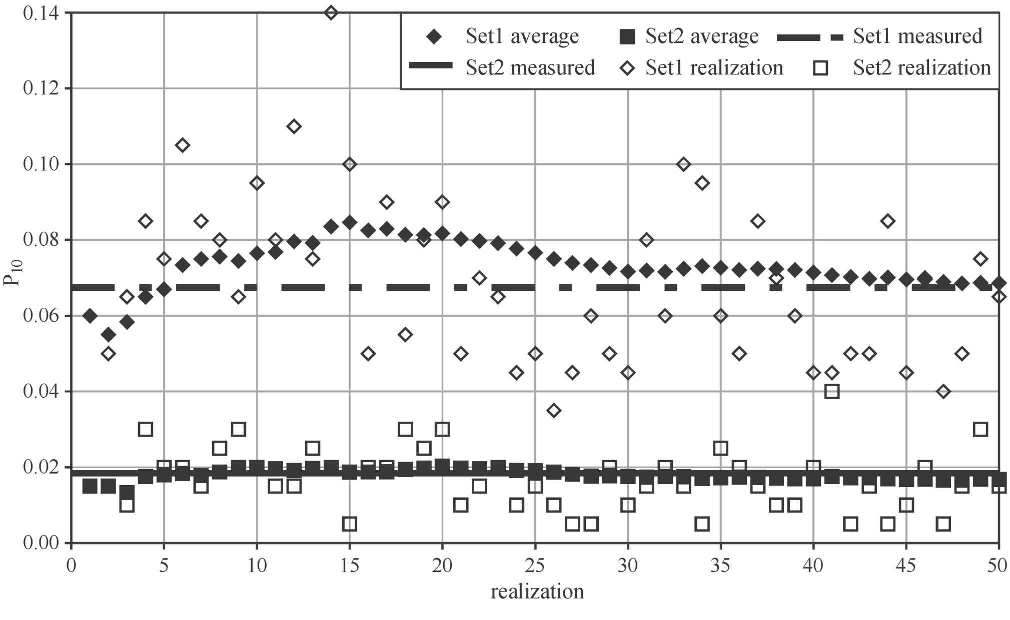

Fig. 5. Comparison of field P_{10} measurements and simulated values from individual realizations with fracture length distribution truncated below 10 m and above 400 m. **Average** — stabilization of average values with realizations; **realization** — calculated value of individual realizations; **measured** — field measurements.

Table 2: Statistical parameters for individual fracture transmissivities derived using the method from Osnes et al. (1988).

	Short-term tests	Long-term tests
Mean (m^2/s), μ_{logT}	3.2×10^{-7}	8.0×10^{-7}
Deviation (m^2/s), σ_{logT}	4.2×10^{-6}	3.4×10^{-6}
Fracture intensity (P_{10})	0.0881	0.0891
The ratio of fractures with a transmissivity less than 1×10^{-8} m^2/s	52.6 % in the model; 47.4 % in field measurements	16.1 % in the model; 9.68 % in field measurements
Kolmogorov-Smirnov test	98.4	95.9

was $\sim 1\times10^{-8}$ m^2/s and therefore test intervals with transmissivity below this threshold were considered non-conductive. The results of simulations for short-term and long-term tests are presented in Table 2. In the further modelling we used lognormal transmissivity parameters derived from long-term measurements.

Deterministic elements

For this study some deterministic continuum elements were generated to represent a future waste disposal tunnel.

The tunnel was placed in the centre of the modelled block so that groundwater flows in the direction perpendicular to it. The longitudinal axis of the tunnel was 100 m long and its cross-section was assumed to be a square with 10 m sides. The hydraulic behaviour of the tunnel content was described by equivalent porous continuum elements (hydraulic conductivity varied from 1×10^{-12} m/s to 1×10^{-3} m/s) with a cell size of 2.5 m×2.5 m×2.5 m.

Results

On the basis of the geometric and flow parameter distributions 50 stochastic realizations were generated. The fracture system for one realization is presented in Fig. 6. Different aspects of the 50 realizations are discussed by Benedek & Mező (2005), in this paper only some selected results are presented.

Equivalent hydraulic conductivity of the modelled region

The equivalent hydraulic conductivity of the modelled region was calculated on the basis of the flow through the constant hydraulic head boundaries. Since the hydraulic gradient was set to be 1%, the application of Darcy's law allows the calculation of the equivalent hydraulic conductivity.

Balla et al. (2004) suggested that the hydraulic conductivity of the fractured granite varies between 1×10^{-12} m/s and 1×10^{-6} m/s at the scale of 10 m packer intervals and that it has a lognormal distribution with a mean of 3×10^{-9} m/s. The

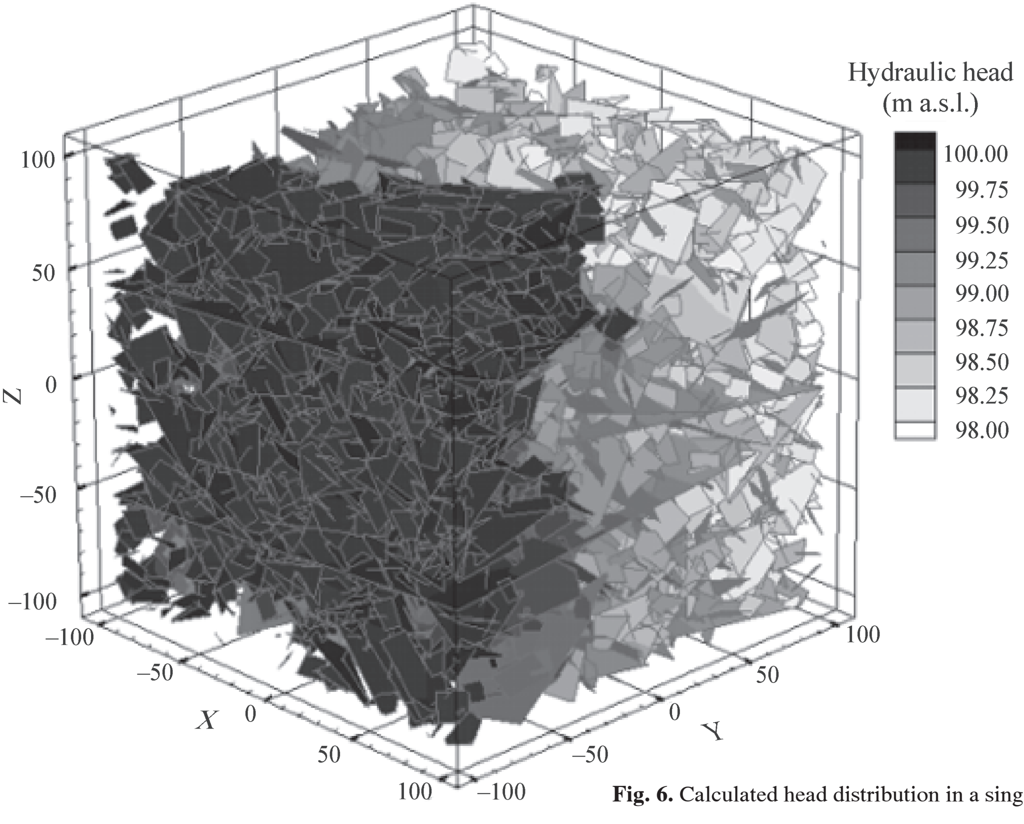

Fig. 6. Calculated head distribution in a single realization.

median transmissivity value for the boreholes considered in this study (southern section of the site, Fig. 1) is 1.4×10^{-9} m/s. The calculated results for the 50 stochastic realizations indicated a median equivalent hydraulic conductivity of 6×10^{-9} m/s, and thus it can be concluded that the model matches the field measurements well.

Flow patterns calculated

Field studies (Ács et al. 2003d) indicated that one of the most characteristic hydrogeological features of the site is the frequently observed smaller-scale hydraulic head-scattering and the larger hydraulic head jumps along individual boreholes (Fig. 2). In this paper the larger hydraulic head jumps and their conceptual origin (in compartmentalization) are not considered.

Figure 6 shows results for a single realization. The calculated hydraulic head does not change gradually from the low hydraulic head boundary to the high hydraulic head one, but it is strongly affected by system heterogeneity. In order to investigate the hydraulic head heterogeneity nine virtual vertical boreholes were inserted and hydraulic head profiles were calculated along them (Fig. 7). The hydraulic head profile for borehole 6 shows a very high head difference (from ~100 m to ~98 m), which covers almost the entire range between the boundary conditions. On the other hand, borehole 3 has a very smooth hydraulic head profile. The interpretation of different hydraulic head profile patterns is that a cluster of fractures may be connected to the high hydraulic head boundary or to the low hydraulic head boundary, and that different fractures or fracture clusters are not necessarily connected directly, but only through the rock matrix. This observation emphasizes the importance of connectivity and geometry in fractured rocks. This conclusion also demonstrates that a fractured rock mass cannot be characterized by a constant, uniform hydraulic gradient, as the actual gradients are highly scale and location dependent.

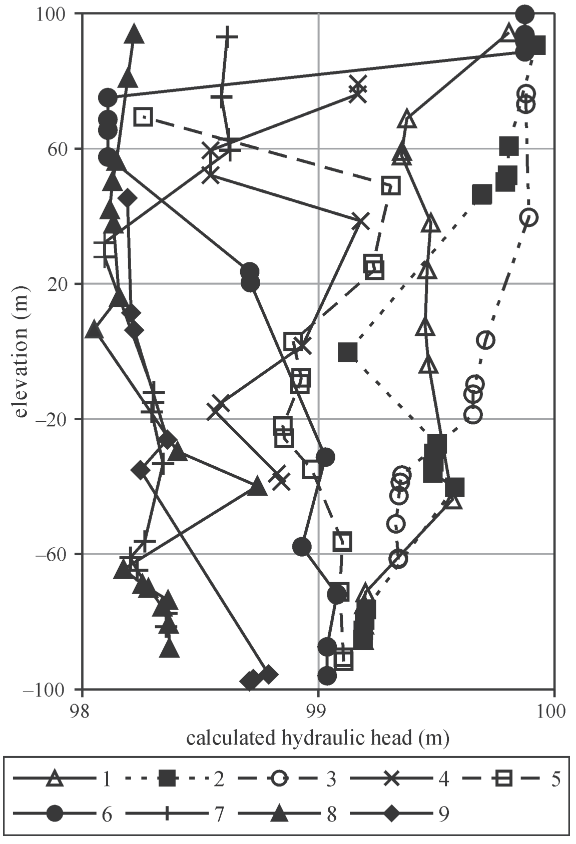

Fig. 7. Head profiles along some vertical boreholes. The numbers refer to the boreholes inserted into the modelled region.

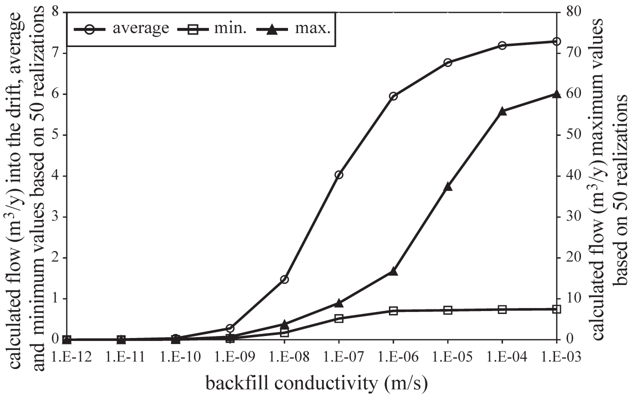

Fig. 8. Average, minimum and maximum values of inflow through the walls of the disposal tunnel as a function of tunnel content conductivity.

Flow into the tunnel

One of the most important parameters for performance assessment obtainable from hydrogeological models is the flow through the disposal tunnels, as groundwater can transport radionuclides to the geosphere and biosphere. The flow is influenced by three engineering elements: 1) the material in the tunnel, 2) the excavation disturbed zone, 3) grouting of transmissive fractures. In the study described here only the effect of the material in the tunnel was investigated. The other two elements were studied by Benedek & Mező (2005).

The calculated average, minimum and maximum inflow values through the faces of the drift are displayed as a function of tunnel content conductivity in Fig. 8. There is a threshold under which the reduction of the hydraulic conductivity does not significantly reduce the flow. This threshold is $\sim1\times10^{-9}$ m/s. There is also an upper threshold, above which increasing the hydraulic conductivity does not increase the flow further. This threshold is $\sim1\times10^{-5}$ m/s.

Flux inside a tunnel

The flux distribution within a disposal tunnel may be significant for performance assessment, since in a fractured rock mass concentrated inflow and outflow could occur close to fracture-tunnel intersections and result in heterogeneous conditions. The drift was divided into 40 sections along the longitudinal axis and the flux through each drift section was calculated.

The calculated flux distribution along the longitudinal axis is shown in Fig. 9A,B for one of the 50 realizations. This fig-

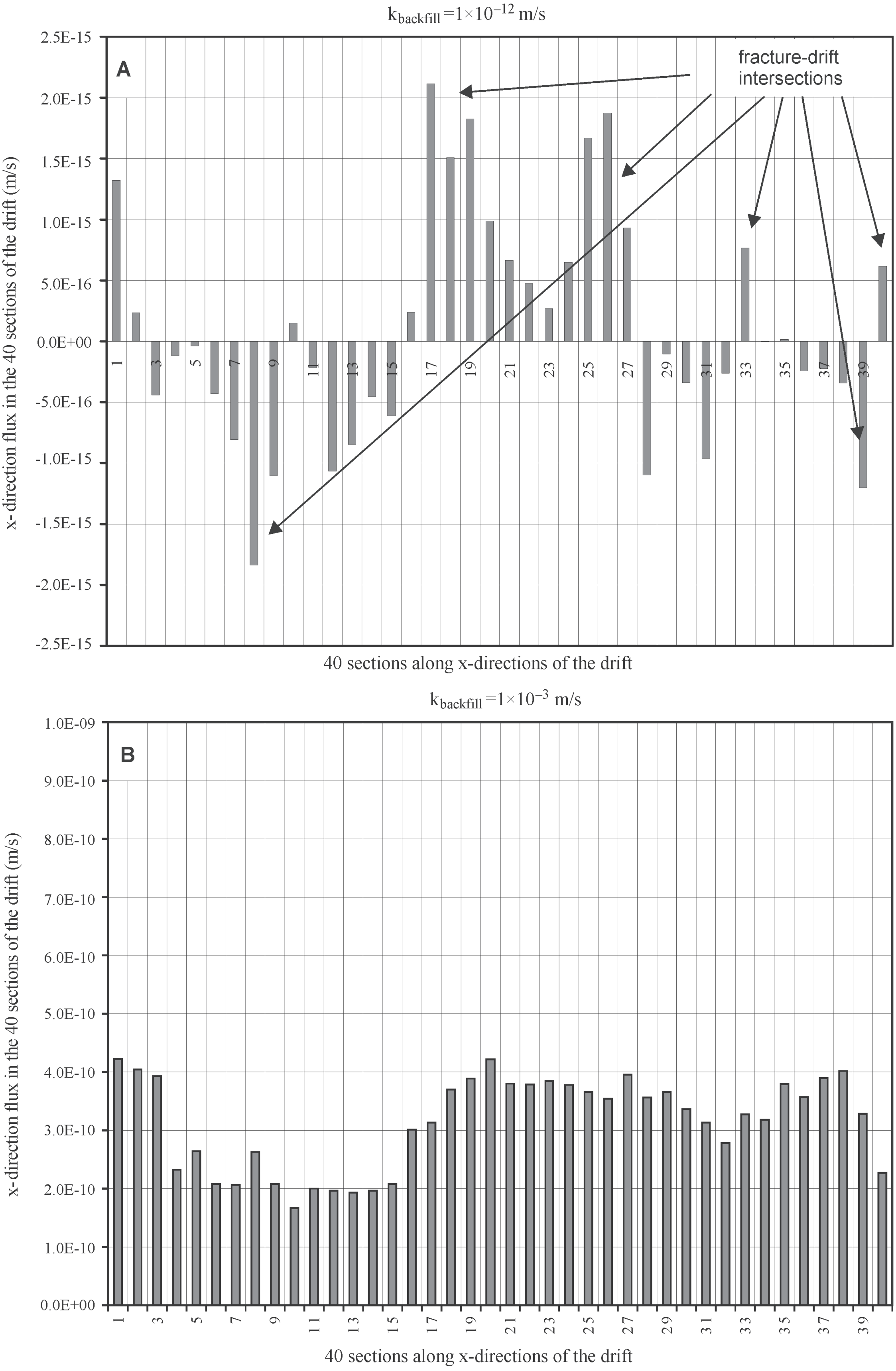

Fig. 9. The x-direction flux in the 40 sections of the drift based on one of the 50 realizations in the cases of low (**A** — 1×10^{-12} m/s) and high (**B** — 1×10^{-3} m/s) backfill conductivity. The negative or positive signs of the values calculated refer to the direction of flux.

ure clearly demonstrates that the flux distribution is not uniform if the tunnel content conductivity is low (1×10^{-12} m/s): flux intensity is much higher close to fracture-drift intersections than far away from intersections. In the case of low hydraulic conductivity (Fig. 9A) some abrupt changes between neighbouring sections can be observed, however, in the case of high hydraulic conductivity (Fig. 9B) the distribution along the axis is more smoothed. In that case the tunnel content connects individual fracture-tunnel intersections and significant longitudinal flux is generated. It may be noted that the small flux values in Fig. 9A,B suggest that the most important transport process inside the tunnel is expected to be diffusion.

Conclusions

To assess a repository for radioactive waste it is crucial to have a good estimate of the flow of groundwater through the waste, since groundwater is able to transport radionuclides into the geosphere and biosphere.

In the study described here, based on the available geological and hydrogeological data sets, the most important parameters describing the hydraulically active fracture systems in the host rock were estimated (orientation, intensity, length, transmissivity, etc.) on a statistical basis. The fracture system was then approximated using a DFN model. In the model the waste disposal tunnel was represented using equivalent porous continuum elements.

In this paper only a few aspects of the DFN model and a selection of results have been displayed in order to demonstrate the capabilities of this technology.

The most important conclusions of the work can be summarized as follows:

- The hydraulically active fractures have a NE-SW strike and the orientation can be described very well with two Fisher distributions. The directions coincide with the main tectonic orientations observed in the granite.
- The fracture length distribution can be characterized with a truncated power-law function based on the trace length measurements at different scales.
- The transmissivity distribution of individual fractures can be defined by a lognormal distribution based on the results of short-term and long-term single-borehole tests.
- The equivalent hydraulic conductivity based on field measurements was well reproduced by the model.
- The model displayed the observed small-scale stochastic hydraulic head-scattering along boreholes.
- The inflow is determined mainly by the content of the emplacement tunnel. The larger its hydraulic conductivity, the larger the flow into the tunnel.
- The flux distribution inside the tunnel is heterogeneous to a degree depending on the hydraulic conductivity of the tunnel content. The smaller the hydraulic conductivity the more pronounced the heterogeneity.
- The flux inside the tunnel is very low, which means that diffusion is likely to be the most important transport process.

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