The Hydrogeological Modelling of the Bátaapáti Site

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Abstract

Since the beginning of the exploration of the Bátaapáti Site numerous hydrogeological, geological, geophysical, geochemical, etc. measurements, observations and interpretations have become available. This enormous data system provides the basis for any further studies and forecasting. In the frame of the hydrogeological conceptualisation at the site studied a hypothesis accordant with most aspects of the data system has been developed.

The conceptual model constructed for the site divides the rock volume into three hydrogeological subunits: 1) weathered granite; 2) fractured granite; 3) sealing features. Based on the recent interpretations the sealing features divide the granite into several rock blocks or compartments and inside these blocks fractured granite is located. The hydraulic communication between different compartments is limited, at least at the scale of available data and studies. On the other hand inside compartments the hydraulic connections are very strong and fast through large, high transmissivity fracture zones. As a consequence of this phenomenon the hydraulic gradient is minimal inside the individual compartments. The conceptual model developed for the site hydraulics was tested by independent geomathematical tools, since poorly understood hydraulics and concept may easily mislead the results of any models and the value of predictions made on the basis of these models may be very limited.

Based on the properties and components of the conceptual model (sealing zones, conductive fractures) several hydrogeological models have been developed. This process brought up some challenges to be solved. One of the most important ones was that most data are available at different scales. This means that data of a single scale might be misleading alone, but evaluation with other scales provided valuable information about the site hydraulics. This methodology lead to the assumption that the transmissivity values are strongly scale-dependent and potentially that there is a correlation between transmissivity and size or scale. Consequently the estimation of equivalent parameters (upscaling) is crucial in modelling studies.

The hydrogeological models have been developed in the frame of two main tasks: 1) site specific models; 2) models related to the site engineering. In both cases two modelling techniques have been applied: 1) deterministic continuum (FeFlow); 2) stochastic discrete fracture network (FracMan).

The results of these two modelling approaches suggested that the conceptual model developed for the site hydraulics is very suitable, the field measurements and observations are in accordance with the results of hydrogeological models. However, these results have also indicated that geometrical (extent, spatial distribution, core and damage zone correlation, etc.) and hydraulic (conductivity) parameters of the so-called sealing zones (faults) are only known in a limited manner. The hydrogeological models constructed describe the most important hydraulic characteristics of the Bátaapáti Site, but information about the transport processes is very limited; this lack has to be addressed in the future.

Introduction

The hydrogeological modelling can be considered as an integration of geological and hydrogeological information of a certain level of knowledge at a specific site. This kind of model is able to integrate geological, hydrogeological, meteorological, hydrological, geochemical, etc. data of different scales from a site. However, in the program targeted to find a suitable place for the disposal of radioactive waste hydrological models are interim products, although hydrogeological models are also a form of conclusion of research. Their primary goal is to characterise the geosphere
module of the site safety assessment models, thus to determine the geological and hydrogeological behaviour of the site. In addition they provide parameters for safety assessment models.

In the period of research and construction of the National Radioactive Waste Repository more and newer information become available about the geology and hydrogeology of the site. This kind of new information may slightly or entirely modify or alter geological and hydrogeological concepts constructed on the basis of former data. By using the new information it is strongly recommended to update older model versions, even though the geological concept has not been changed and the new informations support former interpretations.

In the frame of the ground-based exploration ended on the 1st of September, 2003 several numerical models were constructed in order to describe the primary, undisturbed flow field of the Bátaapáti Site and to prove the suitability of the site. These models were presented in individual reports (HORVÁTH et al. 2004; BENEDEK et al. 2003a; MEZŐ, MOLNÁR 2003a) and in the final report of geological exploration (BALLA et al. 2003). After the demonstration of the suitability of the site the main goal of the hydrogeological modelling was to provide some input parameters for the safety assessment and to investigate the potential interaction of the flow field and the underground facilities.

After the end of the ground-based exploration the main activity of the site exploration has been below the surface, mostly along the access tunnels. In the frame of this stage several new types of information became accessible (depression caused by the excavation, EDZ sections, data from the monitoring system, etc.), which contributed significantly to the improvement of former interpretations (BALLA et al. 2007). All of these made the updating of former hydrogeological models and the integration of new data and observations necessary.

The main source of the new information and data is located mostly along the line of the two access inclines to the National Radioactive Waste Repository. The new results of the access inclines involve data about the horizontal heterogeneity of the system, new rock types, determination of structures of special role in the flow system, new geometries, new samples, etc. In addition to the direct observations, the depression caused by the the excavation of the inclines and the hydrogeological responses of the flow system indirectly suggested the presence of a compartmentalised flow system and helped to understand the geological, hydrogeological behaviour of the studied site.

The Workflow and Role of Hydrogeological Modelling

Based on the results of the geological, tectonical, hydrogeological and geophysical explorations carried out at the Bátaapati Site (Figure 1), integrated hydrogeological models were developed earlier (TÓTH et al. 2003; MEZŐ, MOLNÁR 2003). By using hydrogeological models—based

Figure 1. Generalised map of the Bátaapáti Site
I. ábra. A bátaapáti kutatási terület áttekintő térképe
on the understanding of the site and basic data available—
events occurring in the future can be simulated and
estimated. Besides, the results of the hydrogeological
models are also necessary for the performance assessment
and for the design.

The evaluation of flow and contaminant transport in
fractured rocks is carried out by using different types of
hydrogeological models depending on the aim of the task
and the scale of the explored area. For large-scale flow
systems the equivalent continuum models can be used
properly, but for smaller volumes the hydrogeological
fracture models are more suitable. Whether the flow system
can be best evaluated by continuum models or rather by
fracture models is a function of the scale and timeframe of
the problem investigated.

Due to the complex, multi-factorial processes taking
place in the groundwater flow systems different computer
codes can be applied. Since certain codes are more suitable
for tackling tasks occurring during modelling or inves-
tigating certain problems, several codes with worldwide
application and acceptance have been used for the modelling
activities. Within the investigation framework of the
Bátaapáti Site three codes have been used: ModFlow at the
Hungarian Geological Institute, FeFlow and FracMan at
Golder Associates. In addition also some specific codes have
been applied (in case of reactive transport calculations
CrounchFlow was used, BENEDEK et al. 2008b).

At the same time, the experience coming from previous
years showed that it was always a problem how the models and
their results developed in different environments and scales
connect to each other and how they complement each other
and also how the results can be utilised for the evaluation of
the entire site. To make the connections between the different
tasks carried out by the hydrogeological modelling more
transparent for both the experts and for the readers, a figure
showing the structure and the workflow of hydrogeological
modelling has been compiled (Figure 2).

As with all modelling tasks the hydrogeological
modelling also starts with the processing of the available
knowledge, pieces of information and interpretations
(Figure 2). Four basic sources of information have been used
for the hydrogeological modelling:

— geophysics (seismic, inflow measurements, borehole
television interpretations, radar, etc.);

— geology (petrology, evolution, geological mapping
and so on);

— hydrogeology (single borehole and multiple borehole
measurements, hydraulic potential profiles, interference
tests, water balance, flow measurements, hydrogeo-
chemistry, etc.);

**Figure 2. Workflow of the hydrogeologic modelling**

Codes indicate references for the source reports: I—BENEDEK et al. 2007, II—BENEDEK et al. 2008a, III—BENEDEK et al. 2008b, IV—BENEDEK et al. 2008c

2. ábra. A modellezés folyamata a bátaapáti kutatás keretében

Based on all the data, knowledge and interpretations a conceptual model (see later) describing the behaviour of the whole system is compiled. In practice the conceptual model is the essence of the whole process since it determines the process of modelling and the methods applied during it. MEYER et al. (2004) give the following definition for the conceptual model: “...the conceptual model is a hypothesis or interpretation about the behaviour of the system to be modelled and of the connection between the components of the system”. It is worth emphasising that if the conceptual model is not correct—based on the same input data—absolutely misleading results can be obtained. Utilising this perception the literature puts even more emphasis on the fact that not only the uncertainty of the available parameters, measurements and data shall be considered during modelling tasks but also the uncertainty arising from the interpretations and work hypothesis (“human factor”; MEYER et al. 2004).

After the development of a proper conceptual model the hydrogeological modelling process is started (Figure 2). It is worth noting that the hydrogeological model is not only a consequence of the conceptual model but it also has a strong effect on it and it also provides a tool for examining the concept by theoretical methods.

The hydrogeological modelling tasks of the Bátáapáti Site can be divided into three major groups (Figure 2):
- mathematical preparation;
- equivalent continuum modelling;
- DFN (Discrete Fracture Network) modelling.

From these groups mathematical preparation practically assists the other two (Figure 2). Its main goals can be determined as:
- confirming or challenging the conceptual model by using independent tools;
- spatial extrapolation of parameters, determination of spatial connections and development of spatial models.

It is worth emphasising that a brand new approach was used for the Bátáapáti Site to examine the conceptual hydrogeological model: no different, alternative models were developed and compared, but a certain conceptual model was examined using different mathematical methods.

The equivalent continuum models were developed in four different scales (Figure 2):
- site-scale model and its sensitivity analyses;
- repository-size model;
- gallery model;
- overpack container model.

It is important to note that these models are not independent from each other but that they are in a strong, continuous and two-way connection. On one hand they provide boundary conditions for the higher-resolution models, and on the other hand they provide equivalent parameter values for the lower-resolution models. A structure like this is needed for the modelling tasks as, for example, a site-scale model is not suitable for providing answers on the questions of container-scale (due to the details required for that). This problem is also true the other way round. It is worth noting that the results and experiences coming from these models can and do have an impact on the conceptual model.

The DFN modelling can be divided into two parts based on the conceptual model used for it:
- investigation of heterogeneities within blocks;
- investigation of the barrier or sealing zones.

One of the tasks of these models is to provide input parameters for the equivalent continuum models by using some scaling procedure. The other is that based on this knowledge and results a gallery-scale and a site-scale model can be developed. Just as it was with the equivalent continuum models the information gained from these models can impact the conceptual model significantly.

The ultimate goal of the abovementioned modelling procedures is to provide proper and usable information and data for the performance assessment. This may mean not just to provide actual calculation results (like dilution, transport time) but to influence significantly also the concepts and developments utilised for the performance assessment. The procedure shown in Figure 2 demonstrates this aspect and it has been created by considering the actual questions coming from the performance assessment.

The results of the workflow shown in Figure 2 are published in the reports on the hydrogeological modelling tasks carried out within the framework of the Pre-Operational Performance Assessment and Pre-Operational Performance Report II. (MÉZŐ, BENEDÉK 2007; BENEDÉK et al. 2007, 2008a–c; MÉZŐ 2009; BENEDÉK 2009). In this paper only some selected results of the site-scale FeFlow and the site-scale FracMan models are presented.

Data Used

During the hydrogeological modelling process answers or estimates have had to be given in response to several questions for which different data could have been used. The aims of the modelling process and the questions given for the models could be divided into two major groups:
- site-specific tasks (for example site-scale models, estimation of fracture parameters, migration pathways, location of barrier zones, etc.);
- tasks connected with the construction of the repository (examining elements of the EBS—Engineered Barrier System, development of gallery- and repository-scale models, etc.).

For the first group of tasks the results coming from borehole and EDZ (Excavation Damaged Zone) measurements and calculations (transmissivity) carried out by the experts of Golder Associates Hungary Ltd. (MOLNÁR et al. 2003a–h, 2006b; ÁCS et al. 2003a–d) and borehole television (BHTV) measurements carried out in boreholes by Geo-Log Ltd. (SZÖNGOTH, GÁLSA 2003) were considered.

The borehole radar measurements carried out by the Hungarian Geophysical Institute at the Bátáapáti Site were also taken into consideration (PRÓNAY 2003). The
determination and hydrogeochemical interpretation of water sample compositions coming from the boreholes were carried out by Horváth et al. (2003) and Szőcs et al. (2006). For the interpretation of volumes between boreholes the interference tests carried out by Golder were also considered (Bradley et al. 2000; Ács et al. 2003b–d; Beneke et al. 2003c; Molnár et al. 2006a). The results of the surface seismic reflection measurements were summarised by Prónay et al. (2003). The results of measurements and other explorations carried out within the sub-surface geological exploration and their interpretations were published by Molnos et al. (2006) and Balla et al. (2007).

For the modelling of the second group of tasks a very limited amount of site-specific data was available as the construction of the investigated engineered elements is to be carried out after the modelling process. This means that the primary objective of these hydrogeological modelling tasks was to provide information on the optimisation of the engineered barrier system. Consequently, the hydrogeological modelling was always about developing all versions of the model with reasonable parameter intervals (for the hydraulic conductivity, for example, Beneke, Dankó 2009). Most of the models within this group of tasks were so-called generic models where the main goal was to understand the hydrogeological behaviour of the system, and therefore they had a lot of simplifications.

**Conceptual Model**

The hydrogeological (or hydrostratigraphical) units of a model are subunits of a rock domain in which different hydraulic parameters can be considered as constant. It is important to note that hydrogeological units do not necessarily coincide with geological units: a hydrogeological unit may involve several geological units and vice versa. This feature is an attribute of the site studied. The understanding and detailed description of hydrogeological units and their parameter space—all of these together are the conceptual model—determine the flow system, consequently they strongly influence the validity and certainty of the model predictions. The conceptual model presented here is summarised by Beneke et al. (2009).

The interference tests carried out in several boreholes (Bradley et al. 2000, Ács et al. 2003 a–c) and the results of the monitoring system operating at the site (Beneke et al. 2003b) indicate that the rock domain studied can be divided into several hydraulic compartments with very limited hydraulic communication (Balla et al. 2003 and Figure 3). However, based on field observations, inside individual compartments the hydraulic connections and responses to water pumping are very strong and fast at the scale of some hundred metres (Beneke et al. 2003b). Based on the data available from the site the flow system is compartmentalised at two different scales:

- small-scale (1–5 m) hydraulic head scattering appearing inside the hydraulic compartments (Beneke, Mező 2005);
- larger-scale (5–25 m) hydraulic jumps observed exclusively at the interface of two different, hydraulically isolated compartments (see later).

Three different sources can be made responsible for the recharge of compartments (Figure 3):

- flow through the so-called sealing features (faults);
- precipitation;
- overflow over the top elevation of a sealing feature in case the water level in the upgradient compartment is higher than this elevation.

On the other hand, there are two different ways to discharge compartments:

- minimal flow through the sealing features;
- overflow over the top elevation of a sealing feature; this process may result in the elevation of sealing features determining the maximum water level or hydraulic head inside a compartment;
- discharge at the surface.

![Figure 3. Hydrogeologic concept for the Bátaapáti Site](3. abra. A bátaapáti kutatási területi elvi vízföldtani modellje)
At the boundary of different compartments with limited hydraulic communication boreholes penetrated strongly tectonised, sheared fault zones (sealing zones) with intense mineral alteration and formation of clay minerals (BALLA et al. 2003). The total penetrated thickness of these boundary zones is 2–20 m, but it is important to note that they are often built up from several parallel zones (TÓTH et al. 2003). However the extent of these zones is unknown. Only on the basis of some hydrogeological observations can several hundred metres or even some kilometres be estimated for their extent. The recent tectonic interpretation of the site assumes a lateral strike-slip origin for these zones (BALLA et al. 2007). Based on the results of former hydrogeological models (TÓTH et al. 2003) it is highly probable that the large-scale hydraulic jumps observed along the head profiles of individual boreholes can be related to these zones of very low hydraulic conductivity ($1 \times 10^{-12}$ m/s). Another basic field observation was that inside individual compartments the hydraulic head estimated is almost uniform with very small scattering (ÁCS et al. 2003a–c).

Field studies have indicated that the general frequency of hydraulically separated compartments is higher in the southern part of the site (south of the Zoltán Fault), but in the north a relatively large, uniform block can be assumed (Figure 4). BALLA et al. (2003), BENEDEK et al. (2003c) and BENEDIK, MEZŐ (2005) have presented the list of individual compartments and their boundaries on the basis of different studies and interpretations. The position of potential sealing features has been published by MEZŐ, BENEDIK (2007) by using hydrogeological observations and modelling results. Figure 4 displays the sealing features on the site map by applying available data until December 2009 (MEZŐ 2009). The name of the most important sealing zones is also presented in Figure 4 after MAROS (2008), TÓTH et al. (2003) suggested on the basis of some hydrogeological models that large-scale hydraulic head jumps might be related to the presence of sealing zones also in the weathered granite. Otherwise—since groundwater level is mostly located in the zone of weathered granite—upgradient compartments could provide continuous recharge into the downgradient compartment through the weathered granite, equalising the head in both compartments.

Based on field measurements and observations, within hydraulic compartments highly and less transmissive zones can be distinguished (MEZŐ 2009; BENEDEK 2009). The lessons learned during the excavation of underground tunnels refer to the non-heterogeneous character of the granite studied and highly transmissive features are concentrated along zones, but less transmissive rock domains between them. The location of observed and suspected zones is displayed in Figure 4.

Based on the conceptual model applied at the site (Figure 3) three different hydrogeological units can be distinguished in the saturated zone:
- weathered granite;
- fractured granite;
- sealing features (faults).

The Significance of the Conceptual Model

Former models (before 2006) did not consider the significant compartmentalisation of the Site and the effect of the E–W striking barrier zones. Under such conditions—according to the knowledge of that time and despite the fact that the calibration of the model was adequate—all the flow paths ran towards Bátapáti in NNW direction (MEZŐ, MOLNÁR 2003a). All this means that a properly calibrated model does not necessarily provide reasonable results, close to the reality.

The uncertainty arising from the spatial limitation of available information—according to the present knowledge—can be significantly reduced if an integrated conceptual model can be developed, which does not contradict the pieces of information, observations available from the site, and at the same time which reproduces the geological and hydrogeological phenomena known to exist at the site. MEZŐ and BENEDIK (2007) developed a hydrogeological model based on the conceptual model introduced earlier in the text, which—at least adequately for the site—reproduces the conditions of the groundwater flow system in its primary (without intrusion) state relatively well. BENEDIK et al. (2008c)—based on the information coming from tunneling—modified this hydrogeological model and declared that on the knowledge level available at that time it was impossible to develop a single hydrogeological model without contradictions. The spatial distribution of the static (primary) hydraulic heads could be reproduced with an adequately low margin of error by four, very different versions of the model. The authors came to the conclusion that based on the geological and hydrogeological knowledge level of that time there was not a single model version, which could have been proclaimed to be more reliable than the others if only the agreement of static heads was investigated during model calibration. Decreasing the number of potential model versions was thought to be possible only if further (mainly time-dependent, transient hydrogeological) pieces of information were considered.

The conceptual model described in the previous chapter shows very good agreement with most of the hydrogeological observations. Nonetheless, it is worth mentioning that there is not enough information to define most of the barrier zones deterministically. The location, extent, hydrogeological parameters and the connection between barriers and highly conductive features is not yet known. Most of the information is available for the part of the site which has been explored by boreholes and which has been presented in detail by earlier hydrogeological reports. These pieces of information, appended by the experiences of the tunneling driving activities, have always been included in the model if it was possible.

Within the framework of the Bátapáti (Üveghuta) exploration—in contrast with the approach described in the international literature—significantly different conceptual models of the same value were not developed but rather the
concept and work hypothesis described in previous chapters were tested with different mathematical tools. The investigation of the conceptual model with such—geomathematical—methods was described by Beneke et al. (2008b). It is worth emphasising that during these tasks only the hydrogeological conceptual model was investigated.

During the investigation of the conceptual model it could be stated that the hydraulic head is the only one among the investigated parameters based on which the individual blocks separate from each other and at the same time, regarding the other parameters investigated, no significant differences could be observed between the blocks. This is also true for transmissivity and this means that it is not the
variability of hydraulic conductivity within the blocks that causes the compartmentalisation of the flow system. One of the important conclusions of the comparison of the individual hydrogeological blocks was that no spatial trends could be identified based on the investigated parameters.

**Hydrogeological Modelling**

*Scale-dependent Behaviour of Hydrogeological Data*

After the elaboration and testing of the conceptual model the available site-specific hydrogeological data have been analysed.

The different, yet complementary approaches (FeFlow and FracMan) employed throughout the modelling process need to involve similar hydrogeological properties, such as hydraulic conductivity/transmissivity and porosity/aperture. However, based on international experience, one can observe that the usability of hydrogeological data depends on the scale of the observations. A typical example is the observation of discontinuities within rock mass at several scales. Discontinuities can be studied at the scale of thin sections, excavations and seismic sections. At the scale of thin sections one can observe only small fissures; a thin section would never provide information about fractures with length of several metres or faults with length of several hundreds of metres. The same applies for larger scales, since microscopic fissures cannot be observed by visual perception due to the limited resolution of human eyes. However, the integration of data at different scales could provide essential information about the behaviour of the whole system. The present work demonstrates the scale-dependent behaviour of two datasets, namely the length of fractures and the transmissivity; however, the same principle applies for other kinds of data, e.g. orientation, frequency, aperture and spatial pattern.

For the analysis of the distribution of fracture lengths the following datasets were used:

- geological and tectonics documentation of the trenches A1 and A2 (BALLA et al. 2003; GYALOG et al. 2003);
- borehole radar measurements (PRONAY 2003);
- data of 2D seismic survey (PRONAY et al. 2003);
- geological and geotechnical observations in the access tunnels (MOLNOS et al. 2006).

On the basis of the above data the complementary cumulative density function of fracture trace lengths was constructed in order to compare the observation with data available from different sources (BENEDEK, MEZO 2005). The distribution functions were normalised by the extent of the observation, so the data of different scales could be comparable (see Figure 5). Figure 5 shows a good match of data observed in the access tunnels with those observed in trenches A1 and A2 and with data of different geophysical (borehole radar, seismic) surveys. The goodness of match is defined by the similarity of the slope of the cumulative density functions. It is visible that the normalisation makes fractures of different scales comparable and the dots representing several cumulative density functions fit to a well defined straight line. One can observe, however, that every function deviates from a straight line towards small lengths.

![Figure 5](image-url)  
Figure 5. Complementary cumulative distribution function of trace lengths of different sources

*5. ábra. A különböző léptékben rendelkezésre álló töréshosszadatok kiegészítő kumulatív relatív gyakorisága*
and large scales. This effect is called censoring; it is the result of erroneous size estimation, for example fractures of smaller length than those which can be observed at the given resolution are under-represented and, the size of fractures larger than the extent of observation cannot be determined. The statistical properties of the fracture size distribution can be determined by the slope of the middle, straight line, section of the cumulative density functions. Since the cumulative density functions are plotted on log-log axes, the fracture sizes follow a power law distribution over several magnitudes. The power law distribution suggests that within a distinct rock mass one can observe relatively few large fractures, while the smaller the size of fractures, the larger the frequency expected.

The hydraulic conductivity or transmissivity of the granite at the Bátaapáti Site could be determined from three different sources:

— single-hole hydraulic tests conducted in boreholes drilled from the surface or from the access tunnels (BALLA et al. 2003; BALLA et al. 2007);
— hydraulic tests conducted in boreholes drilled in a fan-like pattern in order to study the hydraulic and mechanical behaviour of the excavation damaged zone (EDZ) near the wall of access tunnels (MOLNÁR et al. 2006b);
— cross-hole hydraulic tests conducted in boreholes drilled from the surface (BRADLEY et al. 2000; ÁCS et al. 2003b–d).

Evaluation of these hydraulic tests provided estimates of transmissivity of the host rock. Transmissivity is a scale-dependent property for several reasons: 1) transmissivity is, by definition, directly proportional to the length of the open interval of the borehole; 2) the longer the duration of the test, the greater the probability that a large-transmissivity fracture affects the pressure history; 3) single-hole tests involve a relatively small volume of rock while data from cross-hole tests are representative of larger rock volumes.

The cumulative density distribution functions of the transmissivities estimated from the three types of hydraulic tests are shown in Figure 6. The most interesting of these is the distribution of the data from EDZ boreholes, which looks bimodal. At larger values \( T > 1 \times 10^{-9} \text{ m}^2/\text{s} \) the data for EDZ boreholes fit well the data for single well tests when the data are normalised by the length of the open section, that is hydraulic conductivities are compared (MEZŐ, BENEDÉK 2007). At smaller values \( T < 1 \times 10^{-9} \text{ m}^2/\text{s} \) the deviation of the functions is remarkable. The deviation may be explained when the difference of the length of the open intervals in the different types of tests is considered: the length of the packed off interval in the surface boreholes was about 10 m, while in the case of EDZ holes the packed off interval was 0.5–1 m long. The lower mode of the distribution of EDZ data is representative of the transmissivity of the intact rock matrix \( T = 1 \times 10^{-12} - 1 \times 10^{-9} \text{ m}^2/\text{s} \) while the transmissivity of the connective fracture network is represented by the range of \( T = 1 \times 10^{-9} - 1 \times 10^{-5} \text{ m}^2/\text{s} \). The data of cross-hole tests however are representative of large fractures with the length of several hundreds of metres \( T = 1 \times 10^{-7} - 1 \times 10^{-5} \text{ m}^2/\text{s} \). The analysis of scale-dependent behaviour provided a good means of

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**Figure 6.** Comparison of measured and modelled transmissivity distributions for single well EDZ and packer interval length of 10 m

Also transmissivity values estimated from interference tests are displayed.
construction of a conceptual model of the fracture network within individual hydrogeological compartments (Bene européenne et al. 2009). According to the conceptual model the major hydraulic processes within each compartment depend on the network of large-size fractures with large transmissivity. The small-size fractures as well as the rock matrix play a minor role in hydraulic processes; however, in the present understanding, they have significant effect in transport processes due to the large volume they represent. The large-size features constitute a hydraulic framework for the rock mass and, due to their high transmissivity, hydraulic heads are equalised even over a distance of several hundreds of metres (as confirmed by field observations).

The two examples described above reveal the problem of scale-dependent behaviour of hydraulic properties of rocks, i.e. observations on one scale cannot provide enough information about the behaviour of the whole system. On the other hand, analysis of data available on multiple scales provides some insight into the problem of upscaling of model parameters.

The next chapters provide a comparative description of the construction of the site-scale models using different approaches such as FeFlow and FracMan.

**Boundary Conditions**

Boundary conditions have a major effect on the result of groundwater models. Boundary conditions link groundwater models of specified geometry to the “external world” or, if applicable, to larger-scale models. When constructing generic models the boundary conditions applied are also generic, since the purpose of these kinds of models is mainly to study the performance of some specific element of a system with simplified boundary conditions. However, for the case of site-specific models the boundaries of the modelled domain are defined by actual geographical or hydrological entities (e.g. valleys, streams), therefore auxiliary information for defining boundary conditions were used.

For the cases of far-field and site-scale modelling the lateral and bottom boundaries were considered as no-flow boundaries (Bene européenne et al. 2008a–c; Mező 2009; Bene européen et al. 2009), in a conservative way. The vertices of the lines of surface streams within and along the model boundaries were specified as nodes of prescribed head. The models were extended to the groundwater table therefore the intensity of net recharge through the upper boundary had to be specified; its value was 25 mm/year (Balla et al. 2003). In the valleys of surface streams the infiltration and evaportranspiration was considered to be in equilibrium, i.e. the net flux is zero. In the FeFlow model a maximum flux boundary constraint equal to zero was employed, i.e. the prescribed head boundary conditions were kept only in nodes where the surface streams discharge the groundwater (the iterative check of water balance and automatic adjustment of boundary conditions is a built-in feature of FeFlow).

The modelling of the effect of tunnel excavation was a specific task during modelling (Bene européen et al. 2008c; Mező 2009). In this case internal subsurface boundary conditions were employed. The inflow to the inclines was modelled by prescribed head nodes with head values varying in time. The elevation of the axes of the tunnels was provided by underground survey and these values were applied as prescribed heads at the nodes of the model. These boundary conditions were applied from the instant when the tunnel face actually reached that node. For this kind of boundary condition time-varying boundary constraints were applied, that is the rate of the inflow to the tunnels in each node was limited in time. The flow rate in each node was prescribed as zero before the excavation of the tunnels reached that node; after that time the constraint was released. FeFlow solves this problem by an iterative process, i.e. the water budget of a node is checked against the prescribed constraint and the type of boundary condition is adjusted if necessary. Another boundary constraint was also applied for the underground boundary conditions along the tunnels: the outflow from the tunnel to the groundwater was set to zero.

**The Geometry of Models**

The different approaches employed by the two modelling software packages result in different model construction. FeFlow employs a deterministic continuum approach with contiguous three-dimensional elements having deterministic model parameters. Conversely, FracMan employs the concept of a discrete fracture network where the fractures are represented by two-dimensional elements, which only contact each other at the lines of intersection. The fracture elements can have stochastic model parameters. These features indicate that the two different modelling approaches involve different model geometry and parameter allocation.

It is important to note that the same conceptual model underlie both modelling approaches. The conceptual model consists of the following major hydrogeological units: 1) weathered granite; 2) sealing features; 3) fractured rock mass within each compartment.

The weathered granite was only considered in the FeFlow model; its thickness was about 20 m.

The sealing features and highly transmissive zones were represented in the FeFlow and FracMan models as shown in Figure 4. The location of the sealing features could be determined at their intersection by boreholes or tunnels (Figure 7, a). However, away from the actual intersections the determination of the geometry of the sealing features can be highly uncertain. Keeping this fact in mind for the former FracMan-based model the geometrical properties of the sealing features were estimated, such as orientation, size, frequency, spatial pattern (Bene européen et al. 2008a). On the other hand, as the exploration progressed, the rock volume investigated and modelled tends to be focused on a single compartment, which involves the site of the repository. Thus parametrisation of sealing features could have been neglected.

In the FeFlow-based model the fracture network inside each compartment is represented by equivalent continuum
and the compartments are bounded by sealing features. In the FracMan approach networks of discrete fractures were generated inside each compartment bounded by sealing features, but highly and less transmissive zones were handled separately. The statistical properties of the fracture network subject to stochastic generation are listed in Table 1.

**Table 1. Statistical properties of the fracture network within compartments (BENEDEK 2009)**

<table>
<thead>
<tr>
<th>Fracture orientation</th>
<th>random sampling in highly and less transmissive zones based on borehole televiewer data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fracture shape</td>
<td>rectangles;</td>
</tr>
<tr>
<td>Fracture size</td>
<td>power law distribution $X_0 = 0.2; D = 3.26$</td>
</tr>
<tr>
<td>Fracture intensity</td>
<td>volumetric intensity $P_{vol}$ (m$^3$/m$^3$) = 12</td>
</tr>
<tr>
<td>Spatial pattern</td>
<td>parallel application of modified Bucher model (Poisson distribution), and exponential model</td>
</tr>
</tbody>
</table>

**Figure 7.** Spatial distribution of hydraulic conductivity (FeFlow model) and transmissivity (FracMan model) 
a) FeFlow model—hydraulic conductivity distribution in the modelled volume, sealing features are indicated by thin orange lines in the central part of the figure;  
b) FracMan model—spatial distribution of fractures in one realisation, the model extension covers only the compartment involving the repository;

**7. ábra.** FeFlow- és FracMan-modell térbeli szivár-gasıtényező-, illetve transzmisszivitáseloszlása 
a) FeFlow-modell — a vízvezető képesség eloszlása a modellezett térőrészken belül, a törlesztő-szigetelő szerkezetek vékony csikokként jelennek meg a központi naranccsára mezőben;  
b) FracMan-modell — egy adott realizációban megjelenő törésök térbeli elhelyezkedése, a modell kiterjedése a tárolórendszer magába foglaló vízföldtani blokkot fed le
Hydraulic Parameters

For the models the following hydraulic parameters were defined: hydraulic conductivity and specific storativity for the continuum models (FeFlow), and transmissivity and storativity for DFN models (FracMan).

For the sealing features in FeFlow-based models the hydraulic conductivity was set to $1 \times 10^{-12}$ m/s. Note that no field measurements for this property are available; however, previous modelling studies (Tóth et al. 2003) concluded that the remarkable drops of hydraulic head observed in boreholes could be reproduced using that value.

A major challenge for modelling was to determine the equivalent hydraulic conductivity of the fractured rock masses inside compartments using the numerous data of the hydraulic tests conducted in boreholes. During early phases of the site characterisation the value of $1 \times 10^{-8}$ m/s was used (Tóth et al. 2003), which is close to the geometric mean of the individual observations (Balla et al. 2004). However, recent studies (Mező, Beneđek 2007; Mező 2009; Beneđek 2009) conclude that this value is an underestimate. Groundwater models constructed on the basis of the conceptual model described above resulted in significant hydraulic gradients when using $1 \times 10^{-9}$ m/s as equivalent hydraulic conductivity. This is in contradiction of the field observations since, for example, the hydraulic heads observed in boreholes Úh–2 and Úh–43 (for location, see Figure 4) are almost equal when their distance is about 500 m. The authors determined an optimum value for the hydraulic conductivity by inverse modelling until the calculated heads matched the observed values. The lowest value of hydraulic conductivity was equal to $1 \times 10^{-9}$ m/s when the hydraulic gradient was as low as the observed value. Another theoretical problem arises when using mean values of field observations, namely the scale-dependent behaviour of the hydraulic conductivity indicated by field measurements carried out at different scales, i.e. the larger the scale of the tests the higher the transmissivity estimated (see Figure 6). This observation indicates that at larger scales (at the scale of compartments) the hydraulic processes are dominated by large-size conductive features while smaller-scale features with lower conductivity play major role in local transport processes. Beneđek (2009) constructed fracture network models on the basis of the relationship between the conductivity and the scale in order to upscale the conductivity. The model calculations resulted in equivalent conductivity for the rock mass inside compartments between $1 \times 10^{-4}$ and $1 \times 10^{-7}$ m/s within less transmissive zones, but between $1 \times 10^{-4}$ and $1 \times 10^{-7}$ m/s in highly transmissive zones. In the most recent FeFlow model the values of $2 \times 10^{-4}$ and $2 \times 10^{-7}$ m/s were applied. Beneđek et al. (2008c) estimated a value of $1 \times 10^{-4}$ m/s for the hydraulic conductivity of the granite on the basis of model calibration against inflow rate measured in the access tunnels. The value of specific storativity was $1 \times 10^{-5}$ l/m, which was estimated by model calibration (Beneđek et al. 2007; Beneđek et al. 2008c).

The fracture network model did not need to be upscaled. On the basis of the field observations a relationship between the conductivity and the scale was constructed, which was used to estimate the transmissivity of individual fractures. The relationship between the fracture size and transmissivity was a power function such as published by Dershowitz et al. (2003). During modelling the parameters of the power function were changed until a good agreement between the distribution functions of the observed and modelled transmissivities was reached (see Figure 6). The storativity of the individual fractures was $1 \times 10^{-3}$, which was estimated by evaluation of the North-western Cross-hole Hydraulic Test.

The transmissivity of the sealing features was estimated as $1 \times 10^{-10}$ m/s in the DFN models. The models were constructed such that the fractures inside individual compartments cannot intersect the sealing features therefore between two compartments hydraulic connection could only exist through the sealing features.

The spatial distribution of the hydraulic parameters for the FeFlow and FracMan models is shown in Figure 7.

Results, Further Investigation Possibilities

It is important to note that it was not a primary goal during modelling to reproduce the field observations as accurately as possible with the hydrogeological models since this would have required the models to be exaggeratedly detailed. During modelling the main purpose was to reproduce and to understand the processes taking place in the groundwater flow system, which are important from the aspect of performance assessment.

The important results of the site-scale and far-field hydrogeological modelling can be summarised as below:

— By using the conceptual model both the FeFlow and the FracMan models were able to reproduce most of the hydrogeological characteristics of the Bátaapáti Site.

— The models developed could reproduce very well the characteristics observed in the hydraulic potential field of the site: 1) significant head jumps through the barrier zones; 2) almost uniform hydraulic heads within the individual hydrogeological blocks. Naturally, the results of the FeFlow model appear only as deterministic whereas the FracMan results are stochastic (Figure 8). The vertical hydraulic gradient calculated by the models along the boreholes shows very good agreement with the field observations.

— Based on the results of transient modelling (interference test) only parts of the observation boreholes showed responses, thus they were in the same hydrogeological block as the source zone. The effects of the hundreds of metres of depressions in the environment of the source zones could not be detected in observation sections separated by barrier zones and response was shown only by intervals which had the same hydraulic head as the source zone.

— The migration pathways and surface discharge points
are determined basically by the spatial location of the barrier zones. All this means that the investigation of the location of the barrier zone is of primary importance in assessing where the potential surface discharge points may be located.

The conceptual model used is adequate not just to model permanent hydrogeological observations but it also proved to be appropriate for reproducing transient processes (interference tests, modelling the depression caused by the access tunnels, Figure 9). At the same time the modelling results for these transient processes cast light on the problem that a very limited amount of information is available on the precise location of the barrier zones and that the reliability of this information steeply decreases further away from the explored areas (boreholes, tunnels, etc.).

It is important to note that these results are related to the hydraulics of the site. However, one of the most important goals of the site investigation is to understand and to characterise the transport of the contaminants released from the repository. It is not sufficient to properly interpret and to model hydraulics, but special underground field experiments have to be carried out to understand transport processes. In the frame of the Bátaapáti exploration

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**Figure 8.** Hydraulic heads calculated by FeFlow and FracMan along borehole Üh–27

More realisations of FracMan approach are displayed

8. ábra. A FeFlow- és FracMan-modellel számított hidraulikus potenciálok az Üh–27 fúrásban

A FracMan modell esetében több realizáció eredményével

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**Figure 9.** Time series of measured and calculated hydraulic heads in the monitoring intervals of borehole Üh–37

The effect of depression could have been detected in several boreholes just after the penetration of Péter Fault (Figure 4).

9. ábra. A hidraulikus potenciál mért és számított értékei időbeli alakulása az Üh–37 észlelőkút meghúzásával

A fúrásban csak akkor jelent meg a lejtősaknák depressziós hatása, amikor azok harántolták a Péter-törést (4. ábra)
numerous field and laboratory studies have been completed to investigate transport processes. The tracer experiment carried out between boreholes Bm–3 and Bm–4 can be considered as one of the most important among these studies. In the frame of this study tracer was injected into one borehole, but water extraction was implemented in the other borehole. The results and the interpretations of the tracer study were summarised by MOLNÁR et al. (2008).

To interpret field measurements several analytical and numerical methods have been considered. Although these methods are different in many ways, all of them indicated that simple advective-dispersive transport is not able to reproduce field data. The tracer experiment investigated the transport of very conservative tracers, but the long tail of the breakthrough curves is not in accordance with this simple transport mechanism. The GoldSim approach assumes matrix diffusion as an important delay mechanism, but the FracMan results refer to the existence of immobile zones along the main pathways. The later interpretation is supported by the extensive fracturing of the host rock.

It is important to note, that the international literature considers the extrapolation of tracer experiment results in space and time as a “hot spot”. Most of the tracer studies are carried out at the scale of some 10 m’s in a few months, but performance assessment investigates a particular site at the scale of some kilometres and some thousand years. The answer to the scale problem at the Bátaapáti Site is not known yet, but available information at different time and spatial scale has to be integrated to have an idea about the future behaviour of the site (Figure 10). In addition, additional field and laboratory studies have to be conducted to investigate transport processes: tracer experiments focusing on the same rock volume with different hydraulic boundary conditions (hydraulic gradient); tracer studies on rock volumes of different hydraulic character (hydraulic conductance).

Further areas for investigation can be outlined based on the modelling results as follows:

— Considering the results coming from the site-scale FracMan and the far-field FeFlow models it is worth developing a semi-deterministic, semi-stochastic model, which can contain most of the features identified or assumed at the site (FeFlow model) and less studied areas can be covered by stochastic methods (FracMan).

— The field observations and the results of hydrogeological modelling lead to the conclusion that the conceptual hydrogeological model used for the site works very well but there is very limited information available for the possible transport processes and for the conceptual model regarding the transport. Based on this it is considered that it is worth giving more attention to the transport processes in the future and also that the results of tracer tests have to be incorporated into the existing hydrogeological models. Based on these investigations estimates can be made.

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**Figure 10.** Spatial and time scale of available transport data from the Bátaapáti Site

10. ábra. A kutatási területről rendelkezésre álló transzportadatok tér- és időléptéke
for such parameters (aperture, dispersivity, matrix diffusion, ratio between mobile and immobile zones, etc.) for which data coming from the literature or expert opinion have been used so far.

It is worth emphasising that the hydrogeological models are not yet final. New data, assessments, observations originating from the underground construction activities may significantly affect the understanding regarding the hydrogeological conditions of the Bátaapáti Site. These results will have to be implemented into future models. Updating the models in the future is necessary.

Summary

During the construction and operation period and after the final closure of a geological repository where low- and intermediate-level radioactive wastes (LILW) are disposed of questions arise to which answers can only be given by reliable hydrogeological model(s). A few of those questions are how much water flows into the chambers and tunnels, what the evolution of the depression caused by the operation of the repository looks like in time, how much time is needed for full re-saturation after closure, and after closing the chambers by what migration pathways the contaminants will reach the biosphere in how much time and with what level of activity.

Within the framework of the Pre-Construction Performance Assessment numerous models were developed based on different approaches and at different scales to answer several questions (BENEDEK et al. 2007; BENEDEK et al. 2008a, b, c; MEZŐ 2009; BENEDEK 2009). The models can be grouped depending on what sort of questions they are trying to answer: 1) site-specific tasks; 2) tasks connected with the construction of the repository. Within this article only some details of the models developed to carry out site-specific tasks were presented.

Before developing a hydrogeological model it is of highest importance to understand as well as possible the hydrogeological behaviour of the site in order to be able to give reliable predictions. Based on international experience the uncertainty of the conceptual model can be just as high as the uncertainty in the values of parameters of the model. Based on the measurements, observations and interpretations of the Bátaapáti Site a conceptual model was developed, which adequately describes the hydrogeological characteristics of the site on the current knowledge level. The conceptual model was tested by independent—geomathematical—tools confirming the model developed based on geological and hydrogeological phenomena.

Based on the conceptual model the site-scale and the far-field models were developed. During the modelling process two approaches were used which are significantly different but which complement each other: 1) deterministic continuum approach (FeFlow); 2) stochastic discrete fracture network approach (FracMan). The geometrical and hydrogeological parameterisation and the problems (scale dependency, scaling) which had to be solved to achieve reliable results were presented in this article for both approaches. The results achieved by the two different approaches confirmed the conceptual model since they were successfully used not just to reproduce the static conditions but also transient processes. The results coming from both approaches indicated that the barrier zones found in the area have major significance for the flow system of the Site but, at the same time, the available information for the geometrical and hydrogeological parameterisation of these features is very limited.

The authors’ view is that the main directions of further advances can be determined as follows: 1) development of a semi-deterministic, semi-stochastic model; 2) detailed investigation of the transport processes by field measurements and by modelling.

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