Numerical simulation of borehole tests in fractured rock at Potůčky-Podlesí site

O. Severýn, J. Maryška, J. Královcová, M. Hokr
Department of Modelling of Processes, Technical University of Liberec, Hálkova 6, 461 17 Liberec 1, Czech Republic. E-mail (corresponding author): otto.severyn@tul.cz

ABSTRACT: A new approach for numerical modelling of processes in hard rock bodies is introduced in the first part of the article. This approach uses a multidimensional technique for representation of the geological reality. The FEM is used for approximation of the linear Darcy’s flow. The second part of the article describes an application of the new approach for simulation of the water pressure tests in the site Potůčky-Podlesí.

1. Introduction

Numerical simulations of groundwater flow, contaminant transport and other processes in hard rock massifs are a challenging problem for scientists for more than thirty years. Despite their effort, number of published papers and permanently growing computational strength of computers, there is still a lot of open problems and opportunities for further research.

There are three main approaches for the numerical modelling of the processes in fractured rock, as they were defined in Bear, 1993: Equivalent porous media, double porosity and discrete fracture networks. Neither of them is universally applicable for all types of problems that can be encountered and each of them has limitations of its usage. Even more, the experiences gained by modelling of various localities proved, that every numerical model should be tailored for specific conditions of that particular locality. Therefore a development of own simulation codes suited for given purpose/locality is meaningful.

Research team of Technical University of Liberec has developed a simulation system for fractured rock environment based on the discrete fracture network approach during the years 2000-2002, see Severýn, 2002. The system was used for simulation of real-world problems connected with the research on the Potůčky site. Although it was able to solve some problems, it could not be used for all desired tasks. Because of that, development of a new simulation system has begun in 2003.

2. Simulation of the processes in compact rock by multidimensional meshes
The models based on the (stochastic) discrete fracture network approach are the most accurate representation of the real fractured rock massif. However, their computational demands are very high, even for present-days computers. The main conceptual problem of these models is the fact that most of the time and computer's memory is used to calculate the physical quantities of small fractures. These small fractures can be described only statistically and their locations and dimensions are chosen arbitrarily, only to satisfy the given statistical properties. They are, therefore, referred to as stochastic fractures. On the other hand, the user of the simulation system is usually interested only in the global results and in the data on the large known fractures. In a typical compact rock massif we can localize only up to tens of such fractures. These, so-called deterministic fractures, conduct most of the groundwater. However, the small fractures cannot be excluded from the calculation because of their high total volume. This volume is significant for transport processes because it creates a huge storativity for the mass.

From the above we can conclude that a meaningful solution of the problem of computational costs is this: Use the discrete fracture network approach only for the deterministic fractures, homogenise the stochastic ones and replace them by blocks of physically equivalent porous media. This leads to the idea of a simulation system, in which the equations describing the processes (flow, transport, reactions and others) are solved on the multidimensional domain. Such a domain consists of 3D blocks of porous media, 2D polygons in the space representing the fractures, and 1D line segments representing the hydraulically significant intersections of the large fractures. If we discretise the multidimensional domain to the computational mesh, we obtain a so-called combined mesh. The mathematical formulation of the problem on the multidimensional domain and its approximation by numerical methods (FEM, FVM) is possible without any serious problems, due to previous works done by the authors in this field (Maryška et. al, 2000, 2005). That is the reason why it was possible to use the existing models during the implementation of the new one.

A very important fact that had to be considered is the complex, irregular geometry of the geological objects, especially the fracture systems. We had to cancel the condition of the compatibility (or conformity) of the mesh between elements of different dimensions. This condition requires the element of the lower dimension to respect the
boundaries of the element of higher dimension. An example of the compatible and non-compatible connection of elements is presented in the Fig. 1.

Fig.1: Compatible and non-compatible connection of elements.

Requiring conformity of the mesh would lead to unsolvable problems at the stage of mesh generation. Present-day topological algorithms are unable to fill the space with spatial elements respecting the already present planar elements. On the other hand, if there is no condition of conformity, we can generate all three meshes (1D, 2D and 3D) separately, the intersections being calculated only at the end. The only constraint is to keep approximately the same discretisation parameter for all three meshes to avoid situations shown in the Fig. 2. In that case, there would be much faster mass exchange between the elements than in reality.

Fig. 2: Unsuitable way of the non-compatible connection of elements.

There was one question that had to be solved, which was the formulation of the problem in the case of a nonconforming connection of the elements. Eventually, the formulation was found. Using the Mixed-hybrid FEM, there is an explicit equation of mass conservation and the neighbourhood between the elements can be specified arbitrarily. More mathematical details are described in Maryška et. al., 2005. The flux
between elements of different dimensions is proportional to the pressure gradient. The coefficient of proportionality depends on the size of the intersection of the elements.

We have implemented a numerical model of steady Dary's flow based on the above-presented ideas. This model was extended to be able to solve also the unsteady case. Finally, the model of advective mass transport was produced.

The models were tested on benchmark problems. After the debugging of the models on the benchmark problems was completed, the simulation of the real-world problems was started.

3. Simulation of the problems at the Potůčky-Podlesí locality.

The Potůčky-Podlesí locality (Fig. 3) is a site, where an intensive research of the hard rock environment is performed since 2000. Three boreholes of the depth approximately 300m were drilled into a compact granitoid body in close neighbourhood. The field measurements were very extensive; they included among others: geologic, hydrogeologic, mineralogical research, core logging, borehole logging, geochemistry, research of the fractures, etc.

Fig. 3: Situation of the locality.
One of the most important measurements were the water pressure tests (WPT). Their principle is shown in the Fig. 4. Water was injected into small part of one drillhole, isolated by packers. The water consumption and pressure responses on the other drillholes were monitored. An example of the results of the tests is shown in the Fig. 5 and 6. More details on the research in the Potůčky site can be found in Rukavičková et al., 2005.

![Fig 4: Water pressure test.](image1)

![Fig 5: Results of the water pressure test – pressure and water consumption.](image2)

**Water Pressure Test.**
Drillhole PTP-4a, depth 71.40 - 95.70 m
3.1. Simulation of the water pressure tests on the fracture mesh.

The simulation was performed for three field measurements: WPT40, WPT36 and WPT35. There were two domains used for the simulation, with the same ground plan. The dimensions of the domains were 30 × 30 m. The domains were located in such a way that each well was at least 10 m from the border. The depths were 40 – 65 m for the first domain and 65 – 95 m for the second one. In these domains, the fracture meshes were generated by the generator, according to the information about the orientation and frequency of the fractures from the drilling. After generation, the meshes were adjusted and corrected. One of the meshes with the position of the drillholes is shown in the Fig. 7.
The calculation simulated the (approximately) steady period of the test, where the pressure and amount of injected water can be considered as constant. The results of one of these calculations are shown in Fig. 8. The models were calibrated by the data obtained during the tests. The calibration variable was the permeability of the environment. The agreement between the model and the experiments was about 20%, after calibration.
3.2. Simulation of the tests with equivalent porous media

It was not possible to simulate a larger domain around the wells by the fracture meshes due to computational costs. Therefore, we have used the above-mentioned results obtained in the fracture network as the inputs for the model based on the equivalent porous media approach. The mesh for this simulation is plotted in the Fig. 9. The shape of the rectangular circular segment was chosen to make the prescription of the boundary conditions easier. The calculated shape of the field of the piezometric head during the test is presented in the Fig. 10. The agreement between the simulation and the results of the experiments is approximately the same as in the previous case.
Fig 9: Ground plan of the mesh for the simulation of WPT with equivalent porous media approach.

Fig 10: Field of piezometric head during WPT.

4. Conclusion

The tools for simulating the processes in compact rock massifs were developed within the scope of executing the project. These tools are based on the combined meshes approach. The unique feature of this approach is the possibility of non-compatible connection of the elements, which makes mesh generation much easier.

The water pressure tests were simulated by discrete fracture networks and by equivalent porous media approaches. In both cases it was necessary to perform the calibration of the models. The calibrated quantity in the model was the hydraulic
permeability of the environment. After the calibration the results produced by the models differ from the measurements less than 10%, which can be treated as a good agreement in this type of problems. For numerical evaluation of the quality of the model we used the pressures in the observation drillholes.

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References


