Modelling of tunnel inflow with coupled 3D groundwater and 2D surface flow concept

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Abstract In this paper we deal with water flow in the vicinity of the water supply tunnel. Motivation for solving this problem is the understanding of flow and solute transport processes in fractured granite considered as the host rock for geological disposal of nuclear waste, considering the tunnel as "industrial analogue". We solve the problem as a coupled problem of groundwater and surface water flow, by means of 3D-2D-1D (multidimensional) geometry. The problem is solved in a program Flow123D, which is developed at the Technical University of Liberec. As the result we evaluate mainly the tunnel inflow, which depends on equivalent hydraulic conductivity and water level related to precipitation variations. From measurements of aggregate inflow in the tunnel parts, we estimate the rock hydraulic conductivity which is in agreement with the literature data of conductivity depth-variability of granites. The temporal variability of inflow could not be currently satisfactorily explained, the reason can be the fracture system without defined water level.

Keywords groundwater; surface water; tunnel; Bedrichov; multidimensional concept

INTRODUCTION

In this paper we deal with modelling of coupled problem of surface water flow and groundwater flow in a vicinity of a supply tunnel near Bedrichov in Jizera Mountains in the northeast of the Czech Republic. Knowledge of coupled processes in the rock becomes essential for solution rock engineering problems. These processes affect behaviour and characteristics of the rock.

Motivation for solving this problem is connected with simulation of thermo-hydro-mechano-chemical (THMC) processes for the purpose of analysis of deep repositories and safe disposal of spent nuclear waste related to Decovalex project. Connection with the tunnel is in similar characteristics of natural conditions of the site. Similar tunnels in similar rock massifs should be in deep repositories too.

We consider two essential variants of the model: 2D cross section model with the tunnel and 3D model of Bedrichov site. 2D model is intended for hydraulic conductivity estimation of tunnel parts with constant average tunnel depth. The first simplified 3D version is not multidimensional (basic variant, Fig.1, left) and it gives a basic estimation of hydraulic conductivity (only with the tunnel). The second multidimensional variant (3D-2D-1D, Fig.1, right) is much more complicated and it is solved in two variants: model without the tunnel (due to verification of the correct model functions) and using information obtained from the first variant we solve the second one: a model with the tunnel.

We test different refinements of the tunnel vicinity mesh with regard to requirements of accuracy. In addition we compare model inflows simulated in our basic variant of 3D model (using an estimation of equivalent hydraulic conductivity from 2D model) with inflows from 2D model.

GOVERNING EQUATIONS AND NUMERICAL SOLUTION

We solve coupled problem of surface water flow and groundwater flow like a potential flow in a domain which is a combination of different dimensions, so called multidimensional model (Sembera *et al.*, 2008). Solved problem is defined like Darcy’s law and continuity equation (Bear, 1993):

$$\vec{u}_i = -K_i \nabla p_i \qquad \text{in } \Omega_i, \quad i = 1,2,3 \tag{1}$$

$$\kappa_i \frac{\partial p_i}{\partial t} - \nabla \cdot \vec{u}_i = q_i \qquad \text{in } \Omega_i, \quad i = 1,2,3, \tag{2}$$

where $\vec{u}_i$ (m s^{-1}) is the vector of velocity of the flow, K_i (m s^{-1}) is the second order tensor of hydraulic conductivity, p_i (m) is hydraulic head, κ_i (m^{-1}) is specific storativity, q_i (s^{-1}) is a function expressing the density of sources or sinks of the fluid and t (s) is time.

We consider first-type boundary conditions – parts of a boundary with prescribed hydraulic head or second-type boundary conditions – parts of a boundary with prescribed flow.

Numerical implementation of the problem is based on mixed-hybrid formulation of finite element method, (Severyn *et al.*, 2008) and it is solved in a program Flow123D, which is developed at the Technical University of Liberec.

Multidimensional model is based on different element types included in discretization: 3D elements for rock equivalent continuum, 2D surface elements for equivalent of surface and shallow subsurface flow (with the rainfall as the source), 1D elements for rivers. Model of potential flow is an empirical replace of physical equations of surface water flow. We consider potential flow as sufficient replace in light of accuracy.

MODEL OF THE BEDRICHOV SITE

The tunnel is situated in the granite massif near Bedrichov in the northeast of the Czech Republic. The tunnel is engaged as a water supply tunnel for near city Liberec. The length of the considered part A of the tunnel is 2600 m, its diameter is 3.6 m and it is situated on the average 100 m below ground level. Size of the model is approximately 5250 × 6007 × 400 m, (Klominsky, 2005).

Characteristics of 2D model

The 2D model is a rectangle vertical cross section (500 × 300 m, 1 m thickness) with a circle hole representing the tunnel (diameter is 1.8 m) with variable tunnel depth between 10 and 200 m. We want to obtain hydraulic conductivity of tunnel parts depending on tunnel depth. Boundary conditions are the following: bottom side – no flow, vertical sides and top side – prescribed hydrostatic pressure and tunnel surface – zero pressure.

Characteristics of 3D models

The 3D model geometry consists of volumes which top is not flat but they have a triangulation on the top representing terrain shape. The triangle side length is about

100 m. Smaller triangles occur near rivers and reservoir bank. The tunnel is represented as a regular dodecahedral prism inside the main geometry.

Material properties and boundary condition for 3D model (Fig. 1, left):

- Material properties:
  - 3D: different model variants with different *K* (Tab.1)
- Boundary conditions:
  - Vertical sides (symmetry planes) and bottom part: no-flow boundary condition
  - Reservoir: value of the piezometric head (water level)
  - Top surface of 3D model: zero pressure (water level on the surface)
  - Tunnel surface: zero pressure (contact with atmospheric pressure)

Material properties and boundary conditions for 3D-2D-1D model with and without the tunnel (Fig.1, right):

- Material properties (extract from tests):
  - 3D: $K = 5.5 \times 10^{-3}$ m day^{-1}
  - 2D: $K = 5.5 \times 10^{2}$ m day^{-1}
  - 1D: $\mathrm{K} = 9.5 \times 10^{3}$ m day^{-1}
- Boundary conditions:
  - Vertical sides (symmetry planes) and bottom part: no-flow boundary condition
  - Reservoir: value of the piezometric head (water level)
  - Tunnel surface: zero presssure (model with the tunnel)
  - 2D triangles on the top of the model: sources (representing rainfall, 3.3×10^{-3} m^{3} m^{-2}day^{-1} = 1204.5 mm year^{-1})
  - Ends of the rivers (inside the model): no-flow
  - Ends of the rivers (model boundary): zero pressure

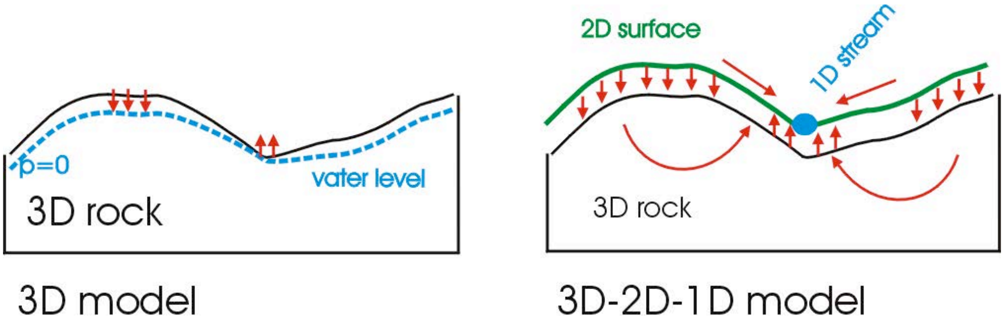

Fig. 1 Schematic representation of 3D model and multidimensional model consists of 1D, 2D and 3D elements.

Discretization

Multidimensional model discretization is made by tetrahedrons, triangles and lines. It is needed the finer discretization in the small tunnel vicinity (Fig.2) but it produces some problems due to model proportions. The tunnel diameter is too small in comparison to the model height. And in addition the tunnel is near the top surface in some cases, so the refinement is not simple.

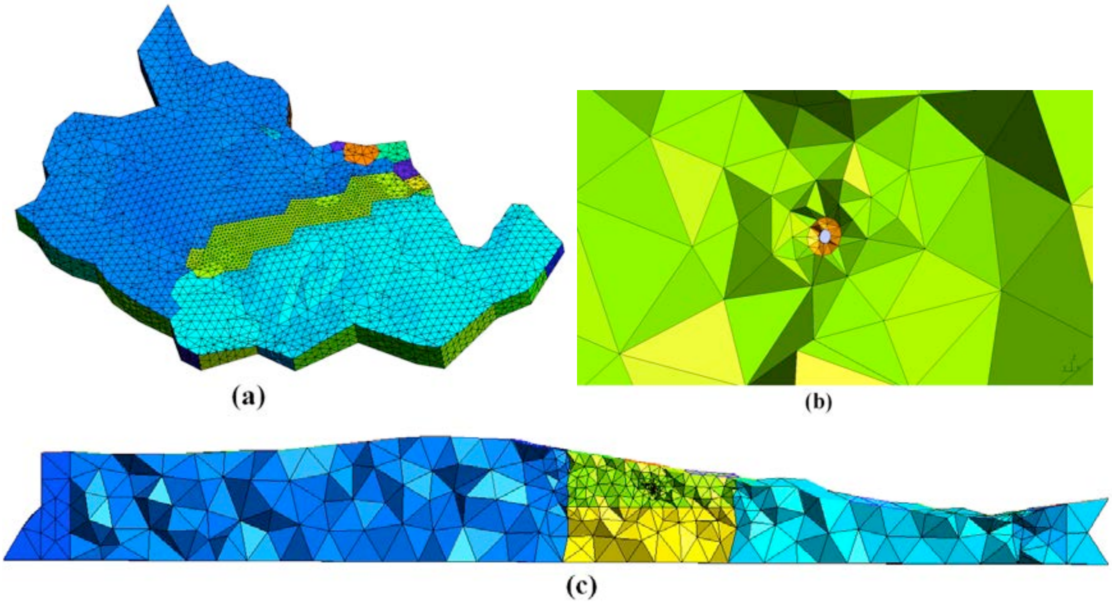

Fig. 2 (a) Discretization of the 3D model with the tunnel, (b) detail of the model discretization cross section, (c) cross section of the model discretization.

MODEL RESULTS AND CONCLUSIONS

2D model

2D model estimated hydraulic conductivity of tunnel parts. Hydraulic conductivity of the beginning and the end parts of the tunnel reaches lower values than middle tunnel parts (Tab.1). These results correspond with reality – hydraulic conductivity is lower in domains with lower values of the depth.

Tab. 1 Hydraulic conductivity estimation of 2D model for the parts with constant tunnel depth.

Position (m)	Flux (m^3 day m^{-1})	Hydraulic conductivity (m s^{-1})	Depth (m)
150	7.258×10^{-1}	1.866×10^{-2}	20
885	1.411×10^{-2}	9.677×10^{-5}	108.4
1995	1.012×10^{-2}	7.880×10^{-5}	92.9
2424	3.424×10^{-2}	4.933×10^{-4}	45.3
2600	8.100×10^{-1}	1.372×10^{-2}	35

3D model – basic variant, comparison 2D and 3D model tunnel inflows

Tab. 2 shows comparison of tunnel inflows of 2D model and 3D basic variant. Hydraulic conductivity is set for the whole model in 3D but inflows are evaluated only for considered tunnel part. So we need five 3D models – one model for every tunnel part. It is obvious that inflows values are similar, variations are about 20 %. Difference is given by the fact that tunnel depth is not constant in the whole considered tunnel part in 3D model. This table also proves that there are lower values of tunnel inflows in the middle parts of the tunnel.

Tab. 2 Comparison of tunnel inflows for 2D and 3D models.

Compared tunnel parts (m)	Hydraulic conductivity (whole model) (m day^{-1})	Tunnel inflows for 3D model for consider tunnel part (m^3 day^{-1} m^{-1})	Tunnel inflow for 2D model (m^3 day^{-1} m^{-1})	Absolute value of differences between 2D and 3D inflow (m^3 day^{-1} m^{-1})	Differences between 2D and 3D inflow (%)
150	1.866×10^{-2}	8.965×10^{-1}	7.258×10^{-1}	1.707×10^{-1}	19.04
885	9.677×10^{-5}	1.196×10^{-2}	1.411×10^{-2}	2.146×10^{-3}	17.94
1995	7.880×10^{-5}	1.052×10^{-2}	1.012×10^{-2}	3.962×10^{-3}	3.77
2424	4.933×10^{-4}	4.872×10^{-2}	3.424×10^{-2}	1.448×10^{-2}	29.73
2600	3.266×10^{-2}	2.357×10^{0}	8.100×10^{-1}	18.002×10^{-2}	18.18

3D multidimensional models

3D multidimensional model (Fig. 3) shows pressure levels corresponding with reality. But these types of models are complicated because of the model sensitivity to hydraulic conductivity of 1D and 2D elements.

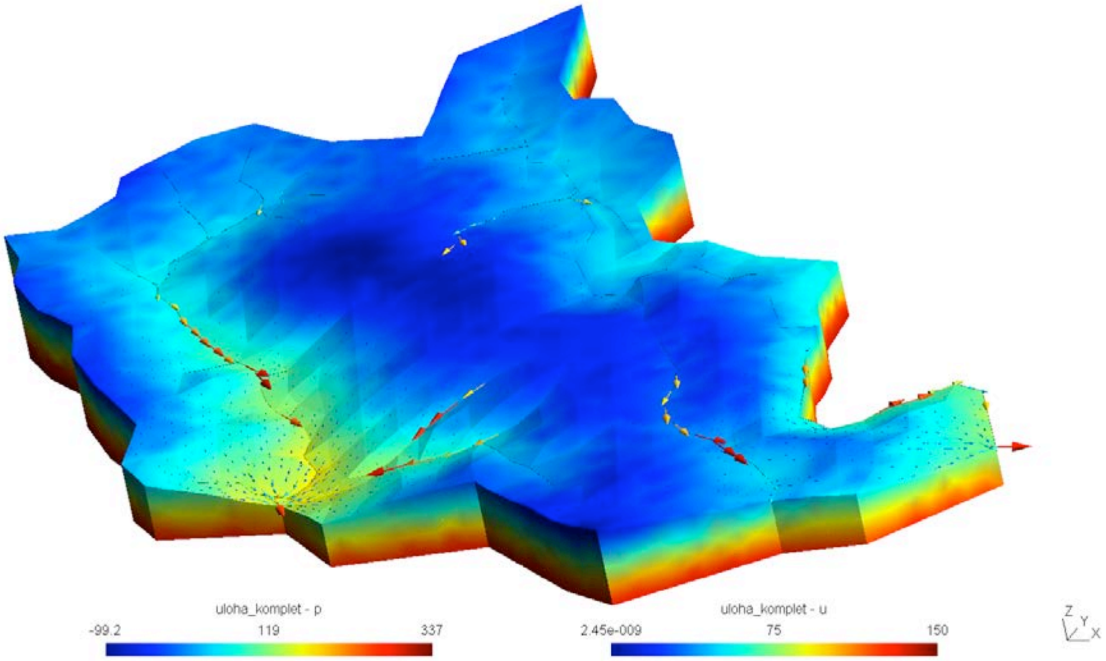

Fig. 3 Pressure distribution with fluxes in the rivers on the surface.

Conclusions

Hydraulic conductivity of rock equivalent continuum was estimated in 2D cross section model. These values are used in 3D models for comparison 2D and 3D tunnel inflows which values are similar.

Multidimensional models shows that water flows according to realistic idea: a part of water flow from hills to valleys, a part soaks into the rock and then water springs at the foot of the hills. These models are very sensitive to hydraulic conductivity of 1D and 2D elements and this fact implicate problems with piezometric head. Because the models are still in process it is necessary to do changes by the reason of better and realistic functionality.

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