Groundwater Modeling for Mining and Underground Construction - Challenges and Solutions

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Abstract

Modeling groundwater flow, solute and heat transport for mine sites and underground constructions such as tunnels or caverns has very specific requirements concerning the workflow for model set-up and the physical processes involved. Geometrical complexity arising from steeply inclined geological structures and fractured systems together with the geometrical constraints imposed by artificial structures like tunnels, caverns, stopes, and excavations challenge the modeller and modeling software. Moreover, many physical processes not relevant to classic groundwater models for water management purposes have to be considered. In particular, these may include unsaturated flow and transport, fracture flow, density effects, chemical reactions, or time-varying behavior of material properties such as conductivity or porosity.

We will present a three-dimensional simulation of cavern construction in hard rock for liquefied natural gas storage. The model involves variably saturated conditions, density-dependent flow (saltwater intrusion), and highly transient behavior of boundary conditions as well as material properties. It serves to illustrate theoretical aspects and practical strategies to achieve reliable simulation results while keeping the modeling effort (and thus costs) within reasonable limits.

Introduction

Quite typically, mining and mined cavern scenarios involve processes beyond those expressed by Darcy flow and the standard advection-dispersion transport approach. Artificial structures may act as a parallel underground flow system, possibly subject to channel- or pipe-type flow. If significant, the geometry of these features needs to be discretized and embedded in the spatial mesh. Even if all flow may be reasonably described by the standard (Darcy) approach, the requirements posed by a sufficient geometric description of a mine or underground storage including all relevant installations will likely make a finite-element mesh with its flexible element size the more practical choice over a rigid, rectangular finite-difference grid.

Many underground excavation applications involve variable saturation which introduces nonlinearity in the flow equation in that both the hydraulic conductivity, K, and the storage capacity depend, via saturation, s, on the pressure-head solution, □. Assuming a stagnant air phase at constant atmospheric pressure everywhere, the equation of continuity with the Darcy law takes the special form of the Richards equation

$$\{Porosity\}\frac{\partial s(\psi)}{\partial\{Time\}} + \nabla\cdot\left[K(s)\left(\nabla\psi + \nabla\{Elevation\}\right)\right] = \{Sources / Sinks\}$$

Proper modeling then rests on reasonable input for the empirical relationships describing the dependencies $s(\psi)$ and $K(s)$. If they are very nonlinear in themselves, particular numerical challenges arise that may, for example, manifest themselves as oscillations in the pressure solution, especially at infiltration fronts. Ideally, a time-step control mechanism will be able to dynamically reduce the time-step length as much as necessary or expand it as much as possible depending on the current state of simulation. The FEFLOW simulation system employs the deviation between a linear prediction and the actual result of a given time step as a practically useful measure of the current degree of nonlinearity.

Another potential source of nonlinearity is the dependency of liquid density, ρ, on temperature and solute concentration. If temperature and/or concentration gradients are sufficiently strong, the gravity term of the flow equation becomes dependent on the result of the heat and/or mass transport equation,

$$\{Fluid\ Flux\} = -K\left(\nabla\psi + \frac{\rho}{\rho_o}\nabla\{Elevation\}\right)$$

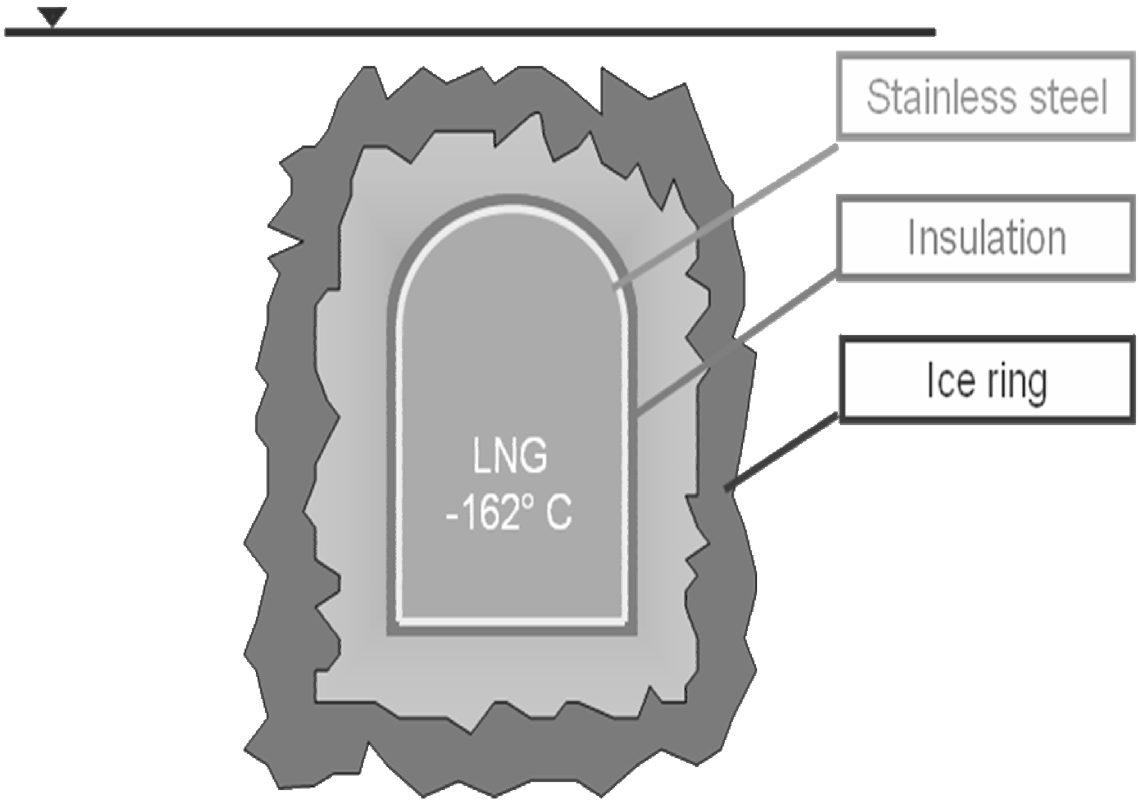
where ρ_o denotes the reference fluid density used to compute hydraulic conductivity from permeability and pressure head from pressure. With flow and transport equations thus coupled, physically instable flow situations can be described up to the limits imposed by the spatial resolution of the mesh. Again, the numerical challenges involved require an intelligent time-step control that is both sensitive and robust.

Simulations for cavern construction

Simulations have been carried out for the construction of innovative underground storage caverns for liquefied natural gas (LNG). For the proposed storage system, caverns are excavated in fissured hard rock (granite, gneiss). During the construction phase, the rock mass is drained to achieve dry conditions in order to proceed with the installation of the membrane ensuring gas tightness. The caverns are then lined with stainless steel plates and insulation panels. The storage is then filled with LNG at a temperature of -162°C. Consequently the rock mass starts freezing. The drainage system is turned off. An ice ring will form around the storage due to the rising water level and the low temperature, providing both mechanical stability and additional containment (Fig. 1).

In a first modeling study, the construction concept and schedule should be tested for the feasibility of complete rock drainage during the construction time and for the risk of increased saltwater intrusion from the nearby sea caused by the cone of depression. A site in South Korea was selected as an example location.

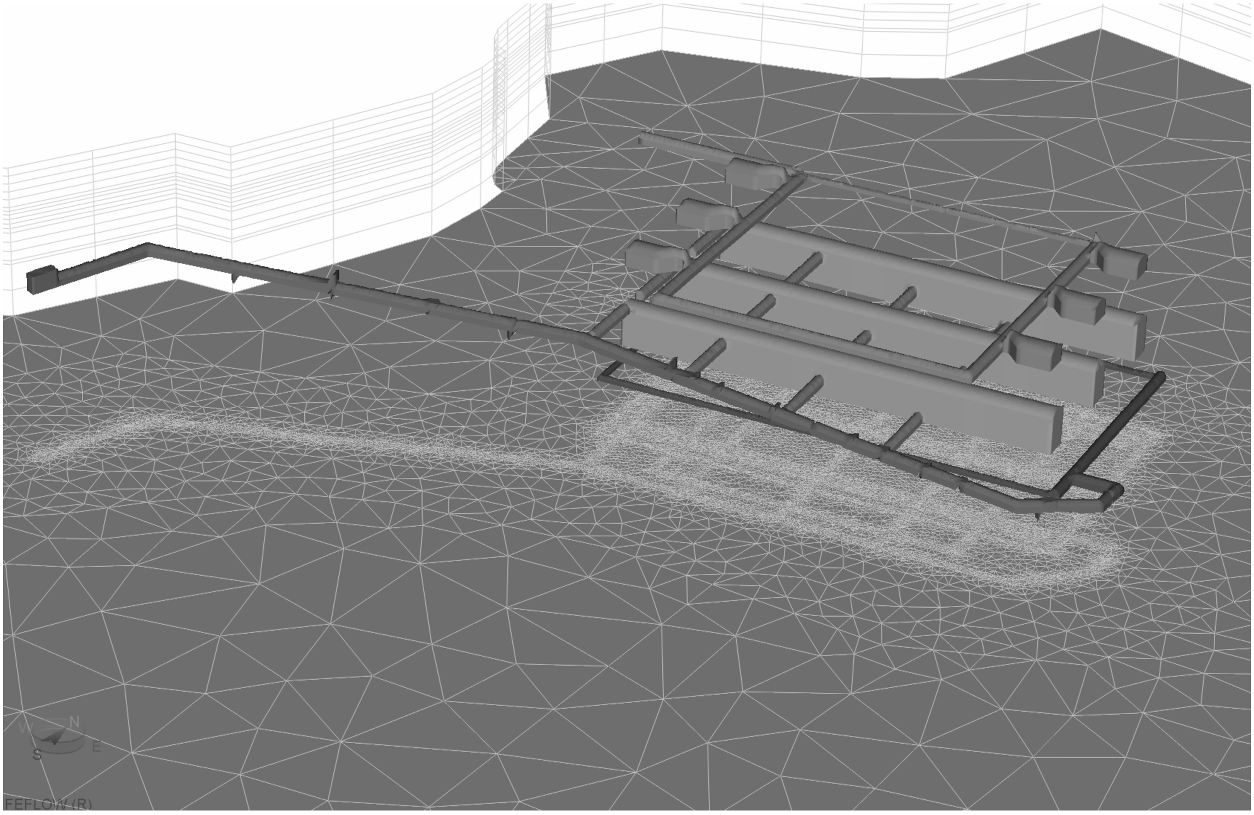
***Figure 1** Schematic cross section through an LNG storage cavern in operation*



Mesh geometry

The horizontal and vertical mesh geometry has been designed to sufficiently represent all parts of the underground construction. Also numerical requirements such as a sufficient vertical resolution for unsaturated flow simulation have to be met. As the FEFLOW simulation system is based on a layered approach for vertical discretization (prismatic elements), all 3D structures were mapped into layers. Thus an elaborate workflow for the data preparation is critical for a good result. For the model presented here, this involved a CAD system to handle and transform the original construction data, a GIS system to better deal with geographical reference, (scanned) raster data and attribute data, and the FEFLOW simulation system. Fig. 2 shows the cavern system as implemented in the final model.

Figure 2 *3D implementation of the cavern system in a layer-based groundwater model (FEFLOW)*



Boundary conditions

Given the modeling task of a four-year construction phase for the storage system, an efficient handling of changing boundary conditions was necessary. The FEFLOW simulation system allows arbitrary time curves for boundary conditions and constraint conditions. However, as the excavation progress had to be considered in two-week increments over the four years, a large number of separate curves would have to be individually defined. To greatly reduce manual data handling and to speed up future model setup, a separate software module has been developed for the open FEFLOW programming interface (IFM). This module is able to deal with extensive list data for groups of mesh nodes and time periods for boundary condition activation, ensuring an efficient workflow for this specific kind of problem.

For the drainage effect of the caverns, boreholes, and tunnels, Dirichlet boundary conditions were applied, using head values equal to the local elevation to impose a zero-pressure head condition. To prevent locally negative pressure-head values from causing artificial infiltration into the desaturated rock, so-called ‘constraint conditions’ limit the applicability of the boundary condition to positive pressure-head values, i.e., drainage. Similarly, constrained Dirichlet boundary conditions were used to describe the salt-water interface. Here, the applicability of a fixed seawater concentration for the transport equation was limited by the constraint to flow entering the model domain.

Material properties

In many mining and underground construction cases, transient material properties play a significant role to mimic the effects of the excavation progress. For example, long-wall coal mining involves backfilling of the mined zones with the excavation residues, which naturally changes the hydraulic properties in these zones. In a typical excavation or tunnel construction model, it can be useful to simulate the drainage effect of the excavated zones by Dirichlet boundary conditions with head values equal to node elevation all around the tunnel or cavern. In such a case it may be necessary to simulate the inner part of the structure with low permeability, thus avoiding artificial flow from the top boundary conditions to the bottom ones. This strategy was applied in the LNG storage model, lowering the hydraulic conductivity for each section after construction. The resulting complex spatial and temporal distribution of conductivity has been implemented as a transient material property in the simulation software.

Results

The entire construction phase was successfully simulated, simultaneously considering variable saturation and variable fluid density. Physically meaningful results obtained from numerically stable computations were deemed reliable. Execution times were kept practically acceptable, with a maximum of five days, by using efficient numerical techniques and parallel processing on multicore hardware.