Flooding of a generic salt mine – concept, processes and simulation of the post-closure phase

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Abstract

The prognosis of the temporal and spatial progression of the mine-water level is an important aspect in the flooding of complex underground cavern structures. Major issues of relevance are mechanical processes like convergence, and the mobilization, transport and retention of contaminants during and after flooding. The numerical simulation tool KAFKA is applied to investigate the processes involved in the flooding of a generic salt mine used for waste storage. KAFKA is particularly suitable for the simulation of multiphase flow and transport processes in underground structures over long time periods. It is a hydro-mechanical-chemical code capable of accounting for numerous chemical phenomena as well as convergence.

In the studied example, the release and transport of toxic contaminants is influenced by gas generation, the convergence of the mine and the physical, chemical and mechanical properties of both the host rock (i.e., the salt) and the backfill. The flooding process is mainly influenced by gas migration and entrapment, and the convergence of the mine.

Due to the flexibility offered by KAFKA for defining a simulation, a broad variety of problems associated with mining activities can be investigated. Modeling results illustrating possible future evolutions in open-pit mines, underground coal mines etc. may help to optimize preparatory measures for mine closure and the post-closure phase in order to best protect groundwater resources and the environment.

1 Introduction

The prognosis of the temporal and spatial progression of the mine-water level is an important aspect in the flooding of complex underground cavern structures. Major issues of relevance are mechanical processes like convergence, and the mobilization, transport and retention of contaminants during and after flooding. Chemical and physical effects (e.g. sorption and solubility, density-driven flow) during flooding need also to be considered. The investigation involves an evaluation of the succession and interdependency of individual processes and the definition of potential countermeasures to be taken based on the general system understanding.

The model-like presentation of processes relevant for the prognosis of a rising water level finds other applications as well, such as:

- The prognosis of the necessity for and potential optimization of water processing plants (duration of use, number of plants, contaminant specifics and location) taking into account geohydraulic, geomechanical and chemical conditions at the site
- The prognosis of consequences of potential intrusions into the underground structures by third parties (e.g. for dewatering, water lifting, energy recovery from the mine water) on the geohydraulic, geomechanical and geochemical conditions in the mine and, potentially, on the water processing
- Protection of groundwater and surface water

This paper uses the example of a generic salt mine to discuss the essential processes which need to be considered in flooding models.

2 The generic salt mine

The influence of the flooding on the flow and transport system of a salt mine was investigated using a simple generic salt mine (Fig. 1). This mine consists of four levels at which the mining activities resulted in large caverns (A1-E4). The caverns are connected horizontally via drifts. Vertically, there are two inside shafts connecting all levels. The three uppermost levels adjoin to the access shaft which was sealed between 170 m and 150 m depth after the abandonment of the mine. From cavern A4, a fracture zone of relatively high permeability defines a flow path to and from the overlying rock, i.e., the stratigraphic formation atop the mined formation.

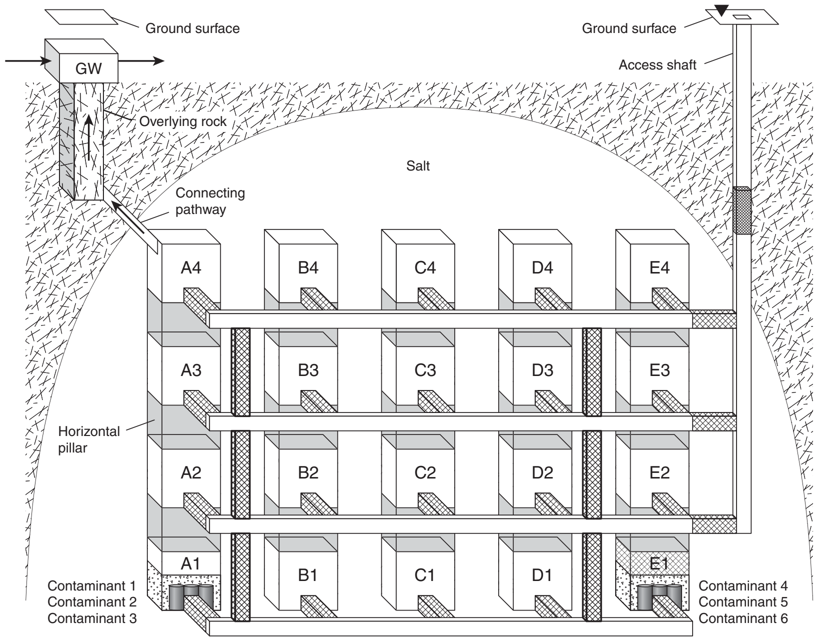

Fig. 1. Schematic representation of the underground salt mine

The transport of potentially toxic substances that are either remains of the mining processes or that have been stored in the mine since its closure is characterized by the distribution of the different contaminants. These contaminants are released from waste disposed of in cavern A1 (contaminant 1 to contaminant 3) and cavern E1 (contaminant 4 to contaminant 6). The differences among the contaminants are indicated in Table 1.

The drifts and shafts are backfilled with incompressible material. The caverns are open excavations without any filling except for caverns A1 and E1. Those two caverns contain incompressible waste material which fills approximately one third of the total pore space. While in A1 the rest of the volume remains open, cavern E1 is completely backfilled. The porosity of the compressible backfill in cavern E1 is 0.4. Initially, the water saturation throughout the mine is equal to the residual water saturation ($S_{l,res} = 0.1$).

In the given example, the following processes influence the flow and transport in the mine:

- Flooding of the mine
- Creeping of the salt
- Contaminant release (caverns A1 and E1)
- Gas production (caverns A1 and E1)

Table 1. Contaminants in the generic salt mine

Contaminant [a]	Location of release	Amount of contaminant	Remarks
Contaminant 1	Cavern A1	100’000 mol	-
Contaminant 2	Cavern A1	100’000 mol	Solubility limit: 1mol/m^3
Contaminant 3	Cavern A1	100’000 mol	Adsorbed on backfilled material and overlying rock: $k_d = 0.5\ m^3/kg$
Contaminant 4	Cavern E1	100’000 mol	-
Contaminant 5	Cavern E1	100’000 mol	Solubility limit: 1mol/m^3
Contaminant 6	Cavern E1	100’000 mol	Adsorbed on backfilled material and overlying rock: $k_d = 0.5\ m^3/kg$

[a] Contaminants 1 and 4, contaminants 2 and 5, and contaminants 3 and 6 are chemically the same.

3 Modeling the flow and transport system

The modeling of the flow and transport system of the mine was performed using the numerical code KAFKA (Schwarz et al. 2002, Poppei et al. 2004). Kafka is a hydro-mechanical-chemical coupled code that has been designed to calculate flow and transport processes in large and complex underground structures over long time periods. Kafka uses an original approach with a space discretization scheme that is based on a simplified geometric layout of the mine workings and that aims to minimize the number of elements. This discretization of the domain into finite volumes implies a geometric abstraction of the mine’s structure. In our concept we summarize the complex geometry of the excavated structures into four principal structural elements. These are (1) caverns, i.e. backfilled or open excavations with a high hydraulic conductivity, (2) drifts, i.e. man-made horizontal hydraulic connections with a distinct hydraulic conductivity and which may serve as hydraulic barriers, (3) shafts, i.e. man-made vertical hydraulic connections with a distinct hydraulic conductivity, and (4) horizontal pillars separating caverns located one upon the other, i.e. vertical flow paths with a hydraulic conductivity increased by stress conditions. Those structural elements are attributed specific properties with respect to hydraulic and chemical behavior. Caverns are, for example, treated as perfect mixing tanks while tunnels portray conventional two-phase flow behavior. The result is a "skeleton model" of the underground mine structures (Fig. 1). Kafka simulates fluid flow and contaminant transport in this skeleton model.

The following processes and couplings are considered in KAFKA:

- Two-phase flow
- Diffusion and dispersion
- Sorption and limited solubility of contaminants
- Radioactive decay
- Time-dependent gas generation due to corrosion and microbial degradation
- Dependency of pore volume (porosity) on convergence and creeping
- Dependency of flow and transport processes on varying permeability and cross-sections
- Dependency of pore volume on dissolution and precipitation
- Dependency of pressure on the chemical composition of the fluid.

The modeling approach of KAFKA is based on mass balances over each volume for the solution, the gas, and the liquid-phase component comprised of a solvent and a solute (density-relevant component). The numerical solution is derived from a finite-volume approximation. For each finite volume, the equation of mass balance is solved for all constituents, that is the contaminants, water, gas and salts subjected to dissolution. The processes described are (1) the volume change due to convergence and dissolution, and (2) the mass changes due to transport and chemical reactions. These changes impose modifications in dependent parameters, e.g. fluid pressure and density, which drive flow and transport.

The relative permeability relationships are parameterized by the Brooks-Corey model (Brooks and Corey 1964). The capillary pressure is taken into account in a simplified manner, i.e., through the threshold gas entry pressure. The representation of volume changes caused by convergence is based on the formulations in Storck et al. (1985).

4 Results

With the start of the simulation, the mine is gradually flooded. Figure 2 shows the temporal evolution of the water saturation for the four levels of the mine. Starting at the residual water saturation of 0.1, the water rises initially in the lowermost caverns at 300 m depth. After these caverns are completely flooded (water saturation $S_l = 1 - S_{l,res} = 0.9$), the next higher level begins to be filled with water and so on. As time passes, due to compression of the residual gas phase the water saturation in the different levels reaches values larger than 0.9. After approximately 40’000 years, in the uppermost caverns at 201 m depth the water saturation decreases as shown for the cavern B4. This is a result of the gas production in cavern E1. The gas migrates upwards through the roof rocks and the shafts and is captured mostly in the cavern E4 at the top level of the mine. Since the drifts that connect the caverns are located at the bottom of the caverns, horizontal gas flow can only occur if the water level inside a cavern falls below the ceiling of the drift. The lowermost water-saturation curve in Figure 2 illustrates that for cavern B4 (201 m depth), gas inflow from cavern C4 via the connecting drift starts at around 40’000 years and triggers a sharp decrease in water saturation. With the onset of gas outflow towards cavern A4, the water saturation in cavern B4 stabilizes at a value of 0.28.

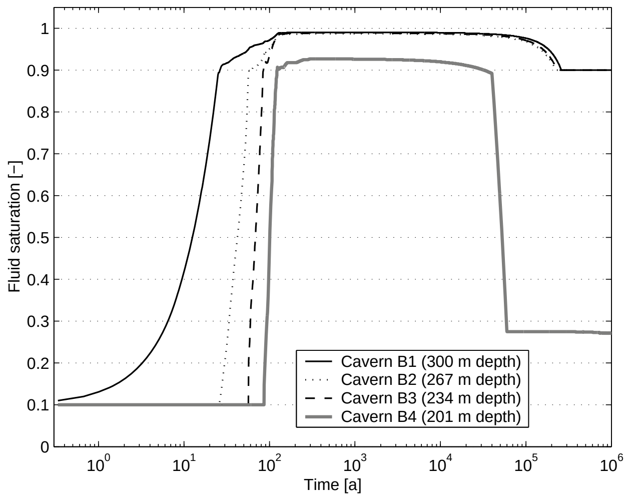

Fig. 2. Temporal evolution of the water saturation in the mine, exemplified with one cavern representing one mine level each (caverns B1 to B4)

The influence of the gas production in cavern A1 on the water saturation in the mine is significantly smaller than the impact of the gas production in cavern E1. In the case of cavern A1, the gas also rises up vertically to cavern A4. However, the connection to the overlying rock that is located at the top of cavern A4 prevents the entrapment of gas in this cavern and allows an immediate propagation of the gas towards the overlying rock.

The temporal evolution of the pore space in the mine is illustrated in Figure 3. After 1’000’000 years, the creeping of the salt has nearly closed the initially open caverns as is indicated in the very small pore volumes. Exceptions are caverns A1 and E1. There, the incompressible waste material counteracts the convergence, resulting in clearly larger pore volumes at the end of the simulation period.

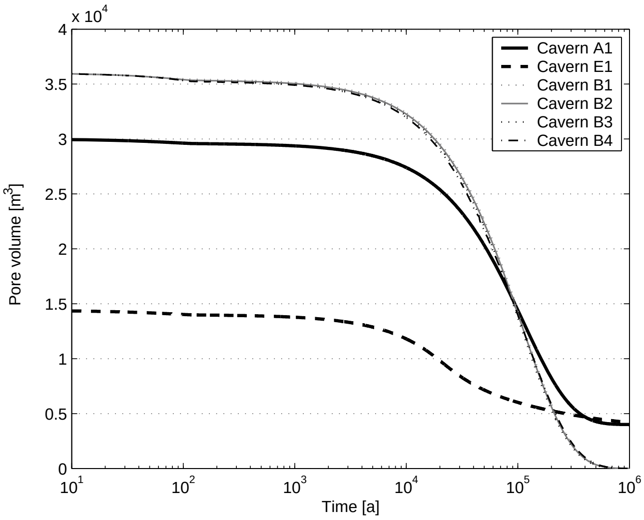

Fig. 3. Temporal evolution of the pore space in the mine, exemplified with the two caverns containing waste materials (cavern A1 and cavern E1) and one cavern representing one mine level each (caverns B1 to B4 = overlapping curves)

Figure 4 shows the contaminant flux from the overlying rock into a near-surface aquifer. For contaminant 1, the predominantly vertical transport from cavern A1 to cavern A4 and the flux of contaminated water from the mine into the overlying rock due to the convergence as well as the gas production cause a relatively fast increase of the contaminant flux after approximately 3’500 years.

For contaminant 1 the flux peaks after 150’000 years. Thereafter, the contaminant flux decreases with the decrease of the flux of contaminated water from the mine into the overlying rock (Fig. 5). Contaminant 2 that is solubility limited exhibits a similar temporal evolution of the flux but with a maximum value that is approximately five orders of magnitude smaller. For contaminant 3, the adsorption within the overlying rock prevents the onset of a significant flux into the near-surface aquifer.

Being released from cavern E1, the transport distance in the mine is greater for contaminants 4 to 6 as compared to that for contaminants 1 to 3. In addition, the gas entrapment in the uppermost caverns may restrict the fluid flow towards the connecting pathway to the overlying rock from cavern A4. Hence, the start of the contaminant outflow into the near-surface aquifer is delayed with respect to that of the contaminants released in cavern A1.

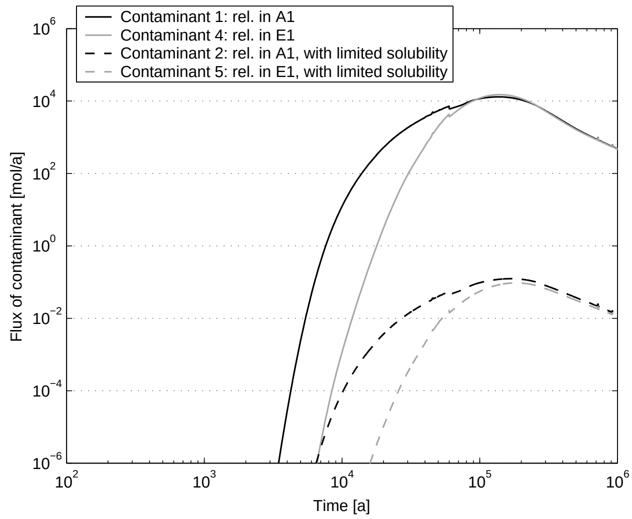

Fig. 4. Contaminant flux from the overlying rock into a near-surface aquifer for contaminants 1 and 2 (released from cavern A1) and contaminant 4 and 5 (released from cavern E1)

The maximum flux of contaminant 4 and 5 is comparable with that of contaminant 1 and 2, respectively. After reaching the maximum value, only very small differences exist in the further temporal evolution of the flux for the chemically identical contaminants 1 and 4 and contaminants 2 and 5. As well as for contaminant 3, the sorption within the overlying rock prevents a significant flux of contaminant 6 into the near-surface aquifer.

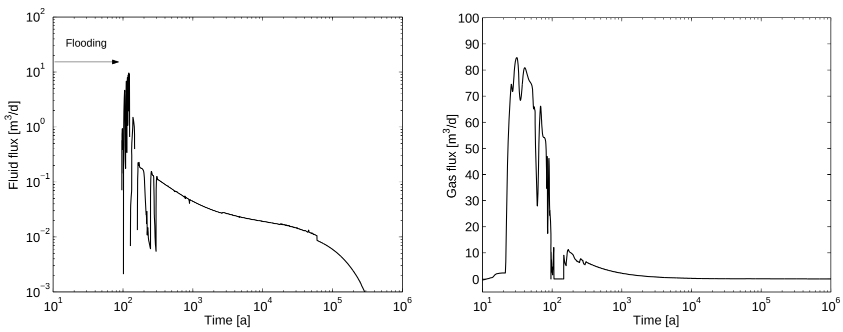

Fig. 5. Fluid flux and gas flux from the mine into the overlying rock via the connecting pathway

5 Conclusions

The behavior of the repository in terms of the release of toxic contaminants is influenced by gas generation, the convergence of the mine and the physical, chemical and mechanical properties of both the host rock (i.e., the salt) and the backfill. Other factors controlling the transport of toxic substances are chemical reactions like dissolution/precipitation of salts in contact with aqueous solutions. Although for the sake of simplicity such effects are not considered here, they can be easily incorporated in applications of the numerical code KAFKA.

The simulation tool KAFKA has been proven to provide an adequate representation of the complexity of processes involved in the flooding of the generic salt mine studied here. KAFKA allows for the fast assessment of the impact of technical measures planned to control the flooding process (especially the gas migration and entrapment) and the release of harmful substances from waste repositories.

In real-world applications a higher complexity of geometric conditions as well as the treatment of parameter uncertainties in a probabilistic manner can be integrated into the simulation approach with KAFKA.

Due to the flexibility offered by KAFKA for defining a simulation, a broad variety of problems associated with mining activities can be investigated. Examples may be post-closure processes in underground coal mines or groundwater-surface water interactions in open mines.

Finally, we have developed an easy-to-use post-processing viewer for KAFKA which greatly facilitates checking intermittent results in the course of calculations and interpreting the final results from complex numerical simulations.

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