A 3D Feflow Hydrogeological Uranium Underground Mine Model, France

Fabrice Compère[1], Guillaume Kern[2], Gaël Bellenfant[1]

[1]*BRGM, 3 av. Claude Guillemin, 45100 Orléans, France, f.compere@brgm.fr, g.bellenfant@brgm.fr*
[2]*ORANO, 2 rte Lavaugrasse, 87250 Bessines-sur-Gartempe, France, guillaume.kern@orano.group*

Abstract

A groundwater flow model was implemented to reproduce the complex hydrosystem behaviour of a remediated uranium mine to better control its environmental footprint. The geology was represented using a layered approach. The open pit, the underground galleries and the tailing storage area were integrated into the model through 3D unstructured finite elements. The model is based on unsaturated Richard's equations and includes interaction between groundwater and rivers. After an inversion procedure, the calibrated model successfully reproduces the observed water level fluctuations (piezometers and open pit).

Keywords: Mine, Hydrogeology, Model, 3D, Geometry

Introduction

During the mining operations, dewatering modifies hydrogeological conditions by lowering groundwater levels which consequently increases infiltration and seepage from the surface water network (Adams and Younger, 1997). When the pumping stops, the hydrogeological system rebalances itself but the remaining mining infrastructures can potentially alter definitely natural groundwater flow, leading to an aquifer with triple porosity (primary porosity of the rock and secondary porosity caused by mining-induced fracturing and mining voids), which can be called a 'mine aquifer' according to Wolkersdorfer (2008).

The main objective of this work is to improve the knowledge of the hydro system of a remediated uranium mine located in France to better control its environmental footprint. More specifically, the local effect on groundwater flow of an open pit mine and flooded underground galleries has been studied using a 3D groundwater model. Considering the necessity to include in a larger system detailed features as an open-pit, underground galleries and a storage area, the finite element method (Rapantova *et al.*, 2007) was selected as a numerical method. On the base of classical layered model, complex geometries were integrated inserting 3D unstructured mesh.

Description of the site

The former mining site (mean altitude of 250 m ASL) is located near the interfluve between two main rivers flooding at the North and the South. The source of two minor rivers is located next to the site, whose upstream part presents intermittent flow (fig. 1).

According to the stratiform conceptual model of hard rock aquifers (Lachassagne,

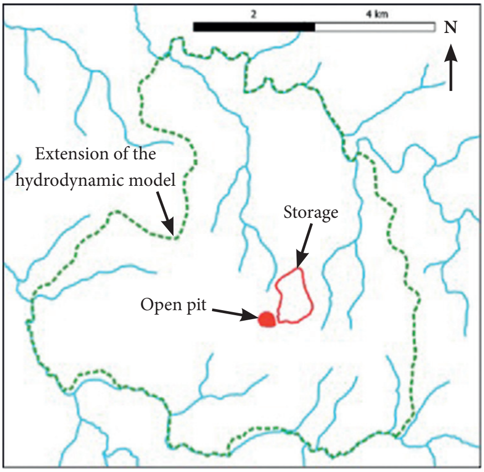

Figure 1 *Extension of the modelized area and rivers network.*

2014), the main geological unit consists of alterites (weathered cover with clay-rich material, with a local thickness from 4 m to 12 m) overlaying horizontally fissured granite (local thickness of 30 m) and a non-altered granite substratum.

The studied area hosts disseminated uranium deposits. Uranium orebodies occur as vertical episyenitic pipes: vuggy granites that resulted from quartz leaching. Nine main ore bodies were identified inclined from 45° to 90° of variable size, with circular horizontal sections ranging from 100 m^2 to 1500 m^2 with a vertical extension from tens of meters to more than 700 m.

Extraction began by open pit method (115 m deep), followed by underground works (maximal depth of 400 m) composed of galleries surrounding extraction zones. Tailings were managed in a dedicated tailing storage facility (TSF) built directly on alterites. The TSF (370 000 m2) includes peripheral and internal dams (made of mine tailings, waste rocks and alterites) which split the storage into 4 different cells (fig. 2).

Following the ending of the mine activity and therefore stopping pumping operations in 2001, the open pit and underground mine cavities are currently entirely flooded. Storage area was covered by a compacted waste rocks layer overlaid with an earth soil layer in 2001 to reduce, amongst other aims, direct infiltration of rainfall. Surface runoff, water percolating laterally through the peripheral dams (collected with surrounding trenches) and water collected from two drains located at the bottom of the storage (North limit), are directed towards various basins.

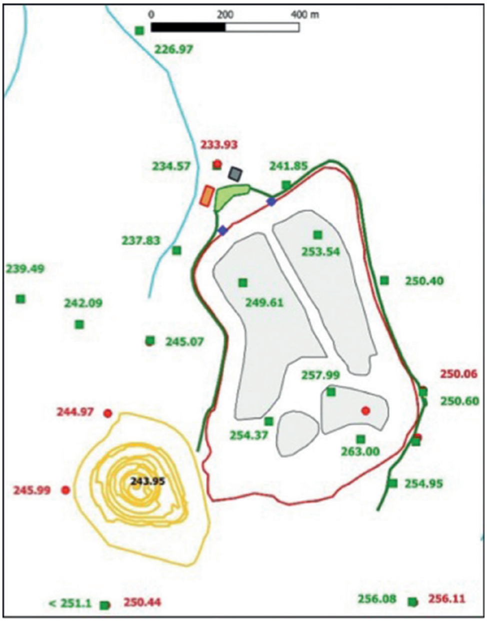

Figure 2 *Map of the site with open pit, storage area, piezometers and piezometric levels (march 2018).*

Hydrogeological context

Aquifers' hydrodynamical properties

Porosity of alterites and fissured granite is generally in the range between 2% and 8%; both formations present very different hydraulic conductivities, with low values for alterites (between 10^{-7} m/s and 5.10^{-6} m/s) and higher values for fissured granite (from 10^{-6} m/s to 5.10^{-3} m/s). Non-altered granite substratum presents very low hydraulic conductivity and storage capacity. Various pumping tests conducted at low flow-rate (about 1.5 m^3/h) on piezometers, allowed to estimate transmissivities from 10-7 m^2/s to a maximum of 2.10^{-5} m^2/s.

Piezometry

Twenty-two piezometers were implemented to monitor groundwater levels and six have been installed in the storage area to measure the water level in the dams and cells filled with tailings. Short piezometers intersect the base of alterites and the upper parts of the fissured granite while long piezometers intersect the lower part of the fissured granite and the top of the non-altered granite substratum.

Figure 2 illustrates piezometric levels measured in March of 2018. Except for the influence of the open-pit and the storage area, the main hydraulic gradient is oriented from the South to the North, following the topography. Highest groundwater levels at the south are close to the topographical limit separating two watersheds. Since 1993, water level series show very low amplitude for most of the piezometers, except those close to the open pit, influenced by the regular rise of the water table.

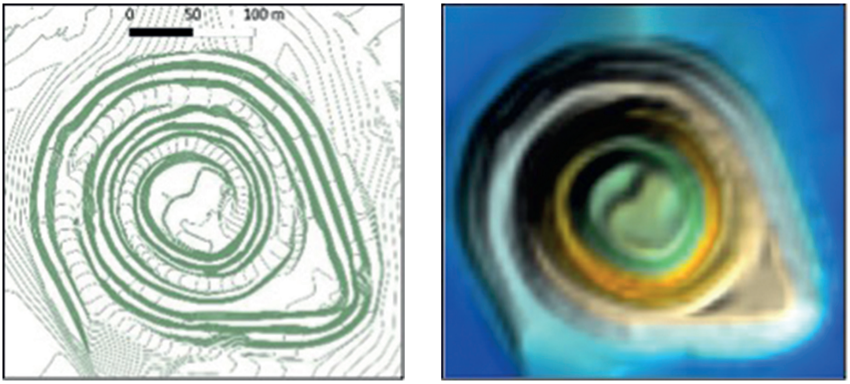

Figure 3 Vectorial topographical map (left) of the open pit and its numerical grid representation (right).

Analysis of the water table rising in the open pit

A deep well, very close to the open pit, has been used to follow the water level rising since the end of dewatering operations. The rising was slower when the water started to fill the open pit. A water balance of the open pit was obtained by estimating 1) direct inflow due to direct precipitation and 2) the evaporation loss (calculated using local meteorological data). A 3D geometry of the open pit was obtained from a digital elevation map (fig. 3), allowing to estimate the surface and volume of the water body in function of the water level in the open pit. Daily evolution of water volume was calculated, and an average value of 14 m^3/h was found. Considering the periods including at least 5 consecutive days without rainfall and constant water level, the groundwater contribution (mean value of 8,5 m^3/h) was supposed equal to the estimated evaporation process.

Model elaboration

Feflow (Diersch, 2014) allows to simulate groundwater flow using Finite Element Method (FEM) technique in discretization of the continuous domain modelling area into set of discrete sub-domains or elements. Division to smaller elements allows accurate representation of complex geometry, specifically using 3D unstructured mesh.

Model extension and FEM meshing

Main rivers were used to delimitate the North and South extension of the model (area of 27 km^2). Null flux boundaries were set on west and east sides to represent the watershed limits (in granitic domain, groundwater flow mainly follows topography). Rivers, open pit,

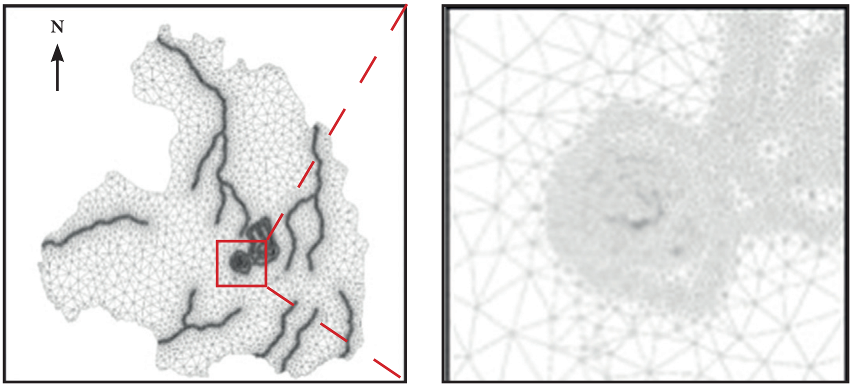

***Figure 4** Finite elements meshing of the whole model (left) and zoom centered on the open-pit (right).*

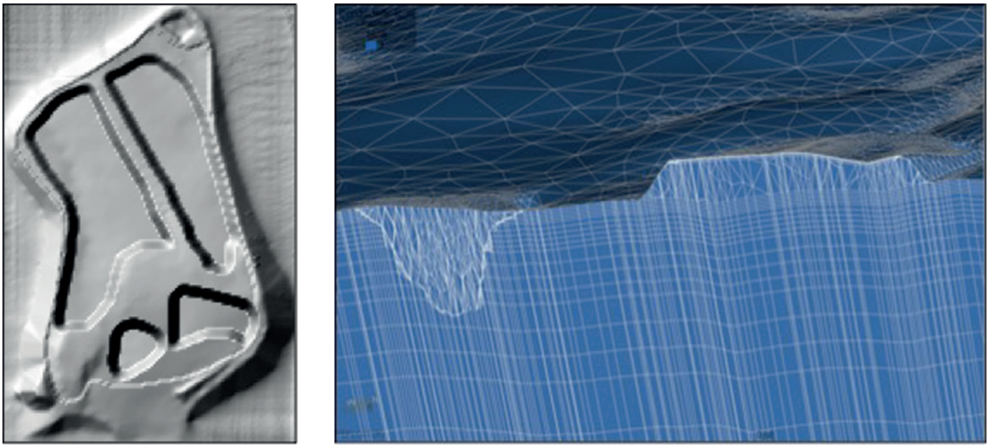

Figure 5 *Storage area with the peripheral and internal dams (left) and vertical slice view into the model displaying the open pit and the storage area filled with unstructured elements (right).*

storage zone geometry and piezometers were inserted as nodes and lines to be integrated in the meshing process. FEM meshing was performed using the "Triangle" algorithm provided by Feflow, ensuring its regularity using "2D mesh smoothing" and respecting the Delaunay criterion (fig. 4).

3D model structure (except galleries network)

Surface topography was obtained merging a large Digital Elevation Model (DEM grid of 25 m × 25 m with meter accuracy in Z) with a more precise one (grid of 5 m × 5 m with centimeter accuracy in Z). Using Golden Software Surfer®, the Radial Basis Function (multi quadratic option and null R^2 parameter) was applied to estimate the Z altitude on each node of the model.

Geometry of the four cells within the residual's storage area was obtained combining various paper maps (particularly the original topography corresponding to the storage basement) and sketches describing the dimensions and shape of the external dam and the internal dams separating the cells. Final geometries grid files (top of the storage, dams, layers of recovering materials, storage cells) were generated using interpolation processes with Surfer® (fig. 5).

A classical layered approach was used for the geological model (470 m thick) including, from top to bottom: alterites (5 × 1 m thick layers), fissured granite (5 × 2 m thick layers and 4 × 5 m thick layers) and non alterated granite substratum (3 × 10 m thick layer, 3 × 20 m thick layer, and 11 layers with thickness increasing from 26 m to 37 m).

Once the layered structure created, the volumes corresponding to the open pit, the tailings and the storage area dams were discretized in 3D unstructured elements (tetrahedrons) using the Feflow TetGen meshing tool (fig. 5).

Generation of underground galleries

Geometry of the central axis of each gallery was available as a georeferenced shapefile (ArcGis format). This skeleton was imported into Blender software (www.blender.org) using Blender GIS (hgithub.com/domlysz/BlenderGIS), an add-on allowing to import and export most common GIS data format.

Once imported in Blender, each continuous segment (3D line) has been treated individually. Using the Bevel data's segments properties, 3D polygons were automatically generated joining square cross sectional shape regularly placed along the line (square side size of 4.5 m for main galleries and 3.74 m for secondary galleries, fig. 6). A special attention has been given to obtain a coherent geometry, limiting the number of faces and avoiding any self-intersection between polygons (i.e. perfect fit at galleries intersections), with manual adjustment if necessary.

Using Blender's Bevel tool, an accurate representation with 3D polygons was

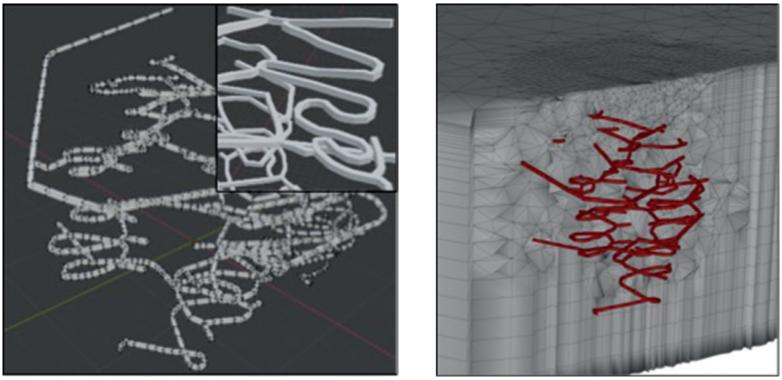

Figure 6 *3D polygonal modeling of underground galleries with Blender (left) and integration into the Feflow model using unstructured elements (right).*

obtained for the whole galleries network, and exported as a 3D shapefile with Blender GIS.

With Feflow's TetGen meshing tool, the full 3D polygonal representation of the underground structures was integrated into the layered geological model using unstructured mesh (fig. 6). As for the open-pit void, a pseudo-porous material ("air layer" approach; Diersch, 2014) was used to simulate the open-pit void with a reasonably high conductivity (several orders of magnitude higher than surrounding rock) and a porosity of one.

River's network

For the main rivers at the north and south of the domain limit and the downstream part of their tributaries, hydraulic head boundary condition has been imposed (first-order limit condition with constant hydraulic head). Upstream part of the tributaries were treated as fluid-transfer boundary condition (Cauchy-type limit with an associated out-transfer coefficient).

Recharge

Since 1979, the daily mean flow-rate is measured in the river flowing at the north limit of the model. To evaluate the part of efficient rainfall distributed between runoff and infiltration into underlying aquifer, Gardenia software (Thiery, 2010) was used. Gardenia is an application for lumped hydrologic modelling, simulating the main water cycle mechanisms in a catchment basin by applying simplified physical laws for flow through successive reservoirs. Fitting the model to the observed flow-rate data, the efficient rainfall is distributed between runoff and infiltration.

Following the analysis of the water table evolution into the open pit, a daily balance series was calculated integrating the loss by direct evaporation, the influxes of rainfall and runoff. An average flowrate over 5-day time step was computed from the water balance and applied as well boundary condition at the bottom of the open pit. The transient simulation started when the open pit was already partially filled (water level at an altitude of about 168 m).

Recharge applied on the storage area was determined, based on the analysis of monthly volumes passing through the collecting basins installed on the site.

Hydrodynamic model configuration

The hydrodynamic model, based on unsaturated Richard's equations (Van-Genuchten model), and including interaction between groundwater and rivers, runs in transient state over 16 years, with a recharge calculated at a time step of 5 days. Calculation time-step is automatically controlled and limited to a maximum of 10 days.

Calibration of the model

Using an inversion process (FePest tool integrated in Feflow – Doherty, 2007), the hydrodynamics properties (hydraulic conductivities, specific storage, parameters specific to the unsaturated flow) of the

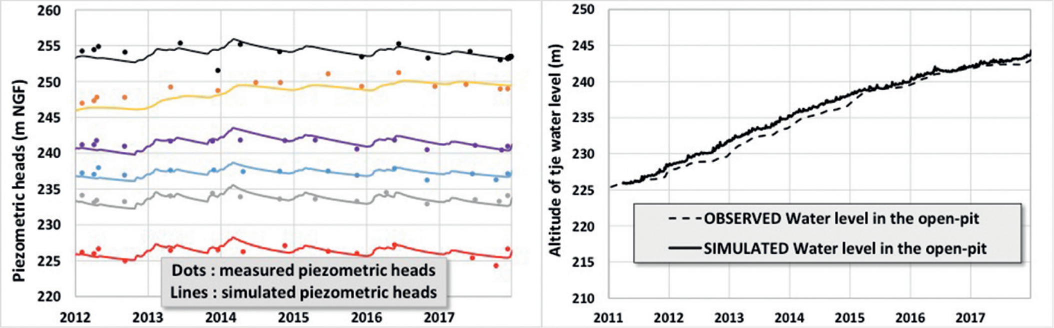

Figure 7 *Comparison of observed and simulated series (piezometers and open pit).*

geological formations and the material constituting the storage area, have been fitted to reproduce the evolution of piezometric heads measured on multiples piezometers and the observed raise of the water table into the open pit. Pilot point method was used to calibrate the model considering the spatial variation of the parameters. Comparison between observed and simulated data is presented in figure 7.

Conclusion

3D unstructured elements meshing allowed to insert in an large hydrodynamic model very detailed features as an open pit, a network of underground galleries and a storage area (including dams, storage cells containing residuals, covering layer).

Tedious integration of high-resolution structures into a 3D model, requires a coherent software chain (ArcMap, ArcScene, Surfer®, Blender, Feflow), with strong effort dedicated to the mesh quality. Workflow induces time consuming phases as digitalization, georeferencing, numerical interpolation and adjustment of 3D automatically generated polygons.

The general hydrodynamic configuration of the site is well reproduced, with a strong effort focused on the modelling of the water level rising in the open pit.

Future works will focus on transport simulation to characterize the migration of solutes within the various components of the site and particularly the behavior of the water flowing through the residuals of the storage area.

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