Underground Mine Site Investigations for Estimating Hydrogeological Properties of Regional Fractured Rock Aquifers

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Abstract A number of analytical models developed either for mines, tunnels or for collector wells can be used to estimate the hydraulic conductivity of a regional aquifer in fractured rock based on data collected at underground mines, in spite of uncertainties affecting the data and the models. Hydraulic conductivity values obtained for the three mine sites (Beaufor, CANMET and Lac Herbin) are presented as intervals of possible values associated with each method. The most probable values are situated between 1.6×10^{-9} m/s and 4.6×10^{-9} m/s, the lowest estimate being 2.0×10^{-10} m/s and the highest 4.4×10^{-8} m/s.

Keywords Regional aquifer, Fractured rock, Hydraulic properties, Analytical methods, Underground mines

Introduction

The hydraulic properties of fractured rock aquifers are largely controlled by fracture networks as well as by major structures such as faults and shear zones. Underground excavations at a mine site constitute a unique opportunity to characterize a fractured rock aquifer in three dimensions, as they provide multiple access points for collecting data and samples at various depth levels. This is particularly useful in areas where limited natural rock exposures and outcrops are available. Mines allow a three-dimensional characterization of an aquifer, observations at various depths, good sampling windows for aquifer structures, and several sampling points for groundwater (fig. 1). However, underground excavations and their dewatering disturb the groundwater flow system, the hydrochemistry and the geomechanical stress fields around the mine.

This project consists of 1-developing and testing methods to characterize fractured rock aquifers at three underground mines (Beaufor, CANMET and Lac Herbin), in the Abitibi mining district located in the Canadian Precambrian Shield, in Quebec, Canada (fig. 2) and 2-assessing the usefulness and effectiveness of using underground mines for characterizing regional aquifers in fractured rock.

Data required for normal mine operation, such as structural survey, mine water inflow and outflow, piezometric data and stress field, can be used to obtain valuable information on the regional hydrogeology of the bedrock. A number of analytical models developed to estimate the hydraulic properties of aquifers are designed for draining conditions similar to those observed at mine workings. Such analytical models that are developed either for mines, collector wells or for tunnel can be used with data collected at underground mines to obtain estimates of the hydraulic conductivity of a regional aquifer in fractured rock.

Regional and local geology

The three mine site under study extract gold; they are located at the border of the Bourla-

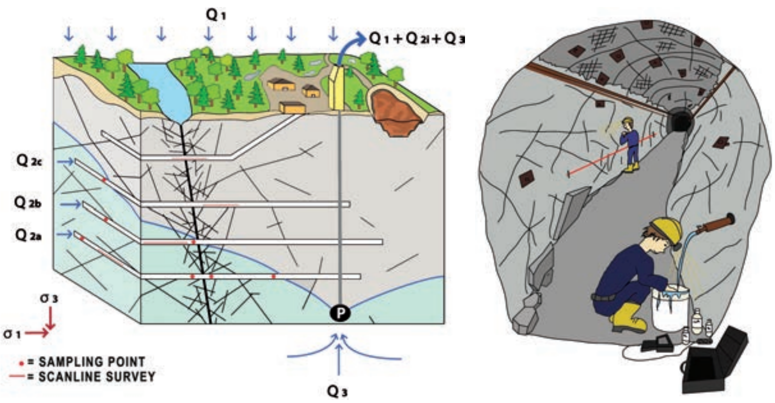

Fig. 1 *Sketches of a mine opening, groundwater sampling and scanline fracture survey.*

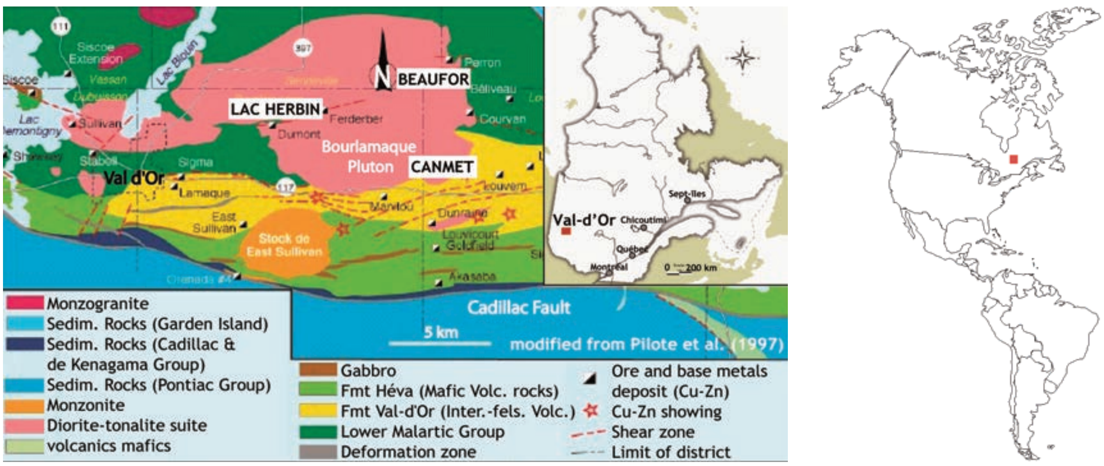

Fig. 2 *Geological map and location of the mines.*

maque pluton (fig. 2) composed of diorite-tonalite rock. This pluton cut volcanic intermediate to felsic rocks of the Val-d’Or Formation and mafic to ultramafic rocks of the Lower Malartic Group. At Beaufor mine, a sand unit overlaying the bedrock can reach 20 m in thickness. Generally, 2 m of silt and 0.6 m of silty clay cover the sand unit; this is overlaid in places by 0.6 m of organic deposits, and 1.8 m to 2.4 m of backfill around the mine installations (Paradis *et al.* 2007). At CANMET mine, a dense till composed of silt and sand covers the bedrock, it is overlaid by organic deposit, and 1.5 m to 3.75 m of backfill. At Lac Herbin mine, surface sediments are constituted of clay and silt, near the Bourlamaque River with silt, sand and gravel over the clay. This river is flowing at less than 500 m from the mine. Some small shallow lakes, including Herbin Lake, are located near the mine workings.

Methodology

The first step consists of collecting available information at the selected mine sites, which may include geological maps (rock and superficial deposits), borehole logs, as well as data on geological discontinuity survey (fault, shear zones, fractures, lithological contacts), stream flow rate, hydrochemical analyses, quantity of water inflow and outflow from the mines, location of the mine pumps, geometry of the mine workings and their extension with past time, meteorological conditions, and geomechanical stress fields. Piezometers located near the mine workings may provide periodic water level data. Local estimates of hydraulic conductivity (*e.g.* from packer tests) and groundwater hydraulic gradient may be available. Recorded number of pumping hours may provide estimates of groundwater inflow at different mine levels.

Secondly, analytical approaches provide first estimates of hydraulic properties, since analytical models are relatively simple to use, and they are usually compatible with the quantity and the quality of available data. However, the proper use of these analytical models requires caution, particularly in regards to the limiting assumptions that they imply.

Analytical models that are developed specifically for mine drainage are based on the assumption of a vertical well. The smallest circle that may fully contain the mine plan is determined and a virtual vertical well is located at its center, entirely penetrating the aquifer. Equations have been developed for estimating the flow rate that is required to lower the water table below the circle around the mine (fig. 3; Fawcett *et al.* 1984). This method assumes that the rock mass above the excavation is dewatered. The equivalent radius *r* of a non-circular mine may be determined by the following equation (Mansur and Kaufman 1962), where *Y* and *W* are respectively the length and the width of the mine workings:

$$r = \left(\frac{2}{\pi}\right)\sqrt{YW} \qquad (1)$$

Parameters that are known at a mine site include water inflow, pumping conditions, the geometry of mine workings, groundwater level and general characteristics of the aquifer. Under these conditions, equations of the models may be rewritten in order to obtain an estimate of the rock mass hydraulic conductivity. A hydrogeological section through the mine, superimposed on a simplified geometry of the mine workings, is required to determine the characteristics of the aquifer. The model equations (Table 1 & fig. 3) are based on the following assumptions (Singh and Atkins 1985):

- Infinite aquifer, homogeneous, isotropic, of uniform thickness over the area influenced by mining, with an impermeable boundary at its base;
- The well is pumped at a constant discharge rate;
- The aquifer is fully penetrated by the well, and thus the water flows horizontally the well over the entire thickness of the aquifer;
- Variations in the diameter of the wells do not affect the discharge or drawdown.

The geometry of a radial collector well is similar to mine workings, taking into account the length of lateral drains (fig. 3). The well is constituted of a reinforced central box and a number of underground side drains (arms). Water enters through the arms and flows into the well when the pump is activated. Usually a radial collector well is modeled as a vertical well having a large radius, corresponding to a percentage of the length of his arms

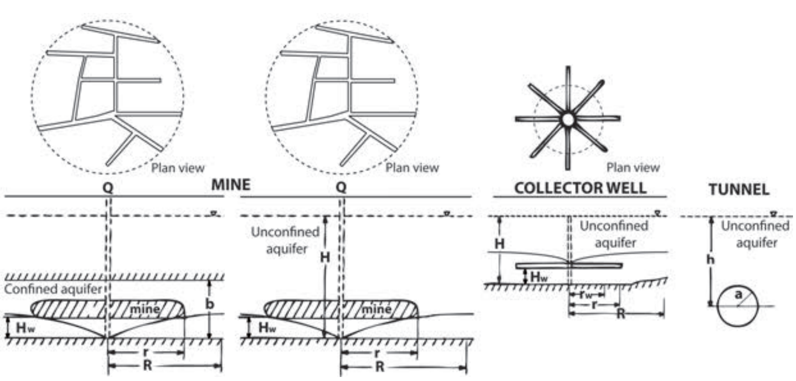

Fig. 3 *Models developed for a mine, a collector well and a tunnel.*

	Condition	Source	Analytical formulas	Variables
MINE, based on well equations	Confined aquifer	Thiem (1906)	$K = \frac{Qln(R/r)}{2\pi b(H - H_w)}$	a: Radius of tunnel [L] *b*: Thickness of formation being dewatered [L] *h*: Depth of tunnel center from the water table [L] *H*: Original water head [L] H_w: Head in the central collector well [L] *Q*: Well discharge rate equivalent to inflow rate in mine [L^3/T] *K*: Hydraulic conductivity [L/T] *L*: Length of drain [L] *R*: Effective radius of influence [L] *r*: radius at which the drawdown is required [L] r_w: Radius of well: ½ L [L] *s*: Drawdown at distance *r* from the well [L]
	Unconfined aquifer	Dupuit (1863)	$K = \frac{Qln(R/r)}{\pi(H^2 - {H_w}^2)}$	
COLLECTOR WELL based on well equations	Confined aquifer	Thiem (1906)	$K = \frac{Qln(R/r_w)}{2\pi b(H - H_w)}$	
	Unconfined aquifer	Dupuit (1863)	$K = \frac{Qln(R/r_w)}{2\pi b(H - H_w)}$	
TUNNEL	Unconfined aquifer	Goodman *et al.* (1965)	$K = \frac{Qln(2h/a)}{2\pi h}$	
	Unconfined aquifer	Rat (1973), Schleiss (1988), Lei (1999)	$K = \frac{Qln\left(\frac{2h}{a} + \sqrt{\frac{h^2}{a^2}} - 1\right)}{2\pi h}$	

***Table 1** Analytical formulas*

(McWhorter and Sunada 1977) which depends on the number of drains. The relationship between these two elements is difficult to assess.

Galleries of underground mines have geometries similar to a tunnel. Several analytical solutions have been developed to estimate water inflow into tunnels for simple cases. They generally assume a homogenous hydraulic conductivity and a flow following Darcy’s Law in two dimensions in a plan perpendicular to the axis of the tunnel, and constant-head boundary conditions at the tunnel wall. The water inflow is estimated per unit of length of a tunnel. The tunnel is dewatered at a steady state in a semi-infinite or infinite matrix which is homogeneous and completely saturated. El Tani (2003) has compiled equations for inflow to a tunnel (Table 1).

Results

The results are presented (fig. 4) as intervals of possible values considering the large uncertainties affecting input parameters (Table 2). Note that the extreme *K* values are very unlikely outcomes as they are obtained using jointly the extreme values of all input parameters. Important assumptions must be made regarding the value of a number of variables and some parameters, such as *Q*, vary through time. The value of H for example, is presumed to be lower than the depth of the mine and the effective radius of influence *R* could be assumed to be equal to the radius of the required drawdown *r* multiplied by a specified factor, such as *R* = 1.6 *r*.

Hydraulic conductivity (*K*) values estimated with analytical formulas (Table 1) are

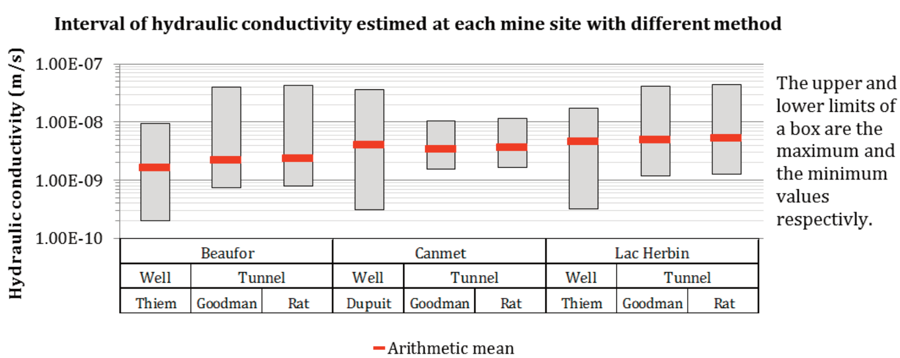

***Fig. 4** Intervals of hydraulic conductivity estimates at each mine with different analytical models.*

Parameter		Beaufor			CANMET			Lac Herbin		
		Value for a minimum *K*	Arithmetic mean	Value for a maximum *K*	Value for a minimum *K*	Arithmetic mean	Value for a maximum *K*	Value for a minimum *K*	Arithmetic mean	Value for a maximum *K*
Q	[m³/s]	0.0055	0.0074	0.0164	0.0017	0.0022	0.003	0.0053	0.0086	0.0104
b	[m]	1181 = H-2	969 = H-14	753 = H-30				894 = H-1	680 = H-15	465 = H-30
r_w	[m]	800 = 1r	520 = 0.65r	240 = 0.3r	375 = 1r	244 = 0.65r	113 = 0.3r	350 = 1r	228 = 0.65r	105 = 0.3r
R	[m]	960 = 1.2r	1280 = 1.6r	1600 = 2r	450 = 1.2r	600 = 1.6r	750 = 2r	400 = 1.2r	560 = 1.6r	700 = 2r
H_w	[m]	500	300	100	500	300	100	500	300	100
H	[m]	1183=683+H_w	983 = 683+H_w	783 = 683+H_w	630 = 130+H_w	430 = 130+H_w	230 = 130+H_w	895 = 395+H_w	695 = 395+H_w	495 = 395+H_w
L	[m]	10000	8000	6000	6000	5500	5000	10000	7000	4000
a	[m]	5	3	1	3	2	1	3	2	1
h	[m]	700	375	50	130	85	40	395	220	45

Table 2 *Possible value for each parameter*

similar from one model to another (fig. 4). The minimum value of *K* is higher for the tunnel models than for other models. The input parameters that have the greatest influence on the calculated *K* value are *Q* and *r*. The calculated value of *K* increases as *Q* increases and as *r* decreases. For a tunnel, the parameter *h* also has an influence on the results; *K* is higher with a smaller value of *h*.

Discussion

All of the analytical models consider a very simple system geometry, and they do not take into account discontinuities such as faults, as well as variations in hydraulic properties with lithology and with depth. In addition, groundwater is commonly observed flowing along fractures and fault zones, from the roof of mine galleries. The assumption of a completely unsaturated rock mass above the mine workings is therefore not exact, as the rock mass remains at least partly saturated. The unconfined aquifer model considers that the rock mass and the overlaying soft material remain unsaturated. However, piezometers frequently show a groundwater table above mine excavations, indicating that at least part of the rock mass above the mine workings remains saturated. This assumption contributes to underestimate the hydraulic conductivities.

Excavations are not homogeneously distributed at a mine site. Mine levels contain different number of galleries, whose length varies in different directions. Assuming a mine as a disk of a radius containing all of the galleries is an important simplification because it overestimates the volume of the excavation, which decreases the estimated hydraulic conductivities. Mine workings are rather constituted of a collection of several galleries and stopes, sometimes with more than one shaft. However, analytical models can easily be used to estimate parameter values considering a number of field cases, using for instance different values of the radius of mine workings. Resulting estimates of hydraulic properties would provide an assessment of their sensitivity to input parameters. Equations used for collector wells are the same as the one used for mines, except that the radius of the well is equal to a percentage of the length of horizontal drains. Analytical models for drainage consider inflow to a single horizontal tunnel without the influence of other drainage tunnels nearby. However, the geometry of a single tunnel is different from the geometry of a mine which is composed of a vertical shaft, stopes, and several sub horizontal galleries. At tunnel having the same diameter as the mine galleries is considered for the estimation; this has the effect of overestimating the hydraulic conductivity.

Models for tunnels are normally used to calculate the inflow by unit length of a tunnel, assuming a value of the hydraulic conductivity of the rock mass. In our application, the hydraulic conductivity is unknown, but a known parameter is the quantity of water pumped for mine dewatering. Generally, the flow quantities provided by different mine levels are rarely known. The use of a tunnel model to estimate the average hydraulic conductivity of the fractured rock mass may require assuming that the total length of the tunnel is equal to the sum of the lengths of all the galleries of the mine.

Conclusion

Results of this study indicate that a number of the analytical models could provide estimates of the hydraulic conductivity of a regional aquifer using available data on groundwater drainage from a mine. Using more than one model provides a greater level of confidence on the estimated hydraulic property values. The obtained values could then be used as input to groundwater flow models either at a regional or a local scale. Mine excavations also provide unique opportunities to characterize the fracture networks and to collect water samples at various depths, which allow an hydrogeochemical characterization of the regional aquifer.

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