DETAILED HYDROGEOLOGICAL STUDY OF A FRACTURED DOLOSTONE

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INTRODUCTION

Groundwater flow in rocks is primarily controlled by fractures. As a result, flowpaths can be very tortuous due to the high degree of spatial heterogeneity induced by the fractures. Conceptually, groundwater flowpaths can thus be as numerous as the number of open fractures in a rock formation. However, this generalization of flow in fractured rock might not always hold when, for example, it is necessary to remediate a contaminated rock formation with a significant number of fractures. Furthermore, several types of fractures can be distinguished in a rock formation, depending on their orientation, size or their mode of formation. The influence of a given type of fracture on groundwater flow and contaminant transport can greatly vary according to its nature. The need to clearly identify the type of fractures that most affect the rock mass strongly suggests that the structural analysis of a rock formation must be realized in concert with hydraulic investigations. The objective of this study is to determine, at the site scale, the type of fractures most likely to conduct groundwater flow in a fractured dolostone located in a quarry. Work performed consisted of detailed structural mapping, borehole geophysics, and a series of borehole hydraulic tests including constant injection tests, open hole slug tests, pulse interference tests, and pumping tests.

SITE DESCRIPTION

This study has been conducted in the St-Eustache quarry near Montréal. The main rock unit at the quarry is a well bedded flat-lying dolostone that belongs to the Beauharnois Formation of the Beekmantown Group, which is part of the St-Lawrence Lowlands. Since the site is located in the quarry, no overburden is present. The detailed structural mapping in the area and description of more than 800 fractures in the quarry revealed that major tectonic events have not greatly affected the rocks of this region. The only major observable geological features in the quarry apart from the fracture sets are minor strike-slip faults and altered dikes that all occur locally. Vertical fractures occurring within the dolostone are distributed within distinct sets according to their orientation and are compatible with the regional fracture pattern. Although the vertical fractures cut across several dolostone beds, they generally terminate on the bedding planes. Careful observation of seepage on the quarry walls shows that bedding planes also act locally as groundwater flowpaths.

Figure 1 shows the location of three vertical boreholes of 76.2 mm in diameter that were diamond-drilled directly on the quarry floor, each to a depth of approximately thirty meters. Excellent recovery during drilling allowed a direct description of the cores, which revealed that the main structural features are the bedding planes outlined by stylolites, similar to those observed on the quarry walls. No vertical fractures were intercepted by any of the three boreholes as can be expected from vertical drill holes.

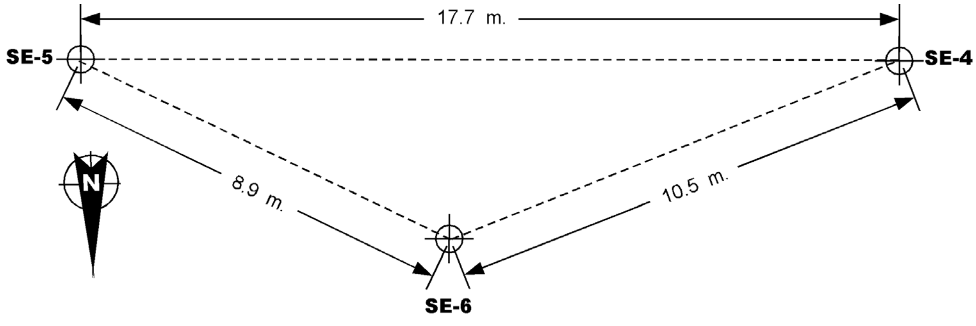

FIGURE 1. Plan view of the borehole locations.

METHODS AND DISCUSSION

A series of geophysical measurements were conducted in the boreholes : caliper, natural gamma, fluid resistivity, single-point resistance, normal resistivity, acoustic waveform, acoustic televiewer, optical televiewer, and electromagnetic flowmeter. During these measurements, groundwater flow was perturbed because the quarry was dewatered by pumping, with pumps located approximately 10 meters from the network of boreholes. Thus, several geophysical measurements, such as fluid resistivity, could not be interpreted. On the other hand, this perturbation provided ideal conditions for the electromagnetic flowmeter, which indicates that the boreholes intersect two major features that create opposite vertical flow directions along the boreholes (fig. 2). These two features are located at depths of 13 and 23 meters. They correspond, as shown by the natural gamma, optical televiewer and description of the cores, to two distinct stylolitic bedding planes. Bedding planes have also been considered as major structural drains by Lapcevic et *al.* (1993) in a study on groundwater flow in a fractured dolostone.

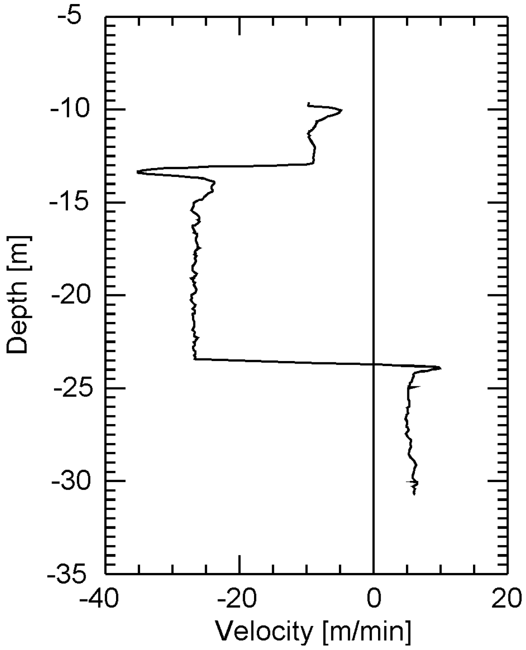

FIGURE 2. Velocity profile obtained by the EM Flowmeter in borehole SE-6 (negative values of velocity indicate a downward flow direction and positive values indicate upward flow direction).

Constant injection tests with inflatable packers were performed to obtain a vertical profile of transmissivity within the three boreholes. A 2-metre interval between the packers was selected on the basis of optimisation of resolution and time allowed for the use of the equipment. A one-meter interval was also used in well SE-5. The transmissivity profiles in the three wells are very similar and show two zones of higher transmissivity. The first zone corresponds to the upper part of the aquifer (from the water table to a depth of 13 m) where the mean transmissivity is approximately $1x10^{-3}$ m²/s. The second high transmissivity zone is located at a depth of 23 meters. This second zone is at the same elevation as the bedding plane that induced a big change in the velocity of the water in the well SE-6 (see fig. 2). Apart from these two zones, all other transmissivity values measured are at least three orders of magnitude lower.

TABLE 1. Transmissivity measured from constant injection tests and open hole slug tests

	Transmissivity [m²/s]	
Borehole	**Constant injection tests**	**Slug tests**
SE-4	**$2.52x10^{-3}$**	**$1.05x10^{-3}$**
SE-5	**$5.61x10^{-3}$**	**$1.22x10^{-3}$**
SE-6	**$7.77x10^{-3}$**	**$9.8x10^{-4}$**

Table 1 shows the summation of all transmissivities measured for each borehole compared to the transmissivities obtained by open hole slug tests. The equivalent transmissivity obtained by the constant injection tests are systematically higher than those obtained by conventional open hole slug tests. Since the test zone was slightly shorter for the constant injection tests, to accommodate the size of the packers in the end of the boreholes, results are questionable and suggest that one of the two tests overestimates the transmissivity.

On the basis of these results, pumping tests and pulse interference tests with inflatable packers were designed to evaluate the connectivity between the two high-transmissivity bedding planes. Figure 3 illustrates the set-up used for pumping tests and pulse interference tests. Prior to performing the hydraulic tests, the hydraulic heads in the packed intervals of the boreholes were monitored for 12 hours because of the fluctuations induced by the dewatering pumps used in the quarry. This monitoring revealed important information on the conceptual model of the aquifer. Hydraulic heads in zones 4 and 5 of the two observation wells, shown on Figure 3, react similarly to the fluctuations of the dewatering pumps. Thus, from the water table to a depth of 13 m, the vertical fractures seem to connect the numerous bedding planes to form a surficial unconfined aquifer. This well-connected network is highlighted by a high transmissivity, as measured by the constant head injection tests. The bottom of this zone at a depth of 13 m also corresponds to the bedding plane assumed to be a major drain as highlighted by the velocity peak measured by the electromagnetic flowmeter (Figure 2). This bedding plane, which is of great lateral extent, drains the water to the well and produces a peak in the velocity of the water in the well. The lower major fracture, at a depth of 23 m, is the second high transmissive bedding plane and may be considered as a “deep” aquifer confined by aquitards above and below. Such a configuration will help determine the role of vertical fractures by pumping the deepest bedding plane.

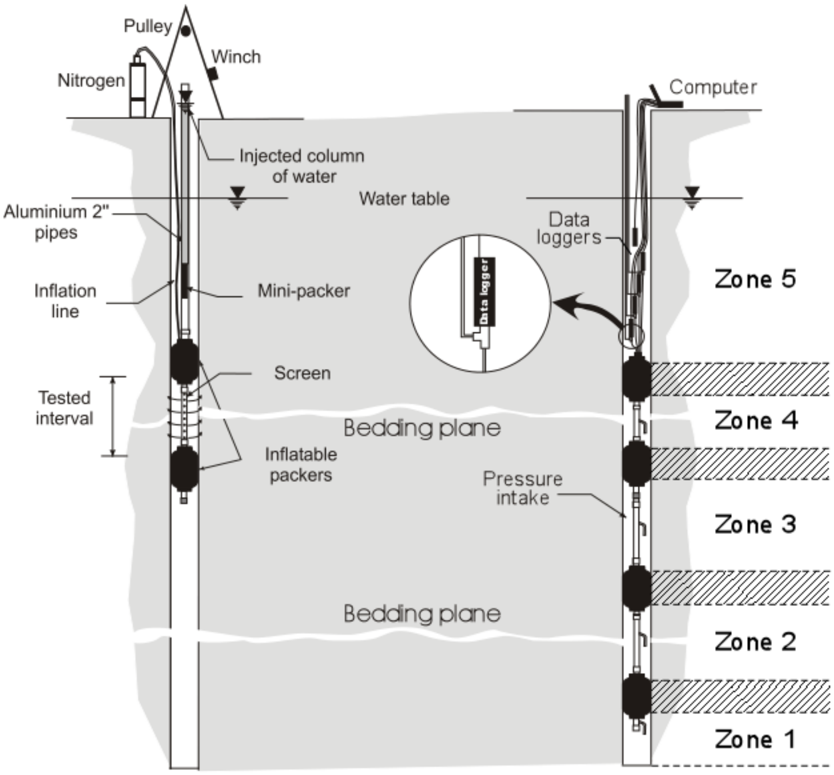

FIGURE 3. Hydraulic testing set-up.

The pulse interference tests were performed in bedding planes to confirm their lateral extent and connectivity between the wells. The first two tests were performed by injecting water in borehole SE-6 at zones 2 and 4 (see fig. 3) and by monitoring the drawdown in boreholes SE-4 and SE-5 in the same zones. The wellbore storage of the injection interval was reduced by using an aluminium casing. The observation wellbore storage was also reduced with the use of a very thin tubing and can be neglected in the analysis according to the Ogbe and Brigham (1984) criteria for a C_D less than 10^4. The same configuration was also used for two other tests, with borehole SE-5 being the injection well and SE-4 and SE-6 the observation wells. Injection in the 13 m bedding plane (zone 4) did not induce any hydraulic response in the observation wells. Because of the high connectivity of the upper part of the site, the volume of water injected might not have been sufficient to induce a response in the observation wells. On the opposite, injection in zone 2 corresponding to the lower bedding plane at a depth of 23 m, produced a response in the observation wells. Hydraulic head response to injection in zone 2 was analyzed using the curve-fitting program TCINV (Piggott et *al.*, 1995) and also with the graphical method proposed by Novakowski (1989). The results are presented in table 2 along with the transmissivity data obtained by constant injection tests and pumping tests. Pulse interference values are the geometric mean of all the tests that were performed in this zone and vary by less than one order of magnitude. Results from the pulse interference tests presented here are preliminary because a perfect fit to the data has yet to be found.

Four different pumping tests were performed with the same geometry as the pulse interference tests. The duration of a test run varies between 3 and 15 hours, with pumping rates between 13 and 28 l/min. As for the pulse interference tests, the pumping tests in the zone 4 induced no drawdown in the observation wells. The pumping tests in zone 2 induced drawdown only in the same zone in the observation wells. No drawdown was observed in the zone 3 immediately above. These observations suggest that zone 2 is, at the site scale, a perfectly confined aquifer and that the vertical fractures do not connect the two bedding planes. Table 2 presents the preliminary interpretation of pumping tests with the Cooper-Jacob straight-line method for radial flow in a confined aquifer.

TABLE 2. Transmissivity of the 23 m bedding plane calculated by different methods

Method	Transmissivity [m²/s]	Storativity
Constant injection test	7.73×10^{-4}	-
Pulse interference test		
- *Graphical method*	2.33×10^{-4}	9.07×10^{-5}
- *Type curve method*	5.64×10^{-4}	1.26×10^{-4}
Pumping test	7.06×10^{-4}	5.16×10^{-4}

CONCLUSION

The aquifer can be divided in two high transmissvive zones : a surficial aquifer for which the bedding planes are connected by vertical fractures. This surficial aquifer is drained by a high transmissive bedding plane with great lateral extent located at a depth of 13 m. The second high transmissive zone is a bedding plane located at a depth of 23 meters that can be regarded at the site scale as a perfectly confined aquifer. Thus, even though vertical fractures are present throughout the section, they only play a signifiant role in groundwater flow in the surficial part of the rock mass.

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