CONTINUOUS DOWNHOLE HYDRAULIC TESTING OF FRACTURED BEDROCK AQUIFERS: METHODOLOGY AND FIELD EXAMPLE

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ABSTRACT
A downhole hydraulic testing apparatus for fractured bedrock has been designed and used successfully on several recent projects. The straddle packer system is designed to measure bulk rock transmissivities ranging from 10^{-4} to 10^{-11} m^2/s (based on a 3 metre test section). Discrete sections of each borehole are isolated using a pair of pneumatically inflated packers and then hydraulically tested using an injection system. Water is injected from ground surface using a series of manometers of varying diameters to accommodate a wide range of transmissivities. The manometers, hydraulically connected to the isolated zone in the borehole, are used to record the rate of decline of the pressure in the test interval to obtain a quantitative measurement of the transmissivity of the bedrock test interval. Real time down hole pressure-transducer readings are also recorded and logged in the field. To interpret the hydraulic testing data collected during the packer testing, data analysis methods based on the Theim equation and modified for single well injection tests are used to estimate the relative transmissivity of each of the intervals tested in the boreholes. This produces a vertical profile of bulk rock transmissivities, which can be normalized using the length of the packer interval to obtain depth dependent hydraulic conductivity estimates. These are then plotted and correlated with other available site data (RQD, fracture frequency, visual inspection of the rock cores, etc.). The hydraulic testing methodology is illustrated using site data from a selected site in Ontario.

RÉSUMÉ
Un appareil de mesure fut développé utilisé avec succès dans le cadre de divers projets récents. Ce système à obturateurs, conçu afin de mesurer la transmissivité globale du roc à l'intérieur d'une fourchette de valeurs variant entre 10^{-4} et 10^{-11} m^2/s (selon un intervalle de mesure de 3 mètres), est présenté dans le présent ouvrage. Des sections précises à l'intérieur de chacun des forages sont isolées à l'aide d'obturateurs gonflés grâce à un gaz comprimé, puis testés par le biais d'un système d'injection. L'eau est injectée à l'aide d'une série de manomètres de divers diamètres, situés en surface afin d'accommoder un éventail de transmissivités relativement large. Les manomètres, en connexion hydraulique avec la zone faisant l'objet du test à l'intérieur du forage, servent à enregistrer le déclin de la pression et ainsi obtenir une mesure quantitative de la transmissivité du roc à l'intérieur de l'intervalle testé. Un estimé quantitatif de la perméabilité de l'intervalle testé est ainsi obtenu. Des données sont également enregistrées sur le terrain en temps réel à l'aide d'un transducteur, afin de mesurer la charge hydraulique à l'intérieur de l'intervalle testé. L'analyse des données recueillies lors des essais de perméabilité est effectuée à partir de l'équation de Theim, modifiée pour convenir à des tests d'injection dans un puits unique, et obtenir un estimé de la transmissivité relative de chacun des intervalles testé à l'intérieur des forages. Le produit de cette analyse comprend un profile vertical de la transmissivité du roc, laquelle peut être normalisée à l'aide de la longueur de l'intervalle testé afin d'estimer la conductivité hydraulique en fonction de la profondeur. Ces valeurs sont par la suite illustrées à l'aide de graphiques, et corrélées avec les informations connexes relevées à l'intérieur des mêmes forages (compétence du roc, fréquence des fractures, inspection visuelle des carottes de forages, etc.). La méthode de test hydraulique est illustrée à l'aide de données provenant d'un site situé en Ontario.

1. INTRODUCTION

The ability to accurately characterize the subsurface, in particular its hydraulic properties, is a crucial component of any hydrogeological investigation. Our ability to understand and predict the movement of groundwater and contaminants is limited by the imperfect knowledge of the preferential pathways available to flowing groundwater. This is particularly true of fractured bedrock settings. While characterizing each of these pathways is impossible, continuous downhole hydraulic testing, performed using a straddle packer system where discrete vertical intervals are isolated using a pair of inflatable packers, can provide investigators with valuable data. This information can be correlated with other depth specific data such as rock quality designation (RQD) and fracture frequency to strengthen a site's three-dimensional conceptual model, and help predict environmental impacts at contaminated sites.

This paper introduces a straddle packer system, used to continuously test the hydraulic properties of a fractured bedrock aquifer in discrete intervals. The apparatus is presented in the next section, along with the details of data analysis and interpretation. Finally, an example of successful application of this methodology at a field site is presented.

2. METHODOLOGY

This section presents a detailed description of the straddle packer injection system used to measure the bulk permeability of the fractured bedrock at discrete intervals. The hydraulic testing procedure is then discussed, along with a quality assurance and quality control protocol, aimed at maximizing data integrity and ensuring consistent and reproducible results. The mathematical theory and interpretation methodology are also described below.

2.1 Testing Apparatus

Figure 1 illustrates the straddle packer injection system used for the hydraulic testing. Two low pressure packers equipped with packer inflation tubing that straddle perforated stainless steel tubing, are used to isolate the chosen interval for the in situ permeability tests. The length of the test interval can be varied according to the study objectives and limitations (e.g. total borehole depth, anticipated fracture spacing of the formation(s) to be tested, available budget, etc.).

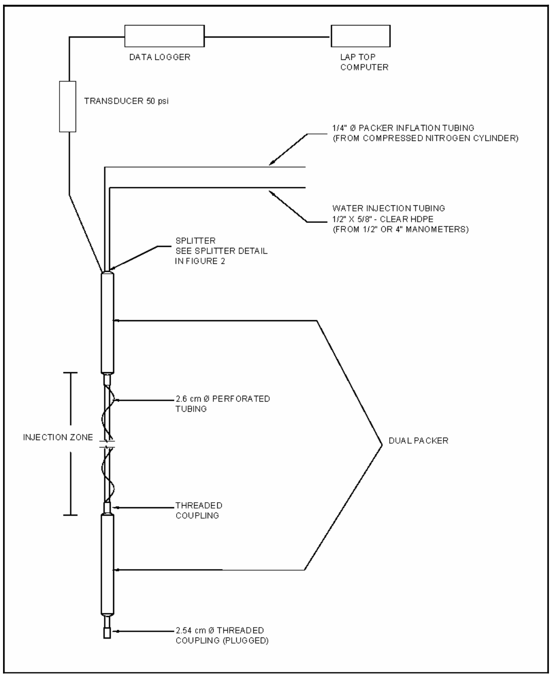

Figure 1. Straddle packer injection system schematic. Details of the head assembly are shown in Figure 2.

The upper packer is connected to the head assembly consisting of a steel splitter and associated hardware (Figure 2), providing a hydraulic connection from the injection zone in the borehole (monitored with a pressure transducer) and the injection tubing at ground surface (monitored with the manometers). Pressure in the injection zone is recorded using a pressure transducer fitted onto the packer assembly head, directly connected to the splitter. Real-time pressure data are recorded using an automated data logger, with output accessed from a portable laptop computer.

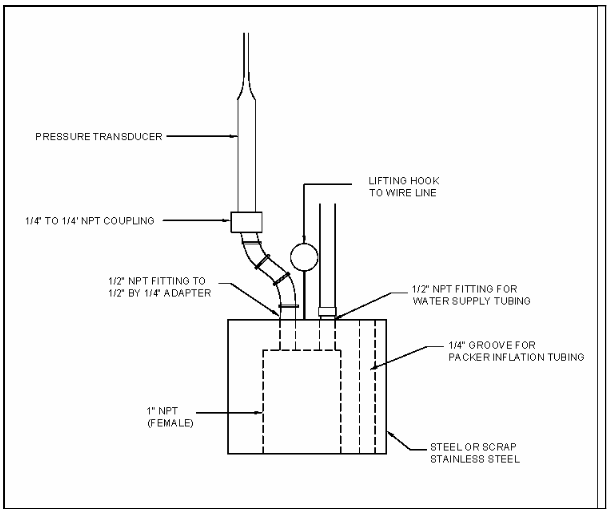

Figure 2. Schematic showing the details of the head assembly.

The packer system is connected to the surface by a wire line support cable, used to lower the assembly down the borehole to the target depth, along with the water injection tubing and the electronic cable carrying the signal for the pressure transducer (see Figure 3).

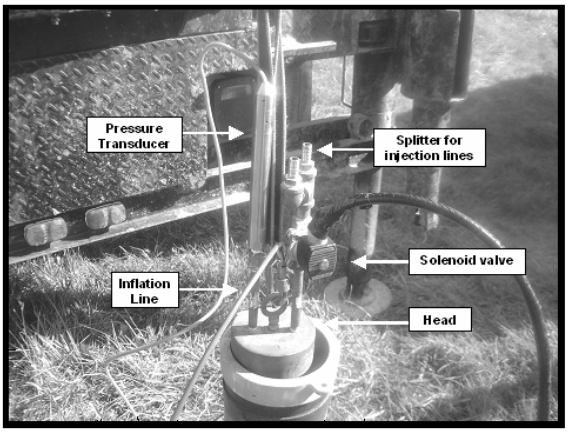

Figure 3. Photograph showing the head assembly being lowered into an open borehole with temporary steel casing secured into the upper bedrock.

2.2 Testing Procedure

At the beginning of each test, the packer system described above is lowered to the desired depth. After allowing sufficient time for the system to return to static conditions, open-hole pressure is measured using the transducer and a static water level is measured manually using a water level tape. Pressure transducer readings are initiated and logged at regular intervals (e.g. 10 s) for the duration of the test. Once the open borehole water level has returned to static conditions the downhole solenoid valve is closed to isolate the injection tubing from the borehole interval to be tested. Note that at this stage, the packers are deflated and the open borehole is under static (natural) conditions.

With the solenoid valve still shut-in, the injection tubing is then flushed with water using a pump at ground surface to remove any air bubbles from the closed loop. Once the closed system is saturated and free of entrapped air, the packers are inflated using compressed nitrogen to a pressure of approximately 700 kilopascals (kPa) above hydrostatic conditions. A pulse of pressure is generated in the isolated vertical interval during packer inflation, and allowed to decay completely as monitored by the data logger and/or portable computer. The static condition within the enclosed interval is noted. To conduct an injection test, the hydraulic head within the manometers must be greater than the static hydraulic head in the test interval.

The duration of the pressure pulse, observed immediately after inflating the packers, is indicative of the relative permeability of the rock formation within the isolated interval (faster pressure dissipation being indicative of more permeable intervals). This initial qualitative response is then used to determine which manometer tube diameter (1.3 or 10.2 cm I.D.) would be most effective for the injection test. The smaller diameter manometer is used for zones of lower permeability, and the larger for intervals where the rate of decline of the water is too rapid to be accurately measured in the smaller manometer. As a rule of thumb, a target injection test duration of at least 15 to 30 minutes is generally appropriate to generate sufficient data for analysis.

Water injection is then initiated by opening the downhole solenoid valve, marking the beginning of the test and allowing water from the appropriate manometer to measure the change in pressure of the isolated interval in the borehole. The decrease in head during the injection is measured both visually at the manometer, and within the packer interval using the pressure transducer. For permeable test intervals, the falling head test is conducted until the water level in the manometer has decreased over the entire length of the manometer. For lower permeability test sections, the test is conducted for a minimum of 15 minutes.

Following the completion of the injection test, the packers are deflated, the pressure transducer data stored in the data logger are downloaded, and the packer assembly is moved up to the next test section. While in the field, a preliminary assessment of the data is performed by comparing the hydraulic testing results against the borehole logs (evidence of presence or absence of significant fractures, RQD, zones of lost drilling water, etc.). If the test results and observations are not consistent, the packer assembly is checked for leaks at ground surface and the interval can be re-tested if necessary.

2.3 Quality Assurance and Quality Control (QA/QC)

A comprehensive protocol is required to ensure that the equipment is assembled and functioning correctly. Below is a list of the procedures that should be followed throughout the hydraulic testing:

- Confirmation of the manufacturer's calibration of the pressure transducer is conducted on-site during the hydraulic testing. This can be accomplished by lowering the transducer down an open borehole to specified depths below the water surface. The voltage read by the transducer through the data logger is then compared to the calculated pressure of the water column, to ensure that the calibration factor provided by the manufacturer is within acceptable limits, e.g. 10% of the known hydrostatic pressure.
- Periodically, the packer system and injection system is completely assembled at ground surface and tested in a section of pipe of appropriate dimensions. The packers are inflated and the inflation line and all air connections checked for leaks by visual inspection and by monitoring pressure gauge readings. Similarly, each connection from the water injection system to the packer system should be inspected to ensure that the system is watertight.
- Duplicate tests should be conducted periodically to ensure the reproducibility of the manometer measurements. If a difference in total test time of 10 % or greater is observed, the system should be checked for leaks.

2.4 Data Interpretation

The data analysis methodology is based on the Theim equation, modified for single well injection tests. It should be noted that transmissivities and hydraulic conductivities on the order of 10^{-11} m^2/s represent the lower limit of the testing method.

The approach described here uses the average volumetric flow rate of the injection water calculated from the change in hydraulic head in the manometer over discrete time intervals to estimate the permeability of the test section. Below is a summary of the Theim equation, including the assumptions associated with the method and a description of the variables.

The Theim equation is given by (e.g. Lapcevic et al. 1998):

$$T = [Q / (\Delta h \, 2\pi)] \bullet \ln(r_e / r_w) \qquad [1]$$

where:

Q average flow rate that entered the isolated test interval during the duration of the test. Q is calculated from the change in head vs. time over discrete time intervals observed in the 1.3 or 10.2 cm I.D. tubing.

Δh $H_{initial} - H_{static}$

$H_{initial}$ Head in the 1.3 or 10.2 cm I.D. tubing in cm above ground surface

H_{static} Static head within the test interval. This value is calculated from the equilibrated pressure transducer readings after shut in.

r_e radius of influence

r_w radius of the well

The radius of influence of the well is generally unknown, and can be assumed to be 10 to 15 m (Bliss and Rushton 1984). Alternatively, r_e can be estimated from the data collected during the hydraulic test from:

$$r_e = 2\ (T/S*t)^{1/2} \qquad [2]$$

where:

S   Storativity (assumed to be approximately 10^{-6})

t   total elapsed time of the hydraulic test

An iterative process must be used to calculate T and r_e within each of the injection zones. First a value of T is assumed to estimate the radius of influence from Eq. 2. The estimated radius of influence is then used in Eq. 1 to obtain a better estimate of T, a process which is repeated iteratively until the values of T in Eq. 1 and Eq. 2 converge.

The assumptions necessary to perform this type of data analysis are summarized as follows:

- Δh is constant. This is considered valid where Δh is significantly greater than the change in head used to calculate Q.
- A storativity of 10^{-6}. Changing S by a few orders of magnitude typically changes the value of T by a factor of less than 3.

The transmissivity determined from the Thiem equation, considered to be directly proportional to the bulk rock hydraulic conductivity, can be converted to hydraulic conductivity (K) by dividing the bulk transmissivity estimated for each depth interval by the length of the test interval. The length of the test interval can be used with the underlying assumption that the presence of both horizontal and vertical fractures allows groundwater to enter the borehole from any direction.

Due to the limit of the hydraulic testing field methods, the range of transmissivities calculated using this method are estimated to be from 10^{-4} to 10^{-11} m^2/s.

3. APPLICATION EXAMPLE

The apparatus and methodology presented herein is versatile and can be adapted to a wide range of applications. For instance, the bulk hydraulic properties of the bedrock can be estimated using boreholes drilled at any angle, from vertical (most common) to horizontal, including any intermediate angle. One example is presented here for illustrative purposes.

The physical properties of the bedrock were assessed using the straddle packer injection system described above, in order to characterize the hydraulic properties of the subsurface at a private landfill site located in Eastern Ontario, Canada. The data collected during the hydraulic testing was used in conjunction with other types of measurements and evidence to develop a sound conceptual hydrogeological model for the site, and ultimately determine the appropriate groundwater monitoring strategy for the facility.

3.1 Site Geology

The site geology is composed of surficial deposits consisting of glacial and related materials interpreted to be ice-contact stratified drift sediments, consisting of a mixture of poorly to well-sorted, stratified gravels and sands, interbedded with lenses of silty sand-gravel till. The deposits are horizontally bedded and often display evidence of cross-bedding, as observed in excavation faces on and near the landfill property. The unconsolidated deposits range in thickness between 2 and 14 m and consist of glacial till, clay, silt, gravel and sand.

Bedrock in the study area consists of grey, fine to medium-grained fossiliferous limestone with some shaly or sandy interbeds. Previous investigations indicated that the bedrock is horizontally-bedded and discretely-fractured, with the fracture frequency decreasing with depth. Regionally, joints have been reported to commonly occur close to – and parallel to – faults, suggesting a genetic relationship between the joints and faults. The bedrock surface slopes in an easterly direction under the study area.

3.2 Results

A total of five boreholes strategically located around the site were drilled to a target depth of approximately 15 m below bedrock surface, and continuously hydraulically tested using the methodology presented above. The information gathered during drilling and later inspection of the recovered cores was used in conjunction with the results from the hydraulic testing to identify changes in the bedrock's hydraulic properties with depth, which were then correlated horizontally in order to derive the site's hydrogeologic conceptual model. The data related to the hydraulic testing are presented here.

Each cored borehole had a diameter in the bedrock of 95 mm (HQ size drill core barrel). Steel casing was temporarily installed through the overburden from ground surface and set into the top portion of the bedrock, in order to prevent unconsolidated sediments from caving into the borehole. During drilling, continuous core sampling was done for each 1.5 m interval of the borehole, logged immediately in the field and placed in core boxes for future inspection and photography. A triple tube core barrel was used to allow careful core recovery and minimize the occurrence of mechanical fractures induced while handling the core. In addition, during drilling activities, the drill rig operator and field staff noted the presence of zones of drilling water loss. For instance, drilling fluid pressure and circulation may provide indications of fractured zones, while the loss of water at low pressures may indicate a significant fracture. Possible intervals of interest were confirmed when logging the cores. The colour of the water was also monitored, as any changes may indicate fractures, lithology changes, etc.

One of the recovered cores is shown in Figure 4, including annotations made directly on the core to show each of the tested intervals (labelled P1 to P6 from deepest to shallowest intervals). Bedrock cores were described in terms of their lithology, colour, bedding, crystal or grain size, structures, texture, mineralogy, weathering/alterations, fossils, and so on. In particular, fracture occurrences and characteristics were described in detail: depths, aperture, spacing, secondary mineralization, surface texture, solution widening (karst), as well as any other potentially useful observations.

Each 1.5 m interval was described quantitatively using the Rock Quality Designation (RQD), as well as fracture frequency (FF). The RQD is a system of classifying the engineering quality of the rock that gives a qualitative indication of the amount of fracturing in the rock. The RQD, expressed as a percentage, was calculated by measuring the total length of recovered core fragments in excess of twice the diameter of the core, and dividing this number by the total length cored (not just recovered). For H-size cores, the recovered pieces greater than 125 mm in length were summed, and then divided by the total length of the coring run (1.5 m). Fragments were included that had obviously broken due to rough handling or drilling shear. The RQD and FF were recorded for all rock cores recovered during this field investigation.

Figure 5 illustrates the results obtained at one of the boreholes during this investigation, and corresponds to the photographed core shown in Figure 4. All information is presented as a function of depth below bedrock as well as elevation in metres above sea level (masl). The use of this dual elevation/depth scale facilitates the cross-correlation and interpretation of data across several boreholes.

In the example shown in Figure 5, a correlation is apparent between the various features at matching depth intervals of the borehole. The frequency of fractures (FF) per recovered core run (1.5 m intervals) is highest in the upper 3 m of the bedrock, where the bulk transmissivity of the formation is also relatively high, and moderate RQD. A high value of FF was again recorded between 4.5-6.0 m below bedrock surface, at a depth where a mineralized vertical fracture was observed (visible in Figure 4, in the middle of the fourth interval from the top). The zone of highest permeability for this borehole was measured at a depth interval between 9.4 and 11.7 m below bedrock surface (labelled as P2 in Figure 4). As would be expected in this relatively permeable interval, a small decline in RQD and increase of FF were observed (see Figure 5), even though larger changes would be anticipated from the marked contrast in transmissivity within the interval. In

Figure 4. Photograph showing recovered core. Top of bedrock corresponds to the upper left, while the borehole bottom is at the bottom right. Hydraulic testing intervals (each 2.3 m in length) are identified directly on the core using the designation P1 (deepest) to P6 (shallowest).

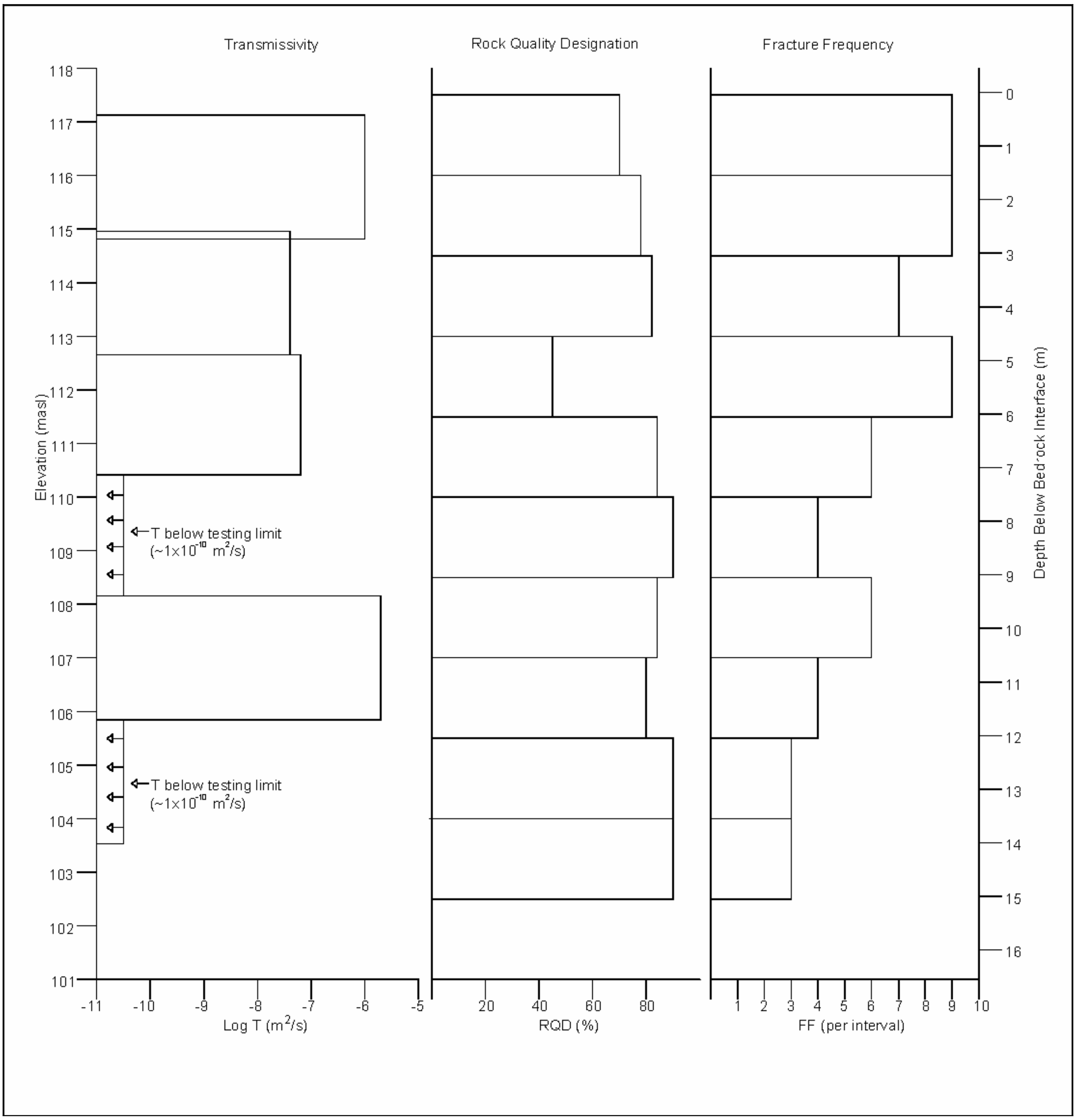

Figure 5. Sample results showing the bulk transmissivity (T), rock quality designation (RQD) and fracture frequency (FF) as a function of both elevation above sea level and depth below bedrock.

contrast, results for the depth intervals located immediately above and below this permeable horizon (P1 and P3 in Figure 4) indicate extremely low transmissivities, and correspond to relatively low FF and very high RQD indicative of competent bedrock.

The same testing procedure and data analysis was applied at other borehole locations on site, and similar hydraulic characteristics were found at most locations. This led to the refinement of the hydrogeologic conceptual model for the site, consisting of two units of relatively high permeability. The upper unit was found at all locations to be consistently located at the interface between the upper, more importantly fractured bedrock, and overlying overburden (glacial sands, gravels and till). Beneath this upper hydrogeologic unit, a horizon of markedly lower permeability indicative of relatively competent bedrock strata was intersected at all five borehole locations. This lower permeability bedrock unit provides some barrier to vertical groundwater flow, isolating the higher transmissivity bedrock unit intersected at greater depth.

4. CONCLUSIONS

Knowledge of the vertical distribution of the bedrock's bulk hydraulic properties allows the investigator to gain invaluable insight into the subsurface characteristics, and in conjunction with other field evidence can generally lead to the development of a sound conceptual hydrogeologic model that can be supported with a high level of confidence.

The hydraulic testing methodology presented above was successfully applied at several sites across Ontario and was found to be relatively easy to implement and inexpensive, as the required hardware can be easily manufactured or rented. Moreover, the data analysis procedure is, as seen previously, straightforward and can be conducted using a conventional spreadsheet.

5. REFERENCES

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