Journal of Hydrology 509 (2014) 163–178

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Hydraulic testing of low-permeability Silurian and Ordovician strata, Michigan Basin, southwestern Ontario

Richard L. Beauheim [a,*], Randall M. Roberts [b], John D. Avis [c]

[a] Consulting Hydrogeologist, 415 Saddle Ct., Grand Junction, CO 81507-3309, USA
[b] HydroResolutions LLC, 1536 Ricasoli Dr. SE, Rio Rancho, NM 87124, USA
[c] Geofirma Engineering Ltd., 1 Raymond St., Suite 200, Ottawa, ON K1R 1A2, Canada

ARTICLE INFO

Article history:
Received 5 September 2013
Received in revised form 16 November 2013
Accepted 20 November 2013
Available online 28 November 2013
This manuscript was handled by Peter K. Kitanidis, Editor-in-Chief, with the assistance of Jian Luo, Associate Editor

Keywords:
Sedimentary basin
Hydraulic testing
Underpressure
Uncertainty analysis
Paleozoic
Low permeability

SUMMARY

Straddle-packer hydraulic testing was performed in 31 Silurian intervals and 66 Ordovician intervals in six deep boreholes at the Bruce nuclear site, located near Tiverton, Ontario, as part of site-characterization activities for a proposed deep geologic repository (DGR) for low- and intermediate-level radioactive waste. The straddle-packer assembly incorporated a hydraulic piston to initiate *in situ* pulse tests within low hydraulic conductivity (<1E−10 m/s) test intervals. Pressure transient data collected during the hydraulic tests were analyzed using the well-test simulator nSIGHTS to estimate the hydraulic properties specified as fitting parameters for the tested intervals, quantify parameter uncertainty, and define parameter correlations.

Horizontal hydraulic conductivities of the Silurian test intervals range from approximately 4E−14 to 4E−8 m/s. The average horizontal hydraulic conductivities of the Ordovician intervals range from 2E−16 to 2E−10 m/s. The Lower Member of the Cobourg Formation, the proposed host formation of the DGR between 660 and 688 meters below ground surface, was found to have a horizontal hydraulic conductivity of 4E−15 to 3E−14 m/s.

The formation pressures inferred from the hydraulic testing, confirmed by long-term monitoring, show that the Upper Ordovician and Middle Ordovician Trenton Group are significantly underpressured relative to a density-compensated hydrostatic condition and relative to the overlying Silurian strata and underlying Black River Group and Cambrian strata. These underpressures could not persist if hydraulic conductivities were not as low as those measured.

1. Introduction

Ontario Power Generation (OPG) is proposing to construct a deep geologic repository (DGR) for its Low and Intermediate Level Waste (L&ILW) beneath the Bruce nuclear site situated in the Municipality of Kincardine, Ontario, on the eastern flank of the Michigan Basin. The DGR is planned as an engineered facility, comprising a series of 31 underground emplacement rooms (Fig. 1) at a nominal depth of 680 m below ground surface (m BGS) within the Ordovician-age argillaceous limestone of the Cobourg Formation. A key issue for the DGR safety case was the occurrence of a diffusion-dominated groundwater system within the Ordovician sediments proposed to host and enclose the DGR. Multi-disciplinary geoscientific studies undertaken to characterize the Bruce nuclear site and assess its suitability for DGR implementation are described by NWMO (2011). In part, these studies were focused on exploring the stability and evolution of the groundwater systems within the 850-m-thick Paleozoic sedimentary sequence beneath the repository site.

As part of site-characterization activities, six deep boreholes (DGR-1 through DGR-6; referred to as the DGR boreholes; diameter 152 mm) were drilled surrounding the proposed repository location, allowing for the collection of approximately 3800 m of 75-mm-diameter core for mineralogical, petrophysical, hydrogeological, geochemical, and geomechanical analyses, as well as the performance of extensive *in situ* hydraulic testing. Borehole DGR-1 was drilled to the top of the Ordovician, allowing testing of the Silurian strata. Boreholes DGR-2, 3, and 4 were drilled to the Cambrian. DGR-5 and 6 were inclined (dip ≈ 60–65°) boreholes drilled to the Ordovician below the proposed repository horizon, intended to intersect high-angle geologic structures such as potential faults. The locations of the six DGR boreholes in relation to the proposed repository are shown in Fig. 1.

Evidence from both historic borehole hydraulic testing and hydrogeochemistry in southern Ontario suggested that hydraulic conductivities within the Silurian and Ordovician bedrock

* Corresponding author. Tel.: +1 970 986 8801.
E-mail addresses: rlbeauheim@gmail.com (R.L. Beauheim), rroberts@hydroresolutions.com (R.M. Roberts), javis@geofirma.com (J.D. Avis).

0022-1694/$ - see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.jhydrol.2013.11.033

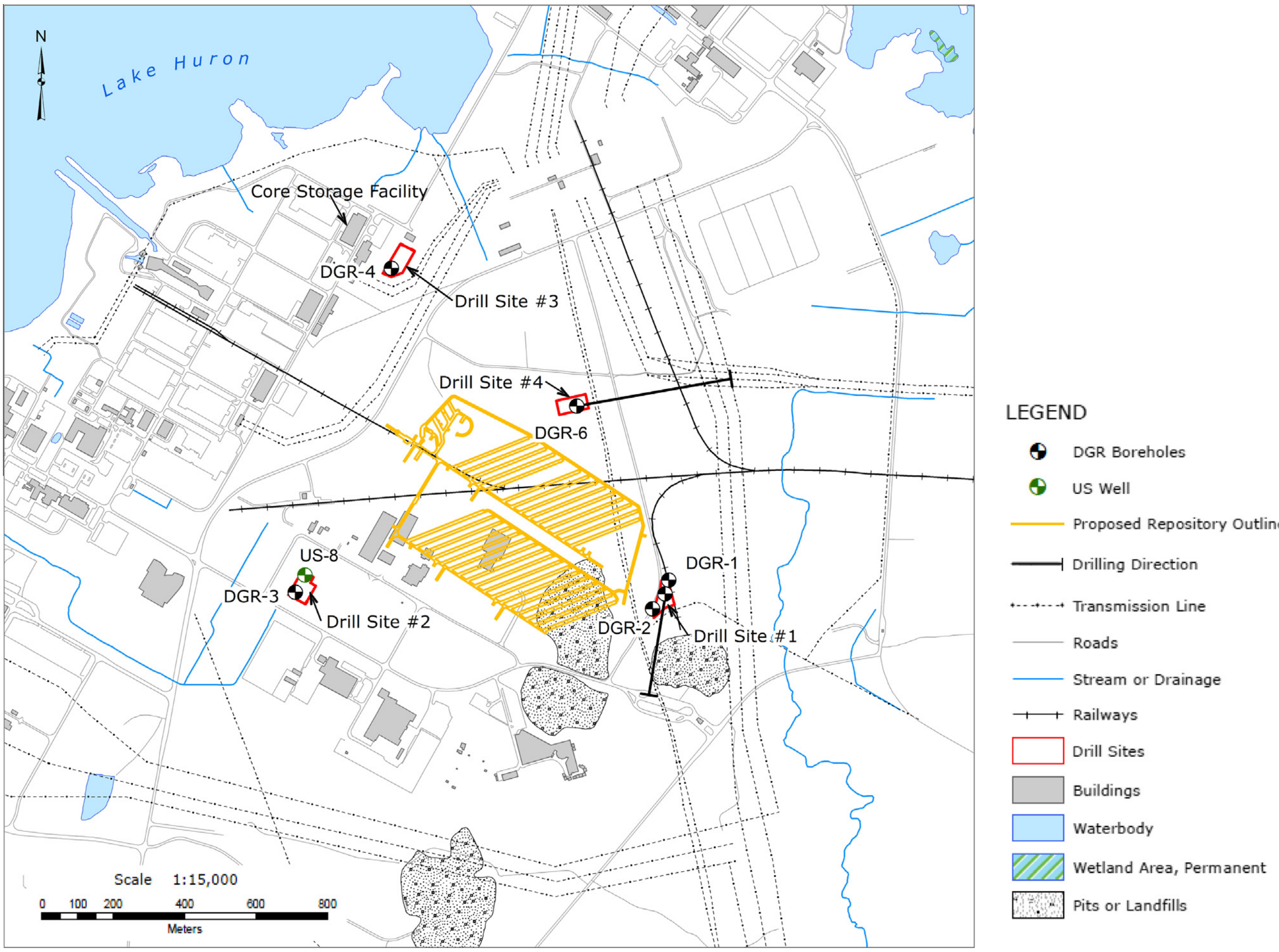

Fig. 1. Proposed DGR layout and locations of DGR boreholes.

formations would be low, particularly at depth (Golder Associates, 2003). As a consequence, the development of a testing methodology focused on three key elements: (i) the design of the downhole straddle-packer system and instrument package, (ii) the development of a formation-specific hydraulic test strategy, and (iii) the technique for numerical analysis of the pressure response of the isolated test intervals. The design of the testing program gained considerable advantage from the experience and knowledge obtained from international waste management programs, particularly the United States Department of Energy's Waste Isolation Pilot Plant (e.g., Beauheim and Roberts, 2002; Beauheim, 2007), Andra's site investigation program around Bure, France (e.g., Delay, 2006), and Nagra's site investigation programs in Switzerland (e.g., Adams and Wyss, 1994). Each of these programs made significant advances in one or more of the three test-related areas listed above that were applied to the testing program at the Bruce nuclear site.

This paper describes the straddle-packer hydraulic testing that was performed in 31 Silurian intervals and 66 Ordovician intervals in the six deep boreholes to estimate the hydraulic properties of the sedimentary strata proposed to host and enclose the DGR. The testing provided continuous coverage using ~30-m straddle intervals of the strata exposed in boreholes DGR-2, DGR-3, DGR-4, and DGR-5, while testing was targeted on discontinuous 12.0-m and 10.2-m intervals in DGR-1 and DGR-6, respectively.

As has become standard practice for radioactive waste disposal programs examining low-permeability media (e.g., Grisak et al., 1985; Almén et al., 1986; Beauheim and Roberts, 2002; Distinguin and Lavanchy, 2007), pulse tests (Wang et al., 1978; Bredehoeft and Papadopulos, 1980; Forster and Gale, 1981; Neuzil, 1982; Pickens et al., 1987) were performed in most of the test intervals; drillstem and/or slug tests were performed in the remaining intervals. Pulse tests entail creating an essentially instantaneous pressure change within an isolated (shut-in) test interval and then monitoring the return of the pressure to equilibrium. This testing program pioneered the use of a hydraulic piston incorporated in the downhole testing assembly to create the pressure pulses, allowing more accurate determination of test-zone compressibility, and hence hydraulic conductivity, than other methods of pulse generation.

The tests were analyzed using nSIGHTS (n-dimensional Statistical Inverse Graphical Hydraulic Test Simulator), a finite-difference code that allows incorporation in the test analysis of the pressure history experienced by a test interval prior to testing, which was identified as a critical consideration in testing of low-permeability media by Pickens et al. (1987). Non-linear parameter estimation methods are used in nSIGHTS to find the optimal values of the model fitting parameters (typically hydraulic conductivity, specific storage, formation pressure, and skin properties) that provide the best statistical match to the observed test data (Geofirma and INTERA, 2011). A unique attribute of nSIGHTS is the ability to perform a perturbation analysis to quantify parameter uncertainty and define parameter correlations that influence confidence in derived formation hydraulic conductivity estimates.