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Variation of horizontal in situ stress with depth for long-term performance evaluation of the Deep Geological Repository project access shaft

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ABSTRACT

A site characterization program was carried out for a proposed Deep Geological Repository (DGR) project for Ontario Power Generation's (OPG) low- and intermediate-level nuclear waste repository near Kincardine, Ontario. The repository is proposed to be constructed at approximately 680 m below ground surface within the competent argillaceous limestone of the Cobourg Formation. The in situ stress state at the project site will have significant impact on both the short- and long-term performance of repository openings, such as emplacement caverns and access shafts. As part of the site characterization program, an evaluation of the in situ stress state of the project site was conducted which consisted, primarily, of a review and synthesis of existing stress measurements conducted at various locations throughout Ontario and the midwestern U.S. Based on geomechanics data from deep boreholes and stress measurement data, a simplified *FLAC3D* model of the full stratigraphic profile was developed and used to simulate the influence of regional tectonic strain in the project area. In particular, this method takes into account the rock properties, such as stiffness, for discrete units at the DGR site. The model was calibrated on the basis of in situ stresses measured at Norton Mine, in a similar geological environment as the DGR site, and with site-specific borehole televiewer observations (i.e., breakouts). The model-predicted horizontal in situ stress profile showed general agreement with the observations and also showed the significant influence of discrete rock unit stiffness.

1. Introduction

Ontario Power Generation (OPG) is evaluating the development of a Deep Geological Repository (DGR) for long-term storage of Low- and Intermediate-Level Nuclear Waste (L&ILW) at the Bruce nuclear site near Kincardine, ON. The repository is proposed to be constructed at approximately 680 m below ground surface (mBGS) within the competent argillaceous limestone of the Cobourg Formation. A conceptual illustration of the proposed DGR is shown in Fig. 1. In support of this project, numerous geoscience and engineering studies have been carried out as part of a site characterization program. A detailed description of these studies is summarized in Intera[1] and NWMO.[2]

From a rock mechanics engineering perspective, one of the key challenges is the determination of contemporary ground stresses at the DGR project site. In situ stresses are influenced by several factors, the most dominant being: tectonic strain, glaciotectonics and isostatic rebound, regional and local structural geology, deposition and erosion, and topography. Moreover, the geological history associated with these events is also a major factor. As a result, the stress regime can be complex and variable.

The stratigraphic profile at the site consists of a near horizontally bedded sequence of carbonates and shales. The strength and stiffness characteristics of these various discrete rock units are anticipated to vary significantly. Amadei et al.[3] and Esterhuizen et al.,[4] have shown that horizontal in situ stresses could be dependent on the stiffness of discrete rock units. Further to that, these horizontal stresses vary with direction in the horizontal plane with a maximum principal horizontal stress, σ_H, and minimum principal horizontal stress, σ_h.

Currently, there are no in situ stress measurements at the project site. There are great challenges in obtaining, within suitable confidence levels, the in situ stress magnitude and orientations at the depth of interest from a surface-based exploratory borehole. This is particularly the case for the horizontally bedded formations at the Bruce nuclear site as hydrofracture techniques cannot be used with confidence because the vertical stress is less than the horizontal stresses.[5] Traditional strain-relief methods, such as overcoring, are suitable only for relatively shallow measurements and testing within exploration boreholes at the repository depth has not been successfully demonstrated. Consequently,

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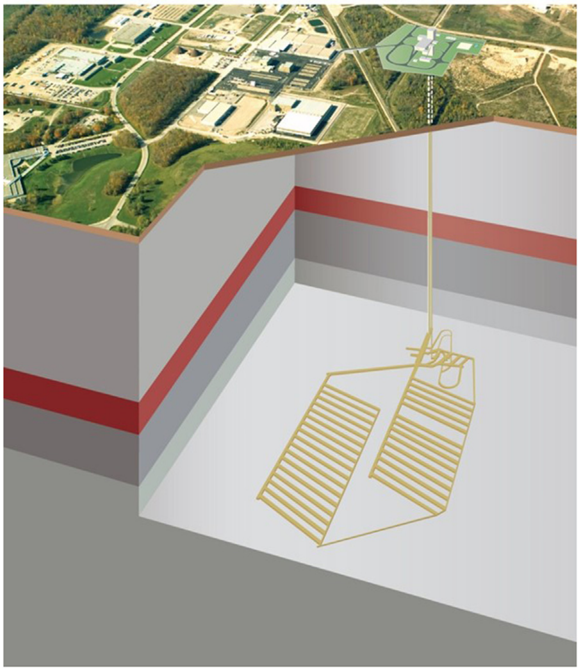

Fig. 1. Conceptual illustration of proposed DGR project at the Bruce Nuclear Site (after[31]).

during the course of the DGR site characterization program, the state of in situ stress was estimated based on several lines of reasoning including: regional stress data[6–9]; observations made during drilling and monitoring of the DGR series of vertical boreholes[1]; and the in situ stress modelling of the sedimentary succession below the site described in this paper.

As part of a project to evaluate the long-term performance of shafts and repository excavation openings,[10] the authors have examined in situ stress conditions, in particular the variation of horizontal stresses due to rock unit stiffness within the sedimentary sequence. This was done by carrying out a three-dimensional finite difference analysis model using *FLAC3D*[11] to simulate the tectonic strain within the sedimentary sequence. The model was calibrated with the site-specific borehole televiewer observations and other in situ stress observations pertinent to the project site.

This paper first presents a review of the in situ stresses from literature followed by the interpretation of acoustic televiewer data from deep exploration boreholes at the site. Finally, the in situ stress model analysis (*FLAC3D*) that accounts for the contrasting stiffness of the various layers is described. The findings from these three approaches are compared.

2. Background: in situ stresses in Southern Ontario

This section presents a brief overview of the geological setting in the project area and a review of in situ stress measurement compilations carried out for the Southern Ontario region. The in situ stress measurement carried out at 670 m depth in Norton Mine, Ohio, is also discussed.

2.1. Geological setting

A summary of the regional site geology of the proposed site is presented in.[1] The NE-SW trending Algonquin Arch separates the Michigan and Appalachian Basins in Southern Ontario (see Fig. 2). The proposed DGR site is in the eastern portion of the Michigan Basin within a sequence of sedimentary units of Upper Cambrian to Upper Devonian age. The sedimentary rocks rest on the southern margin of the Canadian Shield crystalline basement rocks of the Proterozoic Grenville Province. A stratigraphy profile of the bedrock at the DGR site based on four deep boreholes is shown in Fig. 3.[1]

2.2. Vertical stresses

It is generally believed that the vertical in situ stress (σ_v) in the region is comprised of a simple gravitational gradient based on the density of the rocks within the stratigraphic section. Given that the sedimentary rocks in the upper approximately 800 m have similar density, a uniform vertical stress gradient is a suitable approximation for the depths under consideration for the DGR project. Valley and Maloney[12] proposed: $\sigma_v = 0.0259z$ (in MPa): where z is depth in meters.

2.3. Horizontal stresses

Based on the geological (i.e., tectonic) history of the region, high horizontal stresses exist and this has been supported by numerous measurements and observations.[13] The horizontal to vertical principle stress ratios for the maximum horizontal stress ($K_H = \sigma_H/\sigma_v$) and minimum horizontal stress ($K_h = \sigma_h/\sigma_v$) both exceed one. Different horizontal stress gradients have been reported by several authors, some prepared specifically for the DGR project, and these are summarized in the following sections.

2.3.1. Adams and Bell, 1991

Using overcoring stress measurements in shallow boreholes and workings, and deep hydraulic fracturing borehole data from Darlington, Ontario, Adams and Bell[6] demonstrated the high horizontal compressive stress characteristic of the Mid-Plate Stress Province of Eastern North America. Most of the stress data are measured in the Paleozoic rock sequence of Southern Ontario which consists of near flat-lying carbonate, shale and sandstone formations of Ordovician, Silurian and Devonian periods. The state of high horizontal stress in the rock of this region is primarily the product of major depression of the area during the Wisconsin Glaciation and subsequent isostatic rebound. Adams and Bell[6] presented data mostly from Silurian and Ordovician formations while deep hydraulic fracturing stress values, to depths of just over 300 m in the Precambrian Shield basement, were measured at Darlington, Ontario by Haimson and Lee.[14] A compilation of stress measurements in the Precambrian Shield for Northern Ontario was developed by Kaiser and Maloney[8] and updated by Yong and Maloney.[15] The results from the former are discussed in the following section.

The reported strain relief in situ stress measurements conducted at shallow depths were all obtained using USBM (United States Bureau of Mine) borehole deformation gauges. The measurements show significant scattering, but provide a general trend for the in situ stress gradient with depth. Hydraulic fracturing tests indicated a lower vertical stress gradient with depth. Based on these findings, the following expressions of vertical horizontal in situ stress with depth were established (with stress in MPa, and depth in meters, in the following and subsequent equations):

$$\sigma_H = 0.027z \tag{1}$$

$$\sigma_h = 0.017z \tag{2}$$

2.3.2. Kaiser and Maloney, 2005

Kaiser and Maloney[8] published a review of an in situ stress database for the Ontario portion of the Canadian Shield. Much of the shield database was a recompilation of an in situ stress database compiled by CANMET Mining and Mineral Sciences Laboratories.[16] This study utilized linear regression techniques on overcoring measurement data from mines in northern Ontario, subdividing the Shield region into various sub-regions and three depth zones or “stress domains” similar to