Evaluation of coupled hydro-mechanical behaviour of in-situ shaft sealing components

Évaluations du comportement hydromécanique couplé de composants de scellement d'étanchéité in-situ

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ABSTRACT: A full-scale shaft seal was designed and constructed in a 5-m-diameter main shaft at Canada's Underground Research Laboratory (URL) in 2009 to isolate two hydrogeochemcial regimes. Coupled hydro-mechanical (H-M) numerical modelling was conducted using finite element method to examine the performance of this shaft seal and the numerical results were compared with the measured values. Overall predictions of changes in suction and degree of saturation in the clay seal component show good matches with the measured data. As of 2015, both numerical results and measured data indicate that the centre region of the clay seal was not fully saturated yet and still evolving toward its equilibrium. This results in gradual increase in the total pressure in the region because of swelling of clay during hydration. Performance of coupled H-M analyses has provided a better understanding of various inter-related phenomena occurring during hydration of the shaft seal components.

RÉSUMÉ : Un system complet de scellement d'étanchéité a été conçu et construit dans un puit principal de 5 m de diamètre au Laboratoire de recherche souterrain du Canada (LRS) en 2009 pour isoler deux régimes hydrogéochimiques. Un modèle couple hydromécanique (H-M) a été réalisé en utilisant la méthode des éléments finis pour examiner la performance de ce scellement d'étanchéité et les résultats numériques ont été comparés avec les valeurs mesurées. Les prévisions globales des changements de succions et de degré de saturation dans le composant d'étanchéité argileux ont démontré de bons résultats avec les données mesurées. En 2015, les résultats numériques et les données mesurées indiquent à la fois que la région centrale du scellement argileux n'a pas encore été complètement saturée et converge vers son point d'équilibre. Il en résulte une augmentation progressive de la pression totale dans la région en raison de gonflement de l'argile pendant l'hydratation. Les analyses de performance de couplage H-M ont permis de mieux comprendre les différents phénomènes interdépendants ayant lieu lors de l'hydratation des composants de scellement d'étanchéité.

KEYWORDS: shaft seal, coupled hydro-mechanical modelling, fracture zone, clay

1 INTRODUCTION

A shaft seal is one of the engineered barriers considered by Canada's Nuclear Waste Management Organization (NWMO) for use in isolating and containing used nuclear fuel in a deep geological repository (DGR). Shaft seals should be installed at strategic locations such as where significant fracture zones (FZs) are located after completion of operations for nuclear wastes or during repository closure. These shaft seals are normally composed of both clay-based and concrete-based sealing components. The primary function of a shaft seal is to limit short-circuiting of the groundwater flow regime via the shaft.

As part of the closure of Canadian's Underground Research Laboratory (URL), a full-scale shaft seal that is a composite concrete-clay-concrete seal has been constructed at the intersection of a low dipping thrust fault (FZ2 in Figure 1). This shaft seal was required for isolating the two hydrogeochemical regimes (i.e., the shallow-sourced, less saline groundwater and the deeper, higher salinity groundwater).

The evaluation of the functionality of the shaft seal requires a good understanding of the performance of these sealing components and the host medium. The behaviour of the clay-based sealing component is highly complex and involves coupled hydro-mechanical (H-M) phenomena that takes place during hydration of the sealing materials. Numerical modelling can be an effective way to bridge the gap between the theoretical and empirical understanding of the H-M processes occurring and the overall performance of the sealing system. In addition, numerical modelling of the shaft seal as part of repository engineering design allows for longer-term performance assessment than could be achieved by any physical experiment.

This paper presents the numerical results of a coupled H-M analysis of the shaft seal using the best parameter estimation currently available. The results of numeral analysis are compared with the measured field data. The fully coupled H-M analysis allows for understanding the variety of interacting phenomena occurring during hydration.

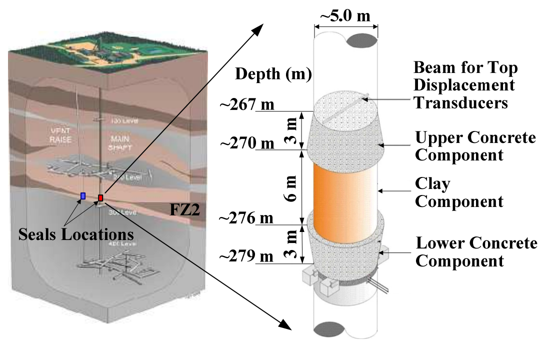

Figure 1. Conceptual shaft seal at fracture zone 2 at the URL

2 DESCRIPTION OF A SHAFT SEAL AT CANADA'S UNDERGROUND RESEARCH LABORATORY

The shaft seal consists of a 6-m-thick clay component sandwiched between 3-m-thick upper and lower concrete components (Figure 1). The clay component is an in-situ compacted mixture of Wyoming bentonite (40% dry mass) and quartz/feldspar sand (60% dry mass). It extends approximately 1 m beyond the maximum identified extent of the fracture zone at either end. A suite of 68 instruments were installed in and around the shaft seal (Martino et al. 2010). The composite concrete-clay-concrete seal constructed in the main shaft at FZ2 represents a real field demonstration and application of conceptual designs. Experiment data has been collected since

2009 and has provided valuable information on the performance of a repository seal system and a valuable opportunity to evaluate what parameters are critical in the hydration process.

3 NUMERICAL MODELLING OF A SHAFT SEAL

In this study, a Finite Element Method (FEM) program, CODE_BRIGHT was used to examine coupled H-M behaviour of the sealing system. An elastoplastic constitutive model was used to describe the behaviour of the unsaturated soil. The Basic Barcelona Model (BBM) developed by Alonso et al. (1990) was used to determine a set of behavioural parameters for use in describing the mechanical behaviour of the sealing system components. The hydraulic behaviour of the sealing components was defined using the van Genuchten's (1980) soil-water characteristic curve (SWCC).

3.1 *Model geometry*

The two-dimensional axisymmetric model of the shaft seal at the URL is shown in Figure 2(a). The domain in the numerical model has 100 m radius and 200 m thickness. This domain size was determined after performing scale effect analysis using different domain sizes. The shaft seal is placed at 97 m above the bottom of the model, corresponding to a depth of 276 m below surface.

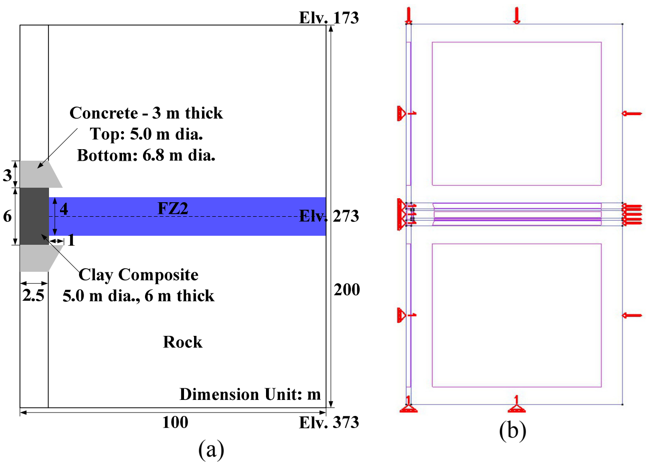

Figure 2. (a) Dimensions of numerical model geometry and (b) initial boundary conditions.

3.2 *Initial and boundary conditions*

In order to complete a numerical simulation of the shaft seal's evolution a series of initial state and boundary conditions must be defined. These are so far as possible based on measured initial conditions. The evolution of the system is modelled using a series of previously established behavioural relationships. The assumed and applied initial and boundary conditions are as follows:

(1) At the time of shaft seal installation, linear change in pore water pressure in the surrounding rock mass and values of 0.9 MPa and 2.9 MPa for the depth of top (-173 m) and bottom (-373 m) were applied respectively.
(2) No fluid flow at the boundary.
(3) An initial stress from 0 to 120 kPa was linearly applied across the clay seal due to its bulk unit weight of 19.9 kN/m^3.
(4) Pore air pressure is constant and equal to zero in the clay seal. Initial suction of 12.8 MPa in the clay seal was applied, corresponding to an initial degree of saturation of ~ 66%.
(5) The top and bottom boundaries of the model were fixed in the Y-direction and the outside boundary of the model was fixed in the X-direction.
(6) FZ2 was assumed to be perfectly horizontal to simplify the conceptual model and homogeneous hydraulic behaviour.

Figure 2(b) illustrates the H-M boundary conditions. Table 1 shows properties of the clay seal component after installation.

Table 1. Properties of clay seal component after installation

Average Dry Density (Mg/m^3)	1.81
Average Bulk Density (Mg/m^3)	2.03
Average EMDD[(1)] (Mg/m^3)	1.04
Specific Gravity, Gs	2.7
Average Water Content (%)	12.1
Porosity	0.33
Initial Degree of Saturation (%)	66.4

Note: [(1)] EMDD (Effective Montmorillonite Dry Density)

3.3 *Determination of material parameters for numerical modelling*

3.3.1 *Hydraulic parameters of clay seal material*

The soil-water characteristic curve (SWCC) for constant volume (i.e., dry density of the clay seal remained unchanged at 1.81 Mg/m^3) was derived using van Genuchten's equation (1980) that is used in CODE_BRIGHT. The SWCC used for this modelling is described by the following equations:

$$S_{re} = \left[1 + \left(\frac{s}{P_0}\right)^{1/(1-\beta_1)}\right]^{-\beta_1} \tag{1}$$

where s is suction in MPa; P_0 is the air entry value. S_{re} is the effective degree of saturation and is expressed as follows:

$$S_{re} = \frac{S_r - S_{rres}}{S_{r\,max} - S_{rres}} \tag{2}$$

where S_r is the absolute degree of saturation, S_{rres} is the degree of residual saturation and S_{rmax} is the degree of maximum saturation. Using existing laboratory data for bentonite-sand (50-50) mixtures compacted to dry density of ~1.7 Mg/m^3 (Anderson 2003, Blatz 2000, Tang 1999, and Wiebe 1996), the fitting parameters of P_0 and β_1 were estimated to be 12 MPa and 0.36, respectively (Figure 3).

It is noted that the clay seal installed in the shaft seal consists of a bentonite/sand ratio of 40%/60%, while the laboratory test data used to generate many of the behavioural parameters has a bentonite/sand ratio of 50%/50%. A key characteristic of the bentonite-sand mixture (BSM) is that when the bentonite content exceeds approximately 30%, the material is considered to have a clay-dominated behaviour (Graham et al. 1992), which means that the fundamental behaviour of these two materials should be similar and existing laboratory-generated test data can be used to estimate the properties of the bentonite-sand mixture.

The hydraulic conductivity of the clay seal material was determined using the following equation presented by Gens et al. (1998), which was described as a function of its saturation.

$$K = K_0 \cdot S_{re}^{1/2}(1-(1-S_{re}^{1/\beta})^{\beta})^2 \tag{3}$$

where K is the hydraulic conductivity of the unsaturated buffer in m/s; K_0 is the saturated hydraulic conductivity. The saturated hydraulic conductivity, K_0 of the clay seal was determined using the relationship between Effective Montmorillonite Dry Density (EMDD) and hydraulic conductivity (Dixon et al. 2002). At installation, the average EMDD for clay seal material was 1.04 Mg/m^3, corresponding to saturated hydraulic conductivity in order of 10^{-12} m/s. The regression parameter β has a typical value of 0.3 for sand-bentonite mixtures was used (Gens et al. 1998).

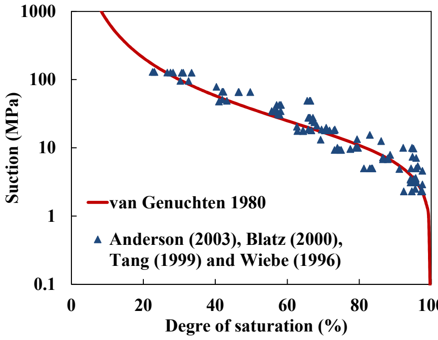

Figure 3. Plot of suction versus degree of saturation for clay seal material using experimental data

3.3.2 *Mechanical parameters of clay seal material*

The following equations of the Barcelona Basic Model proposed by Alonso et al. (1990) were used to determine mechanical parameters of the clay seal material. The equation for the yield curve in p-s space is:

$$\left(\frac{P_0}{P^c}\right)=\left(\frac{P_0^*}{P^c}\right)^{[\lambda(0)-k]/[\lambda(s)-k]} \quad (4)$$

where P_0 is preconsolidation stress at varying suction (s), P_0^* is preconsolidation stress for saturated conditions, P^c is reference stress, and λ(s) is the stiffness parameter at a given suction (s). In the numerical study, preconsolidation stress, $P_0^*$of 1 MPa for saturated condition was used (Blatz and Graham 2003). The stiffness parameter related to suction, λ(s) is calculated by the following equation:

$$\lambda(s)=\lambda(0)[(1-r)\exp(-\beta s)+r] \quad (5)$$

where λ(0) is the stiffness parameter for changes in net mean stress at saturation, r is a parameter defining the maximum soil stiffness; s is suction and β is a constant describing the rate of increase in soil stiffness with suction.

Lingnau et al. (1995) reported 0.12 for λ(0) and 0.0256 for κ, elastic stiffness parameter for changes in net mean stress, from his undrained triaxial tests on saturated bentonite-sand (50-50) mixtures. Values of P_0 and s were obtained from laboratory testing of a bentonite-sand (50-50) mixture (Blatz and Graham 2003). These values were then used to determine values of reference stress (P^c), r and β. Parameters r and β were determined using Equations (4) and (5). The following values were determined and used in this study: r = 0.65, β = $5\text{x}10^{-7}$ Pa^{-1} and $P^c = 1.8\text{x}10^5$ Pa.

A value of 0.0111 for the stiffness parameter κ_s for changes in suction in the elastic region was estimated using laboratory data from Blatz and Graham (2003). A value of 0.111 for λ_s, the stiffness parameter for changes in suction in the plastic region, was estimated based on suggestion provided by Volckaert et al. (1996), which λs would be ten times greater than κ_s. The slope of the critical state line (M) of 0.526 was used for the clay seal material (Lingnau et al. 1995).

3.3.3 *H-M parameters of granite rock*

Soil-water characteristic curve for granite rock was generated using van Genuchten's equation (1980). Values of 0.33 for β_1 and 0.7 for P_0 were suggested for granite rock (Gents et al. 1998 and Thomas et al. 2002). The hydraulic conductivity for intact granite rock typically ranged from 10^{-12} to 10^{-13} m/s (Martino 2006) and the hydraulic conductivity for the intact rock was assumed to be 4 x 10^{-13} m/s. The hydraulic conductivity of FZ2 ranged from 10^{-7} to 10^{-9} m/s (Everitt et al. 1996) and it was assumed to be 1 x 10^{-9} m/s. The granite rock was assumed to be linear elastic. Its Young's modulus was set as 60 MPa and its Poisson's ratio was set as 0.22 as suggested by Graham et al. (1997).

3.3.4 *H-M parameters of concrete component*

The concrete components were assumed to be linear elastic. Its mechanical and hydraulic parameters were assumed to be the same values as those for the granite rock.

4 RESULTS OF NUMERICAL MODELLING

4.1 *Hydraulic behaviour of clay seal compared with expe riment data*

4.1.1 *Suction prediction in the clay seal*

Figure 4 shows predicted evolution of suction in the clay seal with time. The numerical results indicate that the clay seal will be fully saturated after 22 years and the suction of the clay seal will come to equilibrium after 27 years. It also indicates that decrease in suction is concentrated along the fracture zone due to its greater hydraulic conductivity.

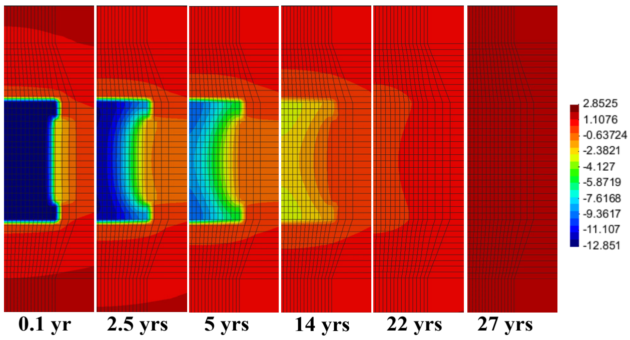

Figure 4. Suction prediction in the clay seal with time

4.1.2 *Prediction of degree of saturation in the clay seal*

For predicting degree of saturation at the mid-height of the clay seal (6 m from the shaft seal), Figure 5 shows good matches between numerical predictions and field time domain reflectometry (TDR) measurements. The reason for the good match can be that the centre region is likely the most homogeneous region and is being directly affected by groundwater flow from FZ2. The numerical results underestimate evolution of degree of saturation in the region from the beginning to approximately 3 years and then capture its evolution reasonably well after 3 years. As of December 2015, both the field data and numerical results indicate that the clay seal was not fully saturated (degree of saturation of ~ 82% at the centre and ~ 90% at 1.25 m from the centre).

4.2 *Mechanical Behaviour of Clay Seal Compared with E xperiment Data*

Figure 6 shows predicted total pressures in the clay seal compared with the measured total pressures. The numerical results show a slow increase in total pressure until ~16 years and a rapid increase after that time, while the measured total pressures start developing gradually after about 0.7 year. The possible explanation of this discrepancy between the measured data and the simulated values is likely that the 2-D numerical model considers only two directions (horizontal and vertical) of groundwater flow from FZ2, while in the real condition of the shaft, groundwater flows radially toward the perimeter of the clay seal. As a result, saturation at the location of the sensors was anticipated to occur more quickly than that of the numerical simulation. Despite the discrepancy observed, the predicted vertical pressure for 100 years is approximately 2.7 MPa, which is close to the final vertical pressure of 3.3 MPa (i.e., swelling pressure of ~0.8 MPa and piezometric pressure of ~2.5 MPa) anticipated after the clay seal comes to equilibrium.

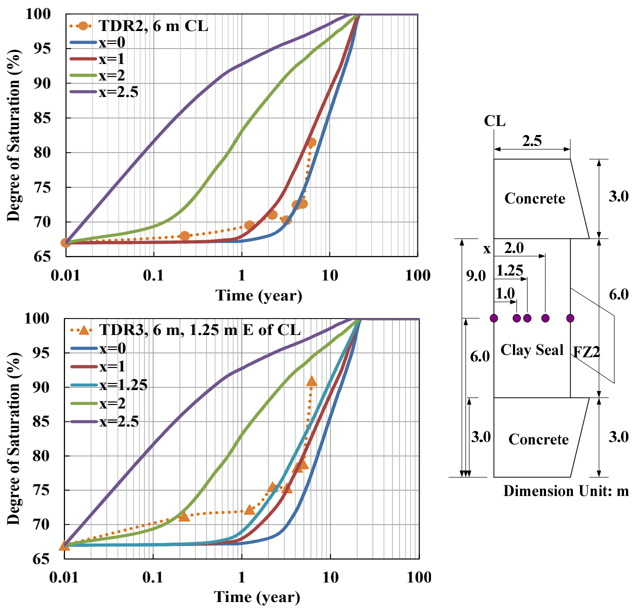

Figure 5. Predicted degree of saturation compared with TDRs

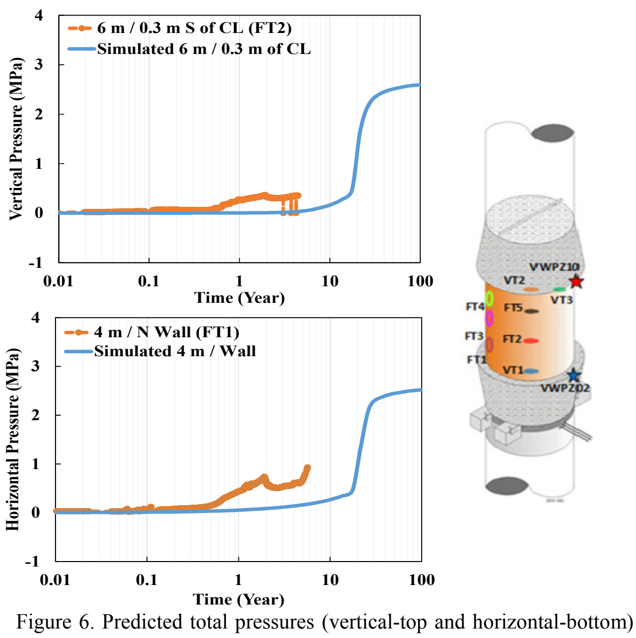

Figure 6. Predicted total pressures (vertical-top and horizontal-bottom) compared with total pressure cell (TPC) data (note: FT-fibre optic TPC)

Within the clay seal no instrument installed to measure the internal displacements during the experiment. Only simulated displacements in the clay seal are therefore presented. Figure 7 shows the horizontal displacement along a vertical line, 1.25 m from the centre of the clay seal. It indicates that the clay seal moves inwards (compression) due to the restraint of the rock wall of the shaft, the effects of water pressure at the perimeter and swelling of the clay at the perimeter. The largest internal radial displacement of about 8.5 mm occurs at 3 m from the bottom of the clay seal, corresponding to the centre region of FZ2.

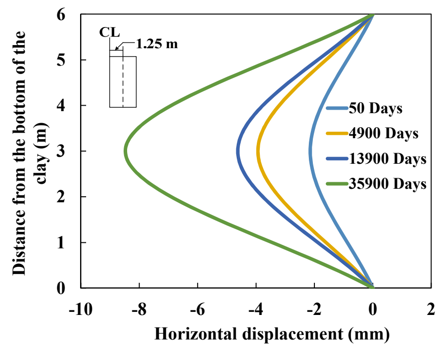

Figure 7. Simulated horizontal (radial) displacement within clay seal

5 CONCLUSIONS

The results of coupled H-M numerical modelling were compared with the field instrumentation readings. Overall the numerical results captured reasonably well the field readings, especially for changes in suction and degree of saturation in the clay seal. The results and the field measurements confirm that the centre region of the clay seal has not been fully saturated yet and still evolving toward its equilibrium, indicating gradual increase in total pressure in the region.

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