Understating the performance of sealing materials under the influence of groundwater salinity

Sumi Siddiqua[1], Deni Priyanto[2] & James A. Blatz[1]
[1] *Department of Civil Engineering, University of Manitoba, Winnipeg, Manitoba, Canada*
[2] *Atomic Energy of Canada Limited, Pinawa, Manitoba, Canada*

ABSTRACT
Two different clay-based sealing materials were examined in the laboratory for understanding the hydro-mechanical (HM) performance of materials as part of the conceptual design of Canadian deep geological repository. Tests were carried in oedometer with several loading schedule and with various concentration of pore fluids. Emphasis was given to evaluate the material parameters under a wide range of pore fluid salinity. Experimental finding provide important material parameters for numerical modeling. These parameters will be used to conduct numerical simulation of the sealing materials using a finite difference based computer code (FLAC).

RÉSUMÉ
Deux différents scellants conformés à l'argile ont été examinés dans le laboratoire pour avoir une meilleure compréhension de la performance hydro-mécanique des matériaux qui font partie de l'étude de conception du dépôt dans des formations géologiques profondes Canadiennes. Des tests d'oedomètre ont été effectués avec plusieurs horaires de chargement et avec divers fluides interstitiels. L'emphase était mise sur une évaluation des paramètres des matières sous une gamme étendue de salinité des fluides interstitiels. L'étude expérimentale fournit les paramètres des matières importantes pour la modélisation numérique. Ces paramètres utilisent une différence finie basée sur le code interne FLAC qui est ensuite utilisés pour diriger la simulation numérique des scellants.

1 INTRODUCTION

Several sealing-system components are proposed to use in the design of engineered barrier system (EBS) in a Canadian deep geological repository (DGR) (Russell and Simmons 2003). Two of the materials are Dense Backfill (DBF) and Light Backfill (LBF). Apart from the sealing materials there are concerns on host rock environmental conditions. Gascoyne et al. (1987) and Mazurek (2004) have collated data from the crystalline rock of the Canadian Shield and the sedimentary rock in southern Ontario, respectively, and observed very high concentrations of dissolved salts. It can be greater than 200 g/L.

Characterization of the DBF and LBF are required to provide an input of the DGR numerical modelling. A series of 1D consolidation tests of the DBF and LBF have been conducted (Baumgartner et al. 2008, Priyanto et al. 2008a, Priyanto et al. 2008b, Kim et al. 2009) to obtain material properties. In these tests, the fluid conditions include distilled water, $CaCl_2$ solution, NaCl solution, and Na-Ca-Cl solution with the Total Dissolved Solid is in the range of 0-250 g/L, to simulate the possible groundwater condition.

This paper presents:

- brief description of laboratory tests on DBF and LBF.
- determination of parameters for DBF and LBF for numerical modelling.
- numerical modelling showing the application of these parameters to embankment loading and investigate the effect of different pore fluid on the consolidation behaviour of the clay based sealing materials.

2 LABORATORY TESTS

A number of 1D consolidation tests in oedometer has been completed on DBF and LBF with an extensive range of pore fluid chemical conditions and boundary conditions during saturation (Baumgartner et al. 2008, Priyanto et al. 2008a, Priyanto et al. 2008b, Kim et al. 2009 and Siddiqua et al. 2009). Chemical pore fluid conditions examined included salinities ranging from 50 g/L to 250 g/L NaCl, $CaCl_2$, or Na-Ca-Cl. Initial chemical conditions included specimen mixing with distilled water followed by saturation with the saline pore fluid of interest, and preparation with the saline pore fluid followed by saturation with the same fluid. Initial boundary conditions included constant volume during saturation and constant stress during saturation.

The DBF used in the laboratory tests is composed of 75% (by weight) crushed granite, 18.75% crushed illite clay (Sealbond) and 6.25% (by weight) Avonlea bentonite (montmorillonite content~80%). The LBF mixture composed of 50% (by weight) Avonlea bentonite and 50% (by weight) silica sand. The LBF was preconditioned to achieve gravimetric water content (w) of ~15% and compacted to dry density (ρ_{dry}) of ~1.24 Mg/m^3 to create the LBF specimens. The DBF mixture was preconditioned to w of ~8.5% and compacted from the mixture the ρ_{dry} of ~2.12 Mg/m^3.

Following saturation, oedometer testing was conducted according to ASTM D 2435 (2004), using conventional dead-weight-type oedometers. Standard 50-mm-diameter cells with 19-mm-thick specimens were used to test the LBF specimens. Larger 101-mm-diameter cells that allowed 101-mm-thick specimens were used to test the DBF specimens which contained granite aggregate up to 35 mm in size.

3 NUMERICAL MODELLING

This section describes the determination of parameters for the DBF and LBF with distilled water and saline solution from the 1D-consolidation test results. The applications of these parameters to simulate geotechnical engineering structure are then demonstrated to investigate the effect of different pore fluid in the consolidation behaviour of the DBF and LBF.

3.1 Model Description

In order to demonstrate the application of the parameters from 1D-consolidation tests, the response of a saturated soil foundation to loading by an embankment was studied in this paper (Figure 1). The soil is 10 meter thick and the groundwater free surface is at the ground level. The embankment was 8 m wide. Utilize the symmetrical feature of the problem, the size of the model is 20 m wide and 10 m thick, and it used 20x10 finite different grids. The mechanical boundary conditions correspond to roller boundary along the symmetry line and the far boundary of the model and fixed displacements in the x and y direction at the model base. The domain used in this numerical model may not be large enough to avoid the effect of the boundary condition. However, it is sufficient to study the relative effect of the different pore fluid on the consolidation behaviour.

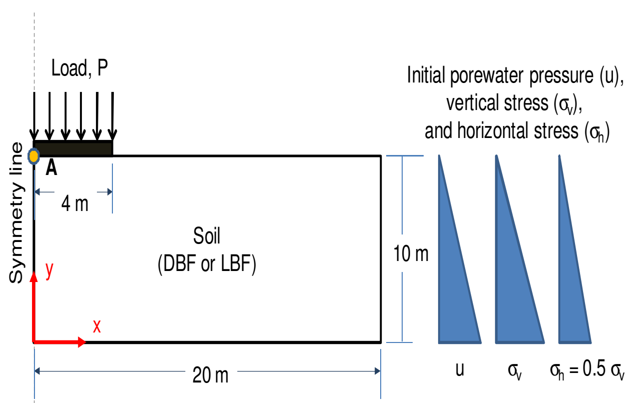


Figure 1. Model geometry and initial conditions

In order to investigate the effect of different pore fluids, four cases in Table 1 were studied. These four cases include:

i. DBF with distilled water
ii. DBF with 250 g/L $CaCl_2$ solution
iii. LBF with distilled water
iv. LBF with 227 g/L $CaCl_2$ solution

The case 1 and case 2 are studied with DBF material. Two different loads (P in Figure 1) such as 50 and 100 kPa were applied for these studies. The material is LBF in case 3 and case 4. The load P was equal to 1 kPa. The laboratory results already confirmed that DBF is stiffer material than the LBF. Therefore, the load P applied to the LBF was less than the DBF in order to limit the maximum displacement.

The initial vertical (σ_v) and horizontal stresses (σ_h) and porewater pressure (u) states correspond to equilibrium under gravity with a ratio of horizontal to vertical stress of 0.5. The distribution of initial σ_v, σ_h, and u are shown in Figure 1 and their values at the model base are summarized in Table 1.

Table 1: Initial vertical stress, horizontal stress and pore water pressure at the bottom

Case No.	1	2	3	4
Material	DBF	DBF	LBF	LBF
Fluid	Distilled Water	250 g/L $CaCl_2$	Distilled Water	227 g/L $CaCl_2$
Applied Load, P [kPa]	50,100	50,100	1	1
Initial vertical stress (σ_v) at the base [kPa]	-22.7	-22.7	-17.5	-17.5
Initial horizontal stress, (σh) at the base [kPa]	-11.35	-11.35	-8.75	-8.75
Initial porewater pressure (u) at the base [kPa]	100	100	100	100

3.2 Parameters

The vertical stress (σ_v) versus specific volume (v) response from the 1D-consolidation tests of the DBF and LBF using distilled water and saline solutions are shown in Figures 2, 3, 4, and 5. In these tests, the volume of the specimen was constant during initial saturation. The fluid used to prepare these four specimens was similar to the fluid in the reservoir during the 1D-consolidation test. The DBF specimen with saline solution utilized 250 g/L $CaCl_2$ solution (Figure 3), while the LBF specimen utilized 227g/L $CaCl_2$ solution (Figure 5).

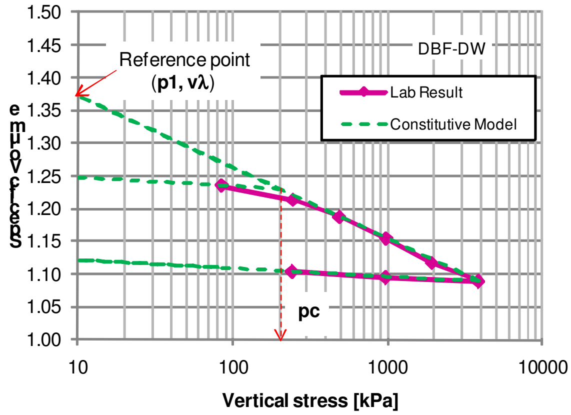


Figure 2. Comparison of laboratory results and the constitutive model response for DBF specimen with distilled water.

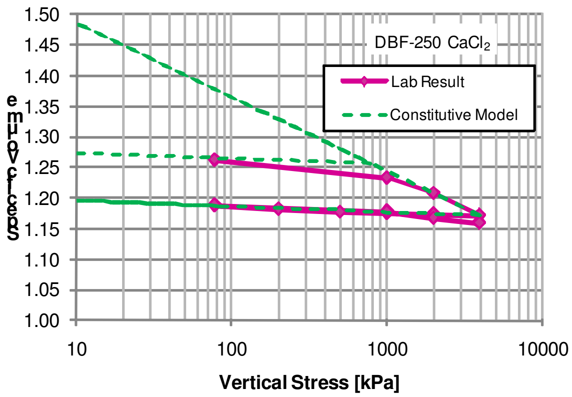


Figure 3. Comparison of laboratory results and the constitutive model response for DBF specimen with 250 g/L $CaCl_2$

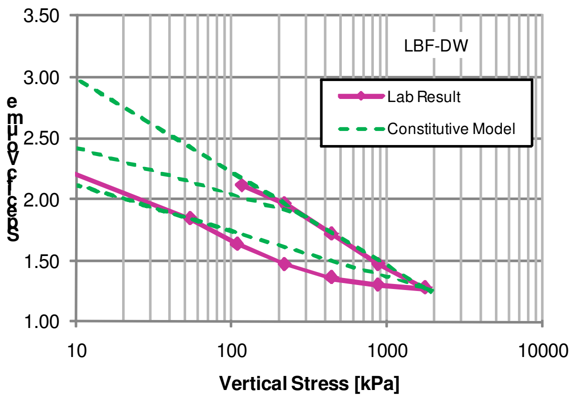


Figure 4. Comparison of laboratory results and the constitutive model response for LBF specimen with distilled water

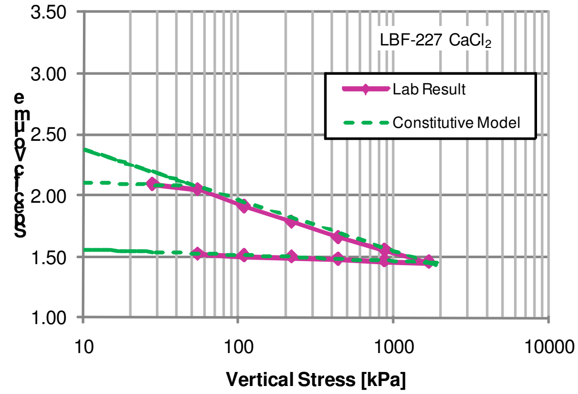


Figure 5. Comparison of laboratory results and the constitutive model response for LBF specimen with 227 g/L $CaCl_2$

This study used modified cam-clay (MCC) model (Roscoe and Burland 1968) to describe the behaviour of DBF and LBF. The parameters used in this study are summarized in Table 2. The results of the 1D-consolidation tests were used to determine the parameters κ, λ, p_c, p_1, and v_λ. Comparison of the MCC model response using these parameters with the 1D-consolidation test results are shown in Figures 2, 3, 4, and 5. Critical state slope, M was determined from the triaxial test results of the DBF and LBF (Man et al. 2010). The poisson's ratio (ν) of 0.3 are assumed for both DBF and LBF.

Table 2: Parameters used in the numerical modeling

Case No.	1	2	3	4
Material	DBF	DBF	LBF	LBF
Fluid	Distilled Water	250 g/L $CaCl_2$	Distilled Water	227 g/L $CaCl_2$
Kappa, κ	0.0054	0.0041	0.1639	0.0209
Lambda, λ	0.0474	0.0525	0.3314	0.1801
Initial preconsolidation pressure, p_c [kPa]	198	784	300	47
Reference point, p1 [kPa]	10	10	10	10
Reference point, v_λ	1.372	1.486	2.984	2.374
Critical state slope, M [a]	1.1	1.1	0.47	0.78
Poisson's ratio, ν	0.3	0.3	0.3	0.3
Hydraulic Conductivity, k_h [m/s]	1e-11	1e-11	1e-12	1e-12
Mobility coefficient [m^2/(Pa*s)]	1e-15	1e-15	1e-16	1e-16
Density of fluid [Mg/m3]	1000	1188	1000	1171
Specific gravity, Gs	2.643	2.643	2.702	2.702

Initial Properties				
Dry density [Mg/m^3]	2.12	2.12	1.24	1.24
Bulk density [Mg/m^3]	2.318	2.318	1.781	1.781
Porosity, n	0.198	0.198	0.541	0.541
Specific volume, v	1.247	1.247	2.179	2.179
Void ratio, e	0.247	0.247	1.179	1.179
Degree of saturation, S [%]	100	100	100	100
Water content [%]	9.3	9.3	43.6	43.6

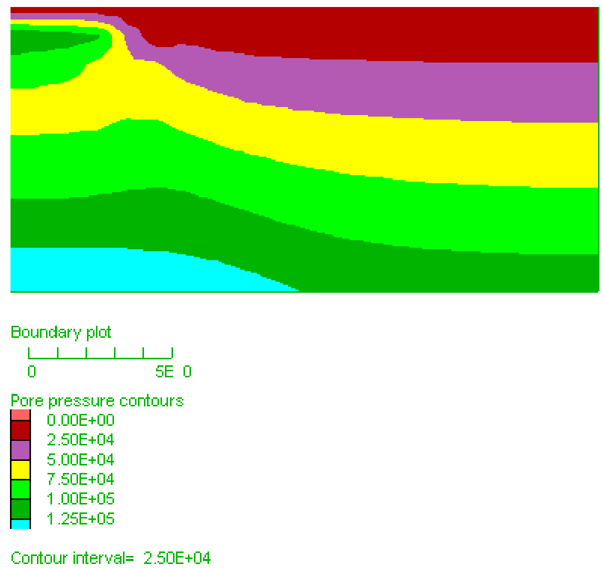
The hydraulic conductivity, k [m/s], was determined from the results of 1D-consolidation tests. Specific gravity (Gs) was calculated from the mineral composition of the DBF and LBF. Gs for the DBF and LBF are 2.643 and 2.702, respectively. The initial dry density of the DBF and LBF are 2.12 Mg/m3 and 1.24 Mg/m3, respectively. Since this analyses assumed 100% degree of saturation, the bulk density of the DBF and LBF are 2.32 and 1.78 Mg/m3, respectively.

4 RESULTS

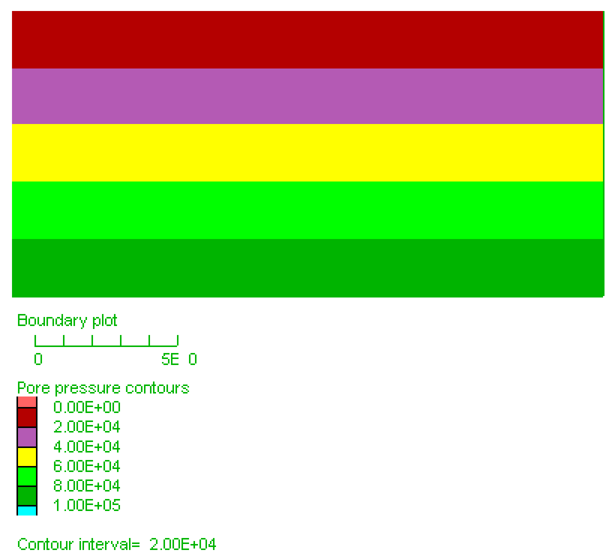
The analyses of the four cases described previously were completed using a 2-D finite difference code (FLAC). The analyses consist of 2 stages: undrained and drained conditions. The undrained condition simulated the short term response after the load being applied. The drain condition simulated the long term response after the load being applied.

4.1 Pore Water Pressure

Figures 6a and 6b show the porewater pressure contour at undrained and drained conditions for case 1, respectively. The porewater pressure underneath the embankment load increase after the load was applied (Figure 6a). After the consolidation process is complete, the porewater pressure contour recovers to the initial condition (Figure 6b).



(a) Undrained response (immediately after loading)



(b) Drained response (at the end of consolidation process)

Figure 6. Porewater pressure contour for the DBF with distilled water and 100 kPa load

4.2 Vertical Displacement

The vertical displacements at point A (underneath the embankment in Figure 1) from different analyses are compared.

Figures 7 and 8 show vertical displacement versus time at point A for DBF and LBF, respectively. Since the DBF is a stiffer material than the LBF, the parameters κ and λ for the LBF are greater than the DBF and the vertical displacement of the LBF is also greater than the DBF. The hydraulic conductivity of the LBF is one order magnitude less than the DBF (10^{-11} m/s for the DBF versus 10^{-12} m/s for the LBF); consequently the DBF reaches 100% consolidation faster than the LBF. The analyses in this study were completed up to 5000 years simulation time to examine the time requires to reach 100% degree of consolidation.

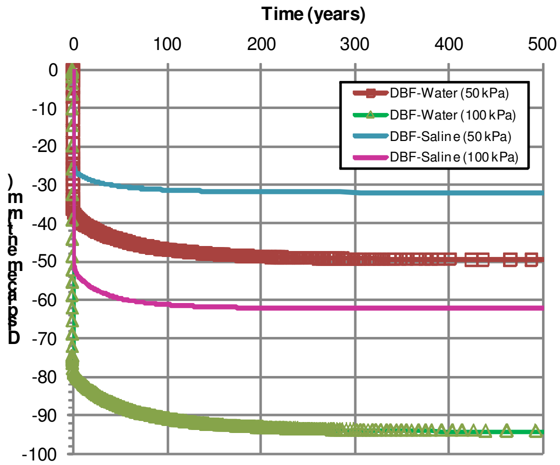


Figure 7.Displacement versus time at point A for DBF

The DBF has reached 100% consolidation within 500 years period (Figure 7). Since the LBF has lower k, the 100% consolidation has not been reached after 5000 years simulation time (Figure 8). The displacement at 5000 years for the LBF with distilled water and saline solution are shown in Table 3. Table 3 also summarizes the final displacements for the DBF with distilled water and saline solution with loads (P) of 50 kPa and 100 kPa.

Figures 7 and 8 show that presence of the saline solution can reduce the consolidation displacements.

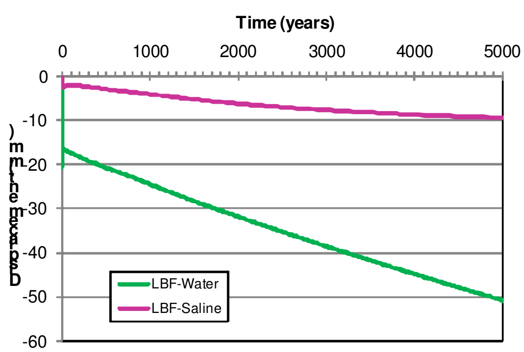


Figure 8.Displacement versus time at point A for LBF

Table 3: Vertical displacement at point A

Soil	Load [kPa]	Vertical displacement [mm]		Percentage of displacement reduced [%]
		D_{water}	D_{saline}	D_{red}
DBF	50	-49	-32	35
DBF	100	-94	-62	34
LBF	1	-50	-10	81

The percentage of the displacement reduces (D_{red}) due to the presence of the saline solution can be calculated as follows:

$$D_{red} = 100\% \times [D_{water} - D_{saline}] / D_{water}$$

where D_{water} is the displacement response for the case of soil with fresh water pore fluid. D_{water} is the displacement response for the case of soil with saline solutuion.

Limited to the case in this paper, the presence of saline solution can reduce the consolidation displacement by 34-35% in the DBF and 81% in the LBF material. It shows that the effect of the fluid salinity is greater in the LBF than the DBF. Note that the LBF has greater bentonite content than the DBF, so that the presence of the salinity has more effect on the LBF than the DBF.

3 SUMMARY

Results from 1D-consolidation tests were utilized to determine parameters to be used in numerical modelling of DBF and LBF materials. Numerical simulation results of porewater pressure and displacement for the two materials are presented. Limited to the cases presented in this study, the presence of the saline fluid can reduce the total consolidation displacement. As preliminary study, only limited data are used for numerical analysis. More laboratory data are available for the DBF and LBF, can be used for similar analyses.

ACKNOWLEDGEMENTS

The authors like to acknowledge the valuable supports from Alex Man and David Dixon.

REFERENCES

ASTM (ASTM International). 2004. Standard test methods for one-dimensional consolidation properties of soils using incremental loading. Standard D2435-04, ASTM International, West Conshohocken, Pennsylvania, USA.

Baumgartner. P, Priyanto, D.G, Baldwin, J.R, Blatz, J.A., Kjartanson, B.H., and Batenipour, H. 2008. *Preliminary results of one-dimensional consolidation testing on bentonite clay-based sealing components subjected to two-pore liquid chemistry conditions.* Nuclear Waste Management Organization (NWMO) Technical Report No. TR-2008-04. Toronto, Canada.

Gascoyne, M., Davison, C.C, Ross, J.D., and Pearson. R. 1987. Saline groundwaters and brines in plutons in the Canadian Shield. In *Saline Water and Gases in Crystalline Rocks*. (Fritz, P. and Frape, S.K., Eds.), Geological Association of Canada Special Paper 33, Ottawa.

Kim, C-S, Priyanto, D.G., Blatz, J.A., Siemens, G.S.,. Siddiqua, S, Peters, S.B and Dixon, D.A. 2009. *The Effects of Fluid Composition on the One-Dimensional Consolidation Behaviour of Clay-Based Sealing Materials (2006-2009).* Nuclear Waste Management Organization (NWMO) Technical Memorandum April 2009.

Man, A., Priyanto, D., Siemens, G., and Siddiqua, S. 2010. *The effect of pore fluid chemistry on strength and stress-strain behaviour of light and dense backfill material.* Paper submitted to the 4th International Meeting on Clays in Natural & Engineered Barriers for Radioactive Waste Confinement at Nantes, France, 2010 March 29 – April 1.

Mazurek, M. 2004. *Long-term used nuclear fuel waste management-Geoscientific review of the sedimentary sequence in southern Ontario.* Institute of Geological Sciences, Univ. of Bern, Technical Report TR 04-01, Bern, Switzerland, available from Nuclear Waste Management Organization, Toronto, Canada (www.nwmo.ca).

Priyanto, D. G., J. A. Blatz, G. A. Siemens, R. Offman, J. S. Boyle, and D. A. Dixon. 2008a. *The effects of initial conditions and liquid composition on the one-dimensional consolidation behaviour of clay-based sealing materials.* Nuclear Waste Management Organization (NWMO) Technical Report No. TR-2008-06. Toronto, Canada.

Priyanto, D. G., J. A. Blatz, G. A. Siemens, R. Offman, J. S. Boyle, and D. A. Dixon. 2008b. *The effects of fluid composition on the one-dimensional consolidation behaviour of clay-based sealing materials*. Nuclear Waste Management Organization (NWMO) Technical Report No. TR-2008-20. Toronto, Canada.

Roscoe, K. H., and Burland, J. B. 1968. On the generalized stress-strain behaviour of 'wet' clay. In J. Heyman & F. Leckie (Eds.), *Engineering Plasticity* (pp. 535-609). Cambridge: Cambridge University Press.

Russell, S.B., and Simmons, G.R. 2003. *Engineered barrier system for a deep geologic repository*. Presented at the 2003 International High-Level Radioactive Waste Management Conference. 2003 March 30-April 2, Las Vegas, NV.

Siddiqua, S. Blatz, J. and Siemens, G. 2009. Evaluation of pore fluid chemistry on the hydro-mechanical behaviour of clay based sealing materials. Manuscript submitted to Canadian Geotechnical Journal to be considered for publication.