Scale-model test for disposal pit of high-level radioactive waste and theoretical evaluation on self-sealing of bentonite-based buffers

| Journal:               | Canadian Geotechnical Journal            |
|------------------------|------------------------------------------|
| Manuscript ID          | cgj-2018-0805.R2                        |
| Manuscript Type:       | Note                                     |
| Date Submitted by the Author: | 06-Apr-2019                         |
| Complete List of Authors: | Komine, Hideo ; Waseda University, Department of Civil and Environmental Engineering |
| Keyword:               | Bentonite, Self-sealing, Swelling, Radioactive waste disposal, Scale-model test |
| Is the invited manuscript for consideration in a Special Issue? | Not applicable (regular submission) |
Scale-model test for disposal pit of high-level radioactive waste and theoretical evaluation on self-sealing of bentonite-based buffers

Hideo KOMINE, Doctor of Engineering
Professor, Waseda University, Department of Civil and Environmental Engineering
3-4-1, Okubo, Shinjuku-ku, Tokyo, 169-8555, Japan
Telephone +81-3-5286-2940
Fax number +81-3-5286-3485
E-mail hkomine@waseda.jp
ABSTRACT

Bentonite is attracting greater attention in Japan and some other countries as a buffer for use in repositories of high-level radioactive waste (HLW). Bentonite-based buffers for HLW disposal are expected, because of their swelling deformation, to fill spaces between buffers and walls of disposal pits, or between buffers and waste containers designated as overpack. Bentonite has self-sealing capability. This study conducts scale-model tests simulating the relation between the buffer and interstitial space. It also investigates the validity of theoretical equations for swelling presented by Komine and Ogata (2003; 2004) to evaluate buffer self-sealing capabilities by comparing calculated and experimentally obtained results of scale-model tests. Results of the experimental work described herein and calculations highlighted bentonite’s self-sealing capability and demonstrated the high applicability of equations of Komine and Ogata (2003; 2004) to quantify filling of interstitial spaces by bentonite-based buffer swelling.

Keywords: Bentonite, Self-sealing, Swelling, Radioactive waste disposal, Scale-model test
INTRODUCTION

Bentonite is attracting greater attention for use as a buffer material in repositories of high-level radioactive waste (HLW) in Japan and other countries. When used for HLW disposal applications, bentonite-based buffers, because of their swelling deformation, are expected to fill interstitial spaces between buffers and walls of disposal pits, and between buffers and waste containers. Bentonite-based buffers have a so-called self-sealing capability. Figure 1 portrays schematic drawings of an HLW disposal facility and an image illustrating the self-sealing capability of bentonite-based buffers.

To design and develop bentonite-based buffer specifications that can ensure self-sealing capability, the author earlier proposed theoretical equations for swelling characteristics of bentonite-based buffer (Komine and Ogata 2003, 2004). Moreover, the author validated those theoretical equations by comparing the calculated results with many experimentally obtained results of swelling pressure and swelling deformation characteristics of various bentonites and sand-bentonite mixtures.

To clarify the extended applicability of the theoretical equations proposed by the author, this study investigates bentonite-based buffers’ self-sealing capability using scale-model tests of a disposal pit and the component materials. This study also assessed the validity of the theoretical equations proposed by Komine and Ogata (2003, 2004) by comparing the results of calculations and experiments.

Many earlier studies exploring swelling of bentonite-based buffers have used experimentation to assess the fundamental swelling properties of bentonite (Agus and Schanz 2008; Alonso et al. 1999; Cui et al. 2002; Delage et al. 1998; Komine and Ogata 1994, 1996, 2003, 2004; Villar and Lloret 2008). Recently, some studies of bentonite swelling in different environmental conditions such as seawater and high temperatures have also been reported from elementary experiments (Karnland et al. 2007; Komine et al. 2009; Villar et al. 2010). Some studies have used numerical analyses and field measurements (e.g. Garitte et al. 2017). By contrast, few reports describe studies using scale-model testing of bentonite-based buffer. A few studies have assessed the self-sealing capability of bentonite-based buffer considering the relation between buffer swelling and interstitial space in the disposal pit and component materials. This study specifically examines the view above and investigates the self-sealing capability of bentonite-based buffer quantitatively.
SCALE-MODEL TESTING OF DISPOSAL PIT AND COMPONENT MATERIALS

This section presents a description of the scale-model test to simulate a disposal pit for HLW disposal presented in Fig. 1 and component materials. The scale-model test is axially symmetric, illustrating the relation between a buffer and space in a disposal pit.

Materials

This study used the sodium-type commercial bentonite, designated as Kunigel-V1 (2.79 Mg/m$^3$ particle density) produced before 1999 at the Tsukinuno Mine in Japan. The montmorillonite contents were calculated using methylene blue absorption values of each bentonite and montmorillonite (White and Michael 1979). The methylene blue absorption values of the old Kunigel-V1 are 67 meq/100 g. That of montmorillonite is 140 meq/100 g. Therefore, the montmorillonite content of the old Kunigel-V1 used for this study is nearly 48%.

The bentonite used for the present study was kept in a room at a constant temperature (22 ± 1 °C) and almost constant humidity (70–80%). The water contents of this material were 7.2–14.0%. This study also used Mikawa silicate sand No. 6, with particles having 2.66 Mg/m$^3$ density and 0.053–0.590 mm diameter.

Buffer specimen specifications and procedures

This study produced compacted bentonites and compacted mixtures of sand and bentonite of five kinds as buffer specimens. The Central Research Institute of Electric Power Industry (CRIEPI) and The Federation of Electric Power Companies of Japan (FEPC) proposed an example of the design of disposal pit and component materials in Fig. 2 (Ogata et al. 1999). According to the above proposal by the CRIEPI and the FEPC, the external form of bentonite-based buffer is toroidal. Also, the buffer outer diameter is 1620 mm; the inner diameter is 820 mm, with horizontal thickness of 400 mm. The toroidal specimen scale, as portrayed in Fig. 3(a), is approximately one-fifth of the specification above. Therefore, the specimen outer diameter is 332 mm; the inner diameter is 172 mm, with 80 mm horizontal thickness. The specimen height is 50 mm. The toroidal form is an effective candidate because constructing the buffer area is easy, as shown in Figs. 1 and 2.

This study used specimens of four kinds as explained by Ogata et al. (1999): those with dry densities of 1.62 Mg/m$^3$ and 1.77 Mg/m$^3$ for bentonite content of 80% and those with 1.61 Mg/m$^3$ and 1.84 Mg/m$^3$ for bentonite content of 100%. The study also used buffer specimens with dry density of 1.81 Mg/m$^3$ and bentonite content 70%, referring to the Japan Nuclear Cycle Development Institute (2000a,b).

https://mc06.manuscriptcentral.com/cgj-pubs
For toroidal specimen production, production jigs such as a mold and piston were made as presented in Fig. 3(b). This study used the compression apparatus of which the maximum capacity of the compression load is 5000 kN and the compression stress for producing specimens is 1.09–31.59 MPa. The compression duration is 15 min for all specimens.

Experimental apparatus and test procedure

This study used the experimental apparatus portrayed in Fig. 4, which simulated a waste container, a bentonite-based buffer, surrounding rock, and the interstitial space among components at the horizontal/radial direction. Those specifications above include the following: 400 mm buffer thickness, 40 mm space between the buffer and pit wall, and 10 mm space between the buffer and container. To measure the buffer pressure after filling up space, three pressure gauges were attached to the acrylic cell as shown in the right drawing of Fig. 4. The maximum pressure gauge capacity is 2000 kPa. The minimum scale is 0.5 kPa. The pressure gauge diameter is 5 mm. For that reason, they are almost non-protuberant on the acrylic cell wall, which has 332 mm inner diameter. As portrayed in Fig. 4, a toroidal specimen of bentonite-based buffer was set on the center of the apparatus. Distilled water was supplied to a specimen from the full-part bottom for approximately two months (59–63 days) to elucidate the relation between the buffer specimen pressure and the elapsed time. The above measuring period was determined by reason that the buffer specimen pressure was convergently almost constant value at that period as after-mentioned in Fig. 5 and the related paragraph.

In these experiments, vertical pressure gauges were not included because they might be obstructive to supplying distilled water as described above. It is also well-known that swelling behavior of bentonite is affected water chemistry, therefore this study was using distilled water.

Experimental results

Figure 5 presents the relation between buffer’s lateral pressures after filling the space and the elapsed time. This figure exemplifies three kinds of experimentally obtained results of the cases of bentonite content 80%, initial dry densities are 1.62 Mg/m$^3$ and 1.77 Mg/m$^3$, and bentonite content 100%, initial dry density is 1.84 Mg/m$^3$. Those results indicate that buffer’s lateral pressures after filling the space are increasing as bentonite content and initial dry density are increasing. Result presented in Fig. 5(a) shows that the variation of lateral pressures measured by the three pressure gauges attached to the acrylic cell are within the range of around 20% for bentonite content 80% and initial dry density 1.62 Mg/m$^3$. From the results shown in Figs. 5(b) and 5(c), the variation of lateral pressures
measured for bentonite content 80%, initial dry density 1.77 Mg/m$^3$ and bentonite content 100%, initial dry density is 1.84 Mg/m$^3$ are in the range of around 10%. The tendency on increasing the lateral pressures are found to be almost same as shown in all of the drawings in Fig. 5. Figure 6 portrays the relation between the average pressure of buffer after filling the space and the elapsed time in all experimental cases. Figure 7 presents observations of space filling by swelling of the bentonite-based buffer. Results demonstrate that the bentonite-based buffer has practical self-sealing capability to fill the space between the buffer and the disposal pit wall. Figure 7 also indicates that seepage water distributed roughly around whole parts of specimen from the viewpoint of color alternation.

**TRIAL EVALUATION OF SELF-SEALING CAPABILITY OF BENTONITE-BASED BUFFER BY THEORETICAL EQUATIONS IN KOMINE AND OGATA (2003,2004)**

This section describes the trial evaluation of self-sealing capability of bentonite-based buffer by the theoretical equations for swelling characteristics of bentonite in Komine and Ogata (2003,2004). Figure 8 presents the schematic drawing of author’s theoretical equations and the evaluating flow chart on self-sealing of bentonite-based buffer by using them.

Firstly, this study investigated the applicability of author’s theoretical equations to evaluate the buffer self-sealing capability by comparing the calculations and experimentally obtained results described earlier. Table 2 presents parameters determined by the fundamental properties of bentonite and sand. Figure 9 shows a comparison of the calculated results with experimentally obtained results. In the calculation, the ion concentration of pore water, $n_0$ is assumed as 30 and 40 mol/m$^3$ by referring previously measured values in Komine and Ogata (2003,2004). It is well-known that swelling behavior of bentonite is influenced by pore water chemistry, so it is considered that the difference between the calculated results and measured values is partially caused by the accuracy for assuming values of $n_0$. Moreover, it is also considered the possibility of hydrating non-homogeneously bentonite block during those experimental periods. However, the prediction results can indicate approximately the experimentally measured values. From the above discussion, the theoretical equations proposed in Komine and Ogata (2003; 2004) are regarded to use for designing the buffer specifications such as the bentonite content, the compaction density, and the dimensions from the viewpoint of “self-sealing.”

For trial evaluating the buffer’s self-sealing capability, the conditions of the disposal pit shown in the lower right drawings of Fig. 1 are simulated using analytical models and author’s theoretical equations. Presumably, the swelling deformation of bentonite-based buffers is equal to the interstitial spaces filled up by buffer swelling.
deformation. Consequently, the relation of the maximum swelling strain, $\varepsilon_{\text{max}}$ (%) of buffer is calculable by the initial buffer volume and the initial volume of interstitial spaces.

For evaluating the buffer self-sealing capability, the following are assumed.

**Assumption 1:** Buffer pressure is homogeneous after the interstitial spaces are filled.

**Assumption 2:** The one-dimensional model consists of a waste container, buffer materials, the disposal pit wall, and interstitial spaces.

Bentonite-based buffers are presumably non-homogeneous when they are manufactured because of the thin layers of montmorillonite minerals that are arranged in a certain direction during compaction. The direction of montmorillonite minerals, however, will be disturbed during the unrestricted swelling process by which spaces are filled. The buffer will be almost hydrated in almost homogeneous after so long-time later such as 10,000 years. Therefore, the author adopted assumption 1 presented above. However, the assurance of the above phenomena should be continued to investigate. The analytical model is established as a one-dimensional model.

In calculating and evaluating the buffer’s self-sealing capability, the key point is to consider and calculate the maximum swelling strain, $\varepsilon_{\text{max}}$ (%) of buffer by derivation from the relation between the width of interstitial space and the bentonite-based buffer thickness by assuming a one-dimensional model of the buffer and space.

The required buffer capacity can be ascertained provided that the buffer pressure after filling up interstitial space to create an effective self-sealing capability is configurable. For instance, it is presumed that self-sealing capability is effective when the buffer pressure after filling up space is greater than 1000 kPa. Some earlier studies conducted in Canada (Atomic Energy of Canada Limited 1994; Dixon and Gray 1996; Dixon et al. 1987) have demonstrated that the required buffer pressure having effective low permeability is greater than 1000 kPa. Therefore, the conditions explained above related to the buffer pressure for effective self-sealing are assumed. Figure 10 presents an example of self-sealing of bentonite-based buffer according to the evaluating flow on self-sealing of bentonite-based buffer presented in Fig. 8. It can calculate and evaluate the required buffer-thickness from the viewpoint of effective self-sealing capability according as material specifications such as kinds of bentonite, dry density and bentonite content with some assumptions such as 1000 kPa of the buffer pressure for effective self-sealing capability. This study adopted provisionally 1000 kPa of buffer pressure after filling up space for effective self-sealing from the previous researches. It is necessary to clarify highly reliable buffer pressure for effective self-sealing capability by future researches.
CONCLUSIONS

For this study, we conducted scale-model tests simulating the relations of buffer and the interstitial space between buffer materials and a disposal pit wall, and between buffer materials and a waste container. Then we evaluated the buffer self-sealing capability quantitatively. The experimentally obtained results of scale model tests indicate that the bentonite-based buffer has practical self-sealing capability to fill interstitial spaces. Moreover, this study introduced the trial evaluation of self-sealing capability of bentonite-based buffer by the author’s theoretical equations when it is assumed that buffer pressure is homogeneous after the interstitial spaces are filled and the one-dimensional model consists of a waste container, buffer materials, the disposal pit wall, and interstitial spaces.

ACKNOWLEDGMENTS

This study, supported by research funds from the Japanese Ministry of Education, Culture, Sports, Science and Technology, was performed as a part of activities of Research Institute of Sustainable Future Society, Waseda Research Institute for Science and Engineering, Waseda University. The scale model test was strongly supported by Dr. Ueda in the Radioactive Waste Management Funding and Research Center (Formerly Tokyo Electric Power Co.), and by Mr. Takao and Mr. Osada of JGS Corporation. The author thanks all members listed above and also the staff and students of the geotechnical laboratory of Waseda University for their kind assistance and discussion.

REFERENCES

Agus, S. S., and Schanz, T. 2008. A method for predicting swelling pressure of compacted bentonites. Acta Geotechnica, 3: 125–137.
Alonso, E. E., Vaunat, J., and Gens, A. 1999. Modelling the mechanical behaviour of expansive clays. Engineering Geology, 54: 173–183.
Atomic Energy of Canada Limited 1994. The Disposal of Canada's Nuclear Fuel Waste: Engineered Barriers Alternatives, AECL-10719 COG-93-8, Whiteshell Laboratories Pinawa, Manitoba R0E 1L0.
Cui, Y. J., Yahia-Aissa, M., and Delage, P. 2002. A model for the volume change behavior of heavily compacted swelling clays. Engineering Geology, 64: 233–250.

https://mc06.manuscriptcentral.com/cgj-pubs
Delage, P., Howat, M. D., and Cui, Y. J. 1998. The relationship between suction and swelling properties in a heavily compacted unsaturated clay. Engineering Geology, 50(1-2): 31–48.

Dixon, D. A., and Gray, M. N. 1996. Swelling and hydraulic properties of bentonites from Japan, Canada and the USA. In Proceedings of the Second International Congress on Environmental Geotechnics (IS-Osaka), Vol. 1, Osaka, 5-8 November 1996. Japanese Geotechnical Society, Tokyo, pp. 43–48.

Dixon, D. A., Gray, M. N., Cheung, S. C. H., and Davidson, B. C. 1987. The hydraulic conductivity of dense clay soils in geotechnique in resource development. In Proceedings of the 40th Canadian Geotechnical Conference, Regina, Saskatchewan, 19-21 October 1987, The Canadian Geotechnical Society, Richmond, pp. 389–396.

Garitte, B., Shao, H., Wang, X. R., Nguyen, T. S., Li, Z., Rutqvist, J., Birkholzer, J., Wang, W. Q., Kolditz, O., Pan, P. Z., Feng, X. T., Lee, C., Graupner, B. J., Maekawa, K., Manepally, C., Dasgupta, B., Stothoff, S., Ofoegbu, G., Fedors, R., and Barnichon, J. D. 2017. Evaluation of the predictive capability of coupled thermo-hydromechanical models for a heated bentonite/clay system (HE-E) in the Mont Terri Rock Laboratory. Environment Earth Sciences, 76:64: 1-18. doi: 10.1007/s12665-016-6367-x.

Japan Nuclear Cycle Development Institute (Japan Atomic Energy Agency at present) 2000a. H12: Project to establish the scientific and technical basis for HLW disposal in Japan, Project Overview Report, JNC TN1410 2000-001.

Japan Nuclear Cycle Development Institute (Japan Atomic Energy Agency at present) 2000b. H12: Project to establish the scientific and technical basis for HLW disposal in Japan, Supporting report 2, Repository Design and Engineering Technology, JNC TN1410 2000-003.

Karnland, O., Olsson, S., Nilsson, U., and Sellin, P. 2007. Experimentally determined swelling pressures and geochemical interactions of compacted Wyoming bentonite with highly alkaline solutions. Physics and Chemistry of the Earth, 32: 275–286.

Komine, H., and Ogata, N. 1994. Experimental study of swelling characteristics of compacted bentonite. Canadian Geotechnical Journal, 31(4): 478–490. doi: 10.1139/t94-057.

Komine, H., and Ogata, N. 1996. Prediction for swelling characteristics of compacted bentonite. Canadian Geotechnical Journal, 33(1): 11–22. doi: 10.1139/t96-021.

Komine, H., and Ogata, N. 1999. Experimental study of swelling characteristics of sand-bentonite mixture for nuclear waste disposal. Soils and Foundations, 39(2): 83–97. doi: 10.3208/sandf.39.2 .83.

Komine, H., and Ogata, N. 2003. New equations for swelling characteristics of bentonite-based buffer materials.
Komine, H., and Ogata, N. 2004. Predicting swelling characteristics of bentonites. Journal of Geotechnical and Geoenvironmental Engineering, American Society of Civil Engineers (ASCE), 130(8): 818–829. doi: 10.1061/(ASCE)1090-0241(2004)130:8(818).

Komine, H., Yasuhara, K., and Murakami, S. 2009. Swelling characteristics of bentonites in artificial seawater. Canadian Geotechnical Journal, 46: 177–189. doi: 10.1139/t08-120.

Ogata, N., Kosaki, A, Ueda, H., Asano, H., and Takao, H. 1999. Execution techniques for high level radioactive waste disposal: IV Design and manufacturing procedure of engineered barriers. Journal of Nuclear Fuel Cycle and Environment, 5(2): 103–121 (in Japanese with English abstract).

Villar, M. V., Gómez-Espina1, R., and Lloret, A. 2010. Experimental investigation into temperature effect on hydro-mechanical behaviours of bentonite. Journal of Rock Mechanics and Geotechnical Engineering, 2(1): 71–78.

Villar, M. V., and Lloret, A. 2008. Influence of dry density and water content on the swelling of a compacted bentonite. Applied Clay Science, 39(1-2): 38–49.

White, D., and Michael, G. P. 1979. A proposed method for the determination of small amounts of smectites in clay mineral mixtures. Proceedings of British Ceramics Society, 28: 137–145.
Figure Captions

Figure 1. Schematic drawings of HLW disposal facility and self-sealing ability of bentonite-based buffers with reference to the concepts of Atomic Energy of Canada Limited (1994) and Japan Nuclear Cycle Development Institute (2000a, 2000b).

Figure 2. Vertical disposal pit dimensions proposed in CRIEPI and FEPC.

Figure 3. Size and outline of toroidal buffer specimen, and specimen production jigs.

Figure 4. Scale-model test apparatus simulated disposal pit of HLW and component materials: a simulated waste container, a bentonite-based buffer, surrounding rock, and the space between components.

Figure 5. Three examples of relations between pressure values measured by each gauge and elapsed time.

Figure 6. Relation between average pressure of buffer after filling up space and elapsed time.

Figure 7. Filling up space by swelling of bentonite-based buffer.

Figure 8. Evaluating flow on self-sealing of bentonite-based buffer by the theoretical equations for swelling of bentonite in Komine and Ogata (2003, 2004).

Figure 9. Comparison of calculated and experimentally obtained results.

Figure 10. Trial evaluating results of self-sealing capability of bentonite-based buffer using theoretical equations according to Komine and Ogata (2003, 2004).
Table 1. Fundamental properties of bentonite (the Kunigel-V1 produced before 1999) in this study

| Type                   | Sodium type     |
|------------------------|-----------------|
| Particle density       | 2.79 Mg/m$^3$   |
| Liquid limit           | 473.9%          |
| Plastic limit          | 26.6%           |
| Plastic index          | 447.3           |
| Activity               | 6.93            |
| Plastic ratio          | 16.81           |
| Clay content           | 64.5%           |
| Montmorillonite content| 48%             |
| Cation exchange capacity| 0.732 meq/g     |
| Exchangeable sodium ion capacity | 0.405 meq/g |
| Exchangeable calcium ion capacity | 0.287 meq/g |
| Exchangeable potassium capacity | 0.009 meq/g |
| Exchangeable magnesium capacity | 0.030 meq/g |

Table 2. Parameters ascertained from fundamental properties of bentonite and sand

| $\rho_m$      | $\rho_{nm}$ | $S_m$     | $S_{nm}$ | $C_m$ |
|---------------|-------------|-----------|----------|-------|
| 2.77 Mg/m$^3$ | 2.81 Mg/m$^3$ | 810 m$^2$/g | 0 m$^2$/g | 48%   |
| CEC           | $\text{EXC}_{\text{Na}}^+$ | $\text{EXC}_{\text{Ca}}^+$ | $\text{EXC}_{\text{K}}^+$ | $\text{EXC}_{\text{Mg}}^+$ |
| 0.732 meq/g   | 0.405 meq/g | 0.287 meq/g | 0.009 meq/g | 0.030 meq/g |

| $(R_{\text{ion}})_{\text{Na}}$ | $(R_{\text{ion}})_{\text{Ca}}$ | $(R_{\text{ion}})_{\text{K}}$ | $(R_{\text{ion}})_{\text{Mg}}$ | $\nu_{\text{Na}}$ |
|---------------------------|-----------------|-----------------|-----------------|----------------|
| 0.098 nm                  | 0.1115 nm       | 0.133 nm        | 0.0835 nm       | 1              |
| $\nu_{\text{Ca}}$        | $\nu_{\text{K}}$ | $\nu_{\text{Mg}}$ | $t$             | $\rho_{\text{sand}}$ |
| 2                         | 1               | 2               | 9.60×10$^{-10}$ m | 2.66 Mg/m$^3$ |

Those parameters are determined based on values quoted from earlier papers and the measured values of Kunigel-V1 bentonite and Mikawa silicate sand No. 6.
Figure 1. Schematic drawings of HLW disposal facility and self-sealing ability of bentonite-based buffers with reference to the concepts of Atomic Energy of Canada Limited (1994) and Japan Nuclear Cycle Development Institute (2000a, 2000b).

Figure 2. Vertical disposal pit dimensions proposed in CRIEPI and FEPC.
Figure 3. Size and outline of toroidal buffer specimen, and specimen production jigs.
Figure 4. Scale-model test apparatus simulated disposal pit of HLW and component materials: a simulated waste container, a bentonite-based buffer, surrounding rock, and the space between components.
Figure 5. Three examples of relations between pressure values measured by each gauge and elapsed time.
Figure 6. Relation between average pressure of buffer after filling up space and elapsed time.

Figure 7. Filling up space by swelling of bentonite-based buffer.

The experiment result above shows that bentonite-based buffer has self-sealing ability.
The details of the variables of physical, chemical and physical chemistry in the equations have been explained in Komine and Ogata (2003, 2004) so refer them.

Figure 8. Evaluating flow on self-sealing of bentonite-based buffer by the theoretical equations for swelling of bentonite in Komine and Ogata (2003; 2004).

\[
p = \frac{1}{\text{CEC}} \sum_{i=Na^+, Ca^{2+}, K^+, Mg^{2+}} \left[ \text{EXC}_i \left( (f_r)_i - (f_a)_i \right) \right]
\]

\[
(f_r)_i = 2nK_{T} \left( \cosh u_i - 1 \right) \times 10^{-3}
\]

\[
u_i = 8 \tanh^{-1} \left\{ \exp \left( -\kappa d_i \tanh \left( \frac{z_i}{4} \right) \right) \right\}
\]

\[
\kappa = \frac{2nL^2e^2}{ekT}
\]

\[
z_i = 2\sinh^{-1} \left( \frac{96.5 \times \text{EXC}_i \left( \frac{1}{S} \right)}{8nK_{T}} \right)
\]

\[
(f_a)_i = \frac{A_h}{24\pi} \left[ \frac{1}{d_i^3} + \frac{1}{(d_i + t)^3} - \frac{2}{(d_i + \frac{t}{2})^3} \right]
\]

\[
\varepsilon_{sv}^* = \left\{ \varepsilon_0 + \frac{\varepsilon_{max}}{100} (e_0 + 1) \right\} \left[ 1 + \left( \frac{100}{C_m} - 1 \right) \frac{\rho_m}{\rho_{nm}} + \left( \frac{100}{\alpha} - 1 \right) \frac{100}{C_m} \frac{\rho_m}{\rho_{sand}} \right]
\]

\[
\varepsilon_0 = \frac{\rho_{solid}}{\rho_{dry}} - 1
\]

\[
\rho_{solid} = \left\{ 1 + \left( \frac{100}{C_m} - 1 \right) \frac{\rho_m}{\rho_{nm}} + \left( \frac{100}{\alpha} - 1 \right) \frac{100}{C_m} \frac{\rho_m}{\rho_{sand}} \right\}
\]

\[
d_i = \frac{\varepsilon_{sv}^*}{100} \left[ t + (R_{ion})_i \right] + (R_{ion})_i
\]

\[
n = \frac{n_0 \left( \text{mol/m}^3 \right) \times N_A}{1 + \frac{\varepsilon_{sv}^*}{100}}
\]

\[
S = \frac{C_m}{100} S_m + \left( 1 - \frac{C_m}{100} \right) S_{nm}
\]
Notation: BC is bentonite content, IDD is Initial dry density and $n_0$ is ion concentration of pore water in theoretical calculation.

Figure 9. Comparison of calculated and experimentally obtained results.

Figure 10. Trial evaluating results of self-sealing capability of bentonite-based buffer using theoretical equations according to Komine and Ogata (2003, 2004).