Experimental approach for understanding the dynamic behaviors of bentonite buffer piping erosion

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Abstract
In Japan, as in other countries, bentonite-based buffer materials are expected to play roles in reducing stress from rock masses and mitigating nuclide migration in the geological disposal of high-level radioactive waste. These roles are achieved by ensuring buffer density and thickness based on the swelling characteristics of clay. However, in practical construction, we should also consider bentonite buffer piping erosion, a phenomenon in which the buffer surface is destroyed by groundwater flowing between the buffer and rock. Such piping erosion may be a serious issue for maintaining an engineered barrier for radioactive waste in the geological system. In this study, the dynamic behaviors of piping erosion were experimentally investigated. In the experiments, 500 mm φ × 600 mm height compacted bentonite specimens were placed in a cylindrical acrylic cell and distilled water was continuously injected at a flow rate of 0.1 L/min from the bottom and the side of the cell. The amount of bentonite that flowed out of the cell was measured by turbidity of the suspended clay in the drainage water. In the results, while the bentonite specimen swelled between about 10 and 20 days and attached to the inside wall of the cell, a dominant flow channel (piping) was observed between the swelled bentonite specimen and the inside wall of the cell. In addition, the relationship between the accumulated amounts of injected water and eroded bentonite showed a constant slope on double logarithmic plots. Such behaviors indicate that the shear stress due to water flow locally exceeded the swelled bentonite’s shear strength. Furthermore, the slopes were similar to those already reported from a test using a smaller size cell. These results suggest that piping erosion proceeds with a simple regularity and that piping erosion in actual-scale bentonite buffers can be predicted using small-scale data.

Keywords: Engineered barrier, Buffer material, Bentonite, Piping, Erosion, Scale effect

1. Introduction

Piping erosion of buffer materials is often caused by the inflow of groundwater scraping off buffer material surface of a clay, such as bentonite, which is placed around an overpack encapsulating radioactive waste. Studies by the Swedish Nuclear Fuel and Waste Management Company (SKB) and Finnish nuclear waste management company Posiva confirmed a piping erosion phenomenon on buffer material surfaces using laboratory tests. Therefore, to avoid buffer material reduction due to piping erosion, an upper limit value for inflow water was determined in a vertical disposal hole (SKB, 2006, 2008; Posiva, 2013). On the basis of these studies, a study on piping erosion was started in 2000 by the Radioactive Waste Management and Funding and Research Center (RWMC). This study focused on the period of resaturation after immediately after the buffer material was installed until the water level returned (RWMC, 2011). On the other hand, a series of erosion studies in Japan have been conducted on phenomena in which buffer materials flowed into rock cracks (Ichikawa, 1997; Matsumoto, 2003). In this case, the erosion was a phenomenon in which the amount of buffer material decreases as suspended bentonite flows into cracks after the host rock around the disposal hole has been resaturated. Currently, also in Sweden and Finland, this erosion phenomenon has been the focus of study as long-term continued phenomenon (SKB, 2018; Posiva, 2017).

In Japan, the amount of spring water in the bedrock until the underground repository is constructed and closed is
greater than that of Nordic rock. Therefore, the loss of the buffer material due to erosion occurring immediately after emplacement is a problem. Considering such groundwater flow conditions, Suzuki et al. (2013) reported the piping erosion phenomena by testing in small cells. Piping has been shown to always converge to a single line, and piping moved toward the surface even when pipes were made inside the buffer material and passed water. In addition, piping formed at the interface between the buffer material and cell continued to erode without being sealed by swelling if there was a certain amount of water flow. The present study examined whether pipe erosion phenomenon has a scale effect. The tests were conducted using a specimen with a diameter of 560 mm and a height of 600 mm and compared the test results with those (Suzuki et al., 2013) using a smaller specimen (diameter of 110 mm and height of 50 mm).

2. Experiments
2.1 Materials
2.1.1 Specimens and injected fluid
Japanese buffer materials are assumed to be bentonite (70 wt.% Kunigel V1) and silica (quartz) sand (30 wt.%). Thus, the specimens in this study had the same composition. Density after saturation was set to 1.6 Mg/m³ in consideration of design values satisfying the required buffer material’s function. This density is set to fulfill the criteria of swelling twice in saline water and this function requires the highest density in the function of buffer material. The specimens were made by compression molding of the bentonite material and were then placed in the cell. The gap between the specimen and cell wall was 30 mm. Water injection from the porous plate at the bottom or the water injection port on the side was performed on the sample to observe the occurrence of piping, and the montmorillonite concentration in the drainage was measured. Two types of silica sand with different grain diameters, No. 3 (2.4–1.2 mm) and No. 5 (0.8–0.3 mm), were used in the same amount.

This material was adjusted to a moisture content of approximately 10% and was then compression molded to a certain size for testing. To make a test specimen with a uniform density, compression was carried out through static compaction of bentonite to a layer thickness of 10 mm at a given density, and specimens were built by repeating compaction in the same mold. The thickness of one compaction should be small to reduce the specimen’s density distribution. This study used ion exchange-treated water as an injected fluid, as was used in Suzuki et al. (2013), to avoid the effects of ions.

2.1.2 Apparatus
To observe piping erosion phenomena, experiments were conducted using an acrylic resin cell approximately 1/4 of the real scale, which was referred to as the “engineering scale” cell in this study. Figure 1 shows photos of the acrylic resin cell. This cell had an inner diameter of 560 mm and a height of 600 mm, and a porous stone was placed at the bottom of the cell. The porous stone plate plays a role for continuously rectifies water, when water inflows from the bottom into the cell. Inlets were provided at the bottom and sides of the cell, and outlets were placed at the top and sides of the cell. Drainage holes at the top were 5 mm pipes installed at four places every 90°.

Fluid was fed by two sets of syringe pumps to provide a constant injection rate. Using a dual syringe pump allowed one syringe pump to inject water into the cell, and the other one was filled with water, thereby making it possible to inject with a constant flow rate for a long time.

Fig. 1 Photos of the acrylic resin cell. Left: overall picture of the acrylic resin cell. Right: porous stones seen from above. The height of this cell is 600 mm and its inner diameter is 560 mm.
2.2 Methods

2.2.1 Experimental conditions

Table 1 shows the experimental conditions. The gap between the specimen and cell, where water flowed through, was a 30-mm-wide ring shape. The initial flow rate was 0.1 L/min in both cases. After that, a test at 0.01 L/min was carried out assuming that inflow water would decrease in Case 1. The maximum injection rate was set to the amount SKB determined as the allowable flow rate per disposal hole (SKB, 2010).

Figure 2 shows the water injection and drainage positions in each case. Case 1 assumes that inflow water is generated from the bottom of the disposal hole immediately after the buffer material is installed and that the inflow water drains to the disposal tunnel. Drainage is performed from the top of the buffer material. Case 2 assumes that inflow water comes from a fracture on the side of the disposal hole and flows to another fracture. Thus, the water was injected from an upper part of the side of the cell and drained from a lower part of other side of the cell. In both cases, pipe formation status and erosion amounts were examined.

### Table 1  Experimental conditions

<table>
<thead>
<tr>
<th>Case</th>
<th>Gap</th>
<th>Flow rate</th>
<th>Water flow direction</th>
<th>Experiment time</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>30 mm</td>
<td>0.1 L/min, 0.001 L/min</td>
<td>Bottom → top</td>
<td>260 days</td>
</tr>
<tr>
<td>2</td>
<td>30 mm</td>
<td>0.1 L/min</td>
<td>Upper side → lower side</td>
<td>100 days</td>
</tr>
</tbody>
</table>

※ ; between the specimen and the cell

Fig. 2 Water inlet and outlet positions. Piping erosion tests were performed in two cases that used the same cell with different water injection routes. In Case 1, water was injected from the bottom porous plates, flowed through the gap between the specimen and cell, and was discharged out the upper outlet port. In Case 2, water was injected from the upper part of the cell and was discharged from the lower part of the cell on the opposite side.

2.2.2 Measurements

The amount of montmorillonite in the drain water was calculated using a calibration curve (Fig. 3) obtained by measuring absorbance (turbidity) with suspended montmorillonite concentration as a parameter. The measurement wavelength was 660 nm. At the time of measurement, a dispersant was added to uniformly disperse montmorillonite, and a sufficiently stirred solution was used. In addition, to obtain piping occurrence, the surface of the buffer material specimen was also observed through the acrylic resin cell using automatic photography.

After completing the test, the cell was disassembled, the determined location was core-sampled, and the specimen’s moisture content and dry density were measured. The sampling position of the core is shown in Fig. 4. Samplers with a diameter of 5 cm and height of 3 cm (volume of 58.9 cm³) were used to sample the core. If a specimen was too hard to use the sampler, then it was sampled in an irregular block shape and its volume was measured using the paraffin method. The range of volumes measured using the paraffin method was 25 cm³ to 370 cm³.
3. Results
3.1 Case 1
3.1.1 Change in injection pressure
Figure 5 shows changes of injection pressure and injected water amount in Case 1 over time. As shown, the injected water rate was constant at 0.1 L/min for approximately three months and then reduced to 0.001 L/min.
After the flow rate decreased to 0.001 L/min, injection pressure rapidly increased. Observations confirmed that a large gap occurred at the bottom of the sample after approximately one week. As the injection rate decreased, the buffer material began swelling and the pipe was sealed. Thus, the water pressure increased and acted from the bottom of the test cell to push the specimen up. However, the water pressure sharply dropped after that, indicating the occurrence of a breakthrough. Sealing and breakthrough were repeated from that point forward and the water pressure alternately increased and decreased while showing a gradual increasing trend. The injection pressure increase suggests bentonite swelling, and thus the piping becomes thinner.
Fig. 5 Accumulated amount of injected water and pressure in Case 1. The horizontal axis is the elapsed time, the left vertical axis shows the accumulated injected water amount, and the right vertical axis shows the injection pressure. The injection pressure tended to gradually increase after the flow rate decreased.

3.1.2 Piping status

Figure 6 shows piping formation during the initial test stages. When water injection was started at 0.1 L/min, piping was generated in the lower part of the specimen and gradually developed toward the upper part, eventually connecting with the outlet port. Therefore, as shown in Fig. 5, the injected pressure remained low even after almost filling the gap. The middle part appeared to be sealed after 17 days. However, loose bentonite was only attached to the surface of the cell and thus the middle part was not completely sealed. The piping converged to a single pipe, with only one remaining to the end of the test.

An aqueous solution of rhodamine B dye was injected, enabling a clear confirmation of the piping position. Figure 7 shows the situation of the upper and lower sides until 8.5 months, with staircase-like piping becoming clearly visible. Moreover, the area where the dye penetrates was extended to the surroundings of the piping because the dry density decreased around the piping due to erosion. After reducing the flow rate to 0.001 L/min, the pipe became thinner, which means that the buffer material swelling progressed as the injection rate was lowered.

![Fig. 6 Piping formation in engineering scale test 1. These photographs show the status of piping under an injection rate of 0.1 L/min for the initial stage. The red arrows indicate the locations of piping. Immediately after the start of the test, piping formed at the bottom and gradually extended to the top. Changes in the route were then seen over time. In the photograph after 17 days in the middle part, the piping seems to be divided; however, loose buffer was attached to the cell surface and the piping was not completely sealed.](image-url)
Fig. 7 Piping formation status in engineering scale test 2. These photos indicate piping formation from the middle period to the later period. This test was conducted for 8.5 months with water injected at 0.1 L/min up to 2.5 months, after which the injection rate was reduced to 0.01 L/min. A dye (rhodamine B) was injected to clarify the piping path at 2 months, making the step-like piping more visible. In addition, the area through which the dye penetrated extended to the periphery of the pipe because the dry density around the pipe was lowered by erosion. As time passed, the portion adsorbed with rhodamine has eroded out, causing the color of the piping path to become faint; moreover, the path gradually changed.

3.1.3 Status of seepage of the upper surface of the specimen

Figure 8 shows a series of photographs taken at a fixed point above the cell that show the specimen’s seepage situation. These observations show that water penetrated the gap between the acrylic top and the specimen immediately after water injection started; however, the wetted area hardly changed until the end of the test. This can be attributed to the surrounding upper edge of the specimen swelling, causing reduced permeability and preventing water from being supplied to the upper surface.

3.1.4 Distribution of density and water saturation degree of the specimen after the test

After the test, the specimen was dismantled, and its density and water saturation degree were measured via core sampling. The bentonite swelled and was firmly in contact with the cells. The surface of the specimen developed dry cracks during the test. This was likely due to the fact that the injected water selectively flowed through the piping and almost no water was supplied to the other parts. The parts other than near the piping gradually dried.

The dry density obtained from the core collected at the position shown in Fig. 4 is shown as a change rate distribution in Fig. 9. The rate of change was defined as the ratio of dry density after dismantling to the specimen’s initial dry density. As shown in Fig. 9, the dry density on the A point side where the piping was generated was low, and that on the opposite side E was high. In addition, inflow from the bottom of the specimen causes the density of the bottom of the specimen to
be low, reducing the density of the entire specimen. This distribution is also consistent with the water saturation degree contour map shown in Fig. 10. Clearly, the place where erosion and swelling simultaneously occurred had a high degree of saturation and reduced dry density. Furthermore, Fig. 10 shows a place where the surface was dried due to low saturation degree.

Fig. 9 Dry density distribution after the test. Here the core was collected, and its density was measured to obtain the specimen’s density distribution. The color in the figure shows the ratio of density change between the start of the test and after the test. As water was supplied from the bottom of the specimen, it infiltrated from the lower part and swelled, making the density on the lower side low. The point indicated by the arrow is the starting point of the piping, and the density on the side where the piping path was present was low.

Fig. 10 Water saturation degree distribution after the test. The water saturation degree was also measured with the same core as in Fig. 9. Water was supplied from the bottom, causing an area of approximately 12 cm from the bottom to be saturated with water. Moreover, the side where the piping path exists had a wide saturated area forward to the inside. On the other side where no piping path exists, there was a low-saturation area on the surface, indicating that the surface was dry.

3.1.5 Montmorillonite content in the erosion material

The change of montmorillonite content in the erosion material over time is shown in Fig. 11. The calculated montmorillonite content rate of the specimen containing 30 wt.% silica sand was 41.3 wt.%, indicated as a blue dotted line in Fig. 11. The montmorillonite content in the erosion material was lower than 10 wt.% during the initial stage. However, after reducing the water injection rate to 0.01 L/min, the erosion material had a higher montmorillonite content than the specimen. This was likely because when the injection rate was high, the mixed silica sand was selectively discharged, and when the rate was low, montmorillonite was selectively discharged. Furthermore, because the initial montmorillonite content in Kunigel V1 is 59 wt.% (RWMC, 2013), the content in the erosion material was higher than that in Kunigel V1. This finding suggests that the accessory bentonite also remained without outflow from the cell.
Fig. 11 Changes in the montmorillonite content in the erosion material. The vertical axis on the left is the accumulated amount of injected water and the vertical axis on the right is the montmorillonite content percentage in the erosion material. The blue dotted line indicates the calculated montmorillonite content in the crude material of the specimen (41.3 wt.%). Water was injected at a flow rate of 0.1 L/min up to approximately 80 days later, and the montmorillonite content measured at that time was 10 wt.% or less. After reducing the flow rate to 0.01 L/min, the montmorillonite content was much higher than that of the raw material at 60 wt.% or more.

3.2 Case 2
3.2.1 Injection water pressure

Figure 12 shows the amount of injected water and injection pressure in Case 2. This test was conducted with a constant flow rate of 0.1 L/min. During the initial period, the water pressure was approximately 7 kPa, which corresponds to the water head difference (approximately 700 mm) between the specimen’s injection position and drain position. On the 11th day, the water pressure increased, so the gap between the specimen and the cell was almost sealed by swelling at this point. After that, the water pressure gradually increased as the specimen continued to swell. However, the pressure did not rise much; thus, the piping phenomenon continued to occur.

The transition of the pressure in case 2 showed no significant difference from the water flow pressure in Case 1 for a water flow rate of 0.1 L/min.

Fig. 12 Accumulated injected water amount and injection pressure of Case 2. Water was supplied at a rate of 0.1 L/min. In the initial period, a water pressure of 7 kPa corresponding to the hydraulic head difference was applied into the cell, and the water pressure started rising on the 11th day. This is because the gap between the specimen and cell was almost filled by the swelling of bentonite. After that, a large rise in water pressure was not observed; thus, the piping phenomenon continued.

3.2.2 Piping phenomenon due to water inlet position differences

Automatic photography was performed for the water injection and drain outlet sides. Figure 13 shows the piping appearance. It was visually confirmed that the gap between the specimen and cell was filled on the 11th day and piping
was confirmed. This was consistent with the injection pressure shown in the previous section increased from day 11th. The piping was observed until the end of the test although its position changed over time. Initially, the piping flow passed clockwise from the injection point, but it changed to counterclockwise in the middle. In the photograph taken on the 97th day, the area around the water is colored blue because a methylene blue solution was injected to facilitate observation of the water. The change in position was significant compared to that of Case 1.

<table>
<thead>
<tr>
<th>The injection side</th>
<th>The Drainage side</th>
</tr>
</thead>
<tbody>
<tr>
<td>After 11 days</td>
<td>After 97 days</td>
</tr>
<tr>
<td>After 21 days</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 13 Appearance of piping in Case 2. Piping was observed from the 11th day. The piping phenomenon continued while changing the position until the end of the test. In the photo taken after 97 days, the piping looks blue due to the injection of a methylene blue solution.

3.3 Relationship between the overall water volume and erosion amount

The relationship between the accumulated injected water amount and accumulated amount of eroded materials in Cases 1 and 2 is shown in Fig. 14. The mass of the eroded material is given as dry weight. In Case 1, water was injected from the bottom and drained from the top, and in Case 2, water was injected from one side and drained from the opposite side. Case 1 and 2 had almost identical behavior and were almost same slope in agreement with the small test’s approximation equation. At a flow rate of 0.1 L/min, the accumulated mass of eroded materials can be expressed by the empirical following equation.

\[ m_s = 0.08 M_w^{0.85} \]

where \( m_s \) is the accumulated mass of eroded materials (dry weight) (g) and \( M_w \) is the accumulated amount of injected water (L).

![Fig. 14 Relationship between accumulated water amounts and mass of eroded materials. Cases 1 and 2 behaved almost identically and had the same slope as the approximation obtained from the results of the small test (Suzuki et al., 2013).](image-url)
4. Discussion

4.1 Piping behaviors

Figure 15 shows an image of the piping formation progress through buffer materials. Buffer material swelling did not uniformly occur in the vertical and circumferential directions. Although the specimens gradually densified to ensure uniform density, swelling of the specimens was not uniform. Basically, when local swelling rates are slightly different between places above and below, horizontal piping would form. Similarly, when swelling rates are different in the circumferential direction, piping would form in the vertical direction. Such piping formation mechanisms can explain the structure of staircase-like piping shown in Fig. 7.

Fig. 15 Image of the piping formation. When water flowed into the gap between the buffer material and cell, the buffer material swelled but did not uniformly swell. Thus, water flowed where swelling was delayed. Because the cross-sectional area of the flow part was narrowed, flow velocity increased. Because the water flowed while scraping the buffer material due to high flow velocity, piping remained even if the buffer material swelled thereafter.

In Case 2, the transition of the unstable piping was likely due to the boundary condition caused by water injection being perpendicular to the side surface. Piping formation was caused by the shape change of the specimen surface due to gravity and/or swelling; however, the direction in which the piping occurred is supposed to depend on the relationship magnitude of these influences. In the case of water injection from the side, the direction of water is considered unstable because the swelling proceeded more unevenly and thus gravity had greater influence.

4.2 Dry density distributions and water saturation degree

The distribution of dry density shown in Fig. 9 was correlated with piping position. Erosion and swelling occurred in places with low dry density and high water saturation degree, as shown in Fig. 10. This result indicates that buffer material was lost as piping erosion occurred and the non-uniformity of the buffer material density progressed. Non-uniformity at the construction time was predicted to be uniformized to some extent by swelling. However, when the extent of buffer material erosion increases, the non-uniformity of the buffer material progresses, and a large density differences remain even after the buffer material is saturated with water. Thus far, long-term behavior evaluation has been performed with a uniform density state as the initial state, but depending on the degree of density distribution, the result of long-term behavior evaluation may be affected. For a more probable evaluation, it is necessary to predict the density distribution of the buffer after saturation and use it as an initial state for evaluating long-term behavior.

4.3 Montmorillonite erosion amount

As described in Section 4.1, the erosion started because the cross-sectional area of the piping narrowed, increasing the flow velocity to some extent. When water injection continued, the flow velocity, swelling, and erosion amount were balanced, and piping continued to present stably while changing the piping route. Because water was supplied at a constant flow rate, the flow velocity depended on the piping cross-sectional area. At that time, the buffer material (montmorillonite) was removed by erosion as much as the swelling amount. Therefore, the cross-sectional area maintained the same level and the flow velocity was also maintained. The erosion amount depends on this balance and the relationship is determined by the swelling properties of bentonite. As a result, the relationship between the water volume and erosion amounts in Cases 1 and 2 have the same slope, as shown in Fig 14.

Furthermore, even in the small-scale test reported by Suzuki et al. (2013), the same phenomenon in which the relationship between water volume and erosion volume had the same slope can be considered to have occurred. The relationship between the accumulated injected water and eroded material is approximately the same because the amount of buffer material (montmorillonite) carried by water per unit volume is the same. This result suggests that the relationship...
may be further expanded, regardless of the size of the test, and provides basic insights for assessing the state of full-scale buffer material after saturation. Based on such knowledge, the state after saturation considering the buffer material erosion must be predicted, and it must be determined whether the buffer material after saturation satisfies the required swelling characteristics such as self-sealing properties. If the loss of buffer material due to erosion is judged to be unacceptable, engineering countermeasures must be taken during installing.

5. Conclusions

In this study, the piping erosion phenomenon of the buffer material, which was previously confirmed only in a small test, was confirmed in a test that was scaled up to a test with a quarter of the actual size. From this result, it is predicted that the piping erosion occurs due to the spring water even in the buffer material of the actual size. Underground spring water in Japan is generally large, and there is a concern that the amount of buffer material will decrease due to the piping erosion of buffer material. Although previous studies were conducted using small specimens, this study scaled up the apparatus (known as an engineering scale) with 560 mmφ × 600 mm specimens. The results of the small-scale and engineering scale tests demonstrated that the correlation between accumulated injected water amounts, MW, and accumulated mass of eroded materials (montmorillonite) in dry weight, mS, can be expressed as the same following empirical equation as mS=0.08MW0.85 under the condition of a 0.1 L/min flow rate in the present tests.

In actual construction, the size of the gap and the spring water environment change depending on the method of buffer material, so piping erosion considering the buffer material installing method is important to assume. Furthermore, depending on the type of bedrock, the presence or absence of cracks, water permeability, water head, etc. are different. So, there are more factors to understand, such as the relationship between the swelling property of the buffer material and the amount of spring water in a disposal hole.

Moreover, for engineering countermeasures to prevent or suppress the buffer material piping erosion, it is clear that the piping erosion phenomenon occurs due to the presence of a gap outside the buffer material, so treatments of the gap is predictably effective. One of them is the pellet filling. One of them is the filling of pellets, and there are other things to examine as engineering countermeasures, such as other fillers, filling methods, and methods to eliminate water gaps.

It is important for study to correctly understand the piping erosion phenomena in real underground environments and to develop countermeasures based on realistic construction method. Further research is needed to ensure the integrity of the buffer material against the piping erosion phenomena.

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Reference

RWMC (Radioactive Waste Management and Funding and Research Center), Evaluation Experiments of Long-Term Performance of Engineered Barriers - Volume (1/2), (2013), (in Japanese)

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