

Experimental investigations of piping phenomena in bentonite-based buffer materials for an HLW repository

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Abstract: During the installation of the buffer in a deposition hole of an HLW repository, it is necessary to control water flow from the fractured rock into the deposition hole. Water flow with inflow rate greater than 0.001 l/min may cause piping and erosion of the buffer, and may trigger mass redistribution of the buffer, sedimentation and material separation of bentonite materials. This paper describes the condition of parameters which cause piping and erosion; revised conditions which keep advection, inflow rate, buffer component, gap between buffer materials, gap between outside wall and buffer block, and type of water. The results from the experiment show the condition of the self-sealing function of bentonite materials, formation of piping, allowable limit of inflow rate in the case of an Na type bentonite block of 70 wt.% Kunigel V1 and 30 wt.% silica sand, or a pellet of 100 wt.% Kunigel V1. Piping and erosion continue until the engineered barrier (EB) is filled with water, and then the hydraulic gradient becomes small. Piping may lead to erosion and redistribution of material which needs to be taken into account in the long-term performance assessment.

KEYWORDS: bentonite buffer, geomechanics, piping, erosion, self-sealing, water inflow.

Bentonite in the early phase of saturation readily suffers piping and erosion when ground water flows into a deposition hole or a tunnel exceeds an inflow rate 0.1 l/min. If the inflow rate is small (e.g. 0.0001 l/min), piping and erosion do not occur, and the specified swelling pressure could be expected. This paper focuses on the early stage of bentonite behaviour, especially on piping and erosion phenomena, considering the relation with inflow rate. Because hydraulic conductivity in Japan seems to be higher than in European countries, special

countermeasures against water inflow should be conducted in order to maintain diffusion.

In Japan the specific sites for a geological repository are not decided and palaeo-seawater and meteoric water should be considered as groundwater when piping phenomena in bentonite are studied. Distilled water and 0.5 M NaCl (saline water) were used for the water types in small-scale experiments. Because the resulting phenomena have been simplified, ionic water becomes the basis of comparison with natural ground water. For the bentonite block, the composition of 70 wt.% Kunigel V1 and 30 wt.% silica sand is the reference design in Japan; it has a dry density of 1.8 Mg/m³ before saturation, and 1.6 Mg/m³ after saturation (JNC, 2000). The mixture of 30 wt.% silica sand

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was selected after considering the result of testing mixtures under pressures of 10 MPa, since the dry density became greater than 2.0 MPa with a water content ratio of 10%, and this block showed the fewest dry cracks at a temperature of 80°C.

The hydraulic conductivity of rock in the fault crashing belt from 300m to 600m depth in Japan is reported to be around 1.0×10^{-8} m/s (JNC, 2000). According to the 1000 m boring data conducted in Tono area and Kamaishi Mine, the hydraulic conductivity of the crushed rock in the fault changes greatly when clay is present inside the fault. In the case when the fault is mixed with clay, the hydraulic conductivity ranges from 1.0×10^{-8} m/s to 1.0×10^{-5} m/s. On the other hand, when crushed rock fills the fault, the hydraulic conductivity ranges from 1.0×10^{-6} m/s to 1.0×10^{-3} m/s. These values are relatively higher than 1.0×10^{-10} m/s of excavation-damaged zones (EDZ) of normal deposition holes in European countries (SKB TR-11-01, 2011), and it is considered that the ground water in Japan will flow into a deposition hole and a tunnel more easily than in Europe. This paper describes the experimental program performed to characterize the piping and erosion behaviour of the bentonite block of 70 wt.% Kunigel V1 and 30 wt.% silica sand; a compacted pellet mixture of 100 wt.% Kunigel V1 was used in the engineered barrier (EB).

The formation of channels in a clay-based buffer material is often referred to as “piping”. Piping is likely to occur in bentonite-based buffer materials in a fractured host rock during the early stages of evolution of the repository when strong hydraulic gradients are present. After water saturation of the repository and re-establishment of the hydraulic gradients, piping will not be an issue (SKB, TR-06-80, 2006).

However, piping in the early phase may still have implications for long-term performance. If the pipes fail to close, conductive pathways in the engineered barrier may remain. Piping may lead to erosion or redistribution of material which needs to be taken into account in the long-term performance assessment. This means that the piping process may affect requirements for rock characterization, water inflow and water management during the installation phase, and may also affect buffer material properties and buffer installation methodology.

As a part of the “Bentonite saturation” programme, experiments on piping processes were initiated. The main objectives of the studies are to answer the following questions:

- Under what conditions can pipes form?
- How do pipes evolve with time and inflow rate?
- When and how do pipes close/self-seal?
- How does piping affect the buffer properties?
- How much mass can be lost by erosion?

The results will be applied to the development of the requirements for the reference design and construction, and also to enable countermeasures against piping and erosion to be taken in Japan.

EXPERIMENTS

Acrylic resin cell

In order to study piping and erosion phenomena, assuming that water flows into the bottom of the deposition hole and raise to the top, two types of experiments were conducted, small-scale and larger scale experiments. In these experiments, in order to investigate the piping phenomena carefully, acrylic resin cells were developed. Figures 1 and 2 show schematic drawings of each experiment and the acrylic resin cell. For the small-scale experiment,

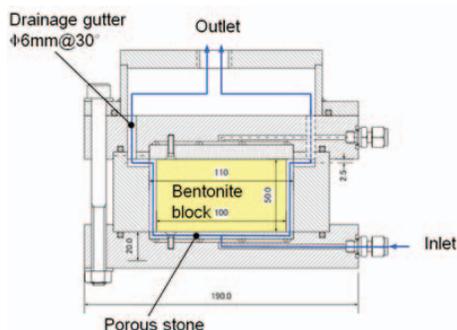


FIG. 1. Schematic drawing of the small-scale experiment and the acrylic cell.

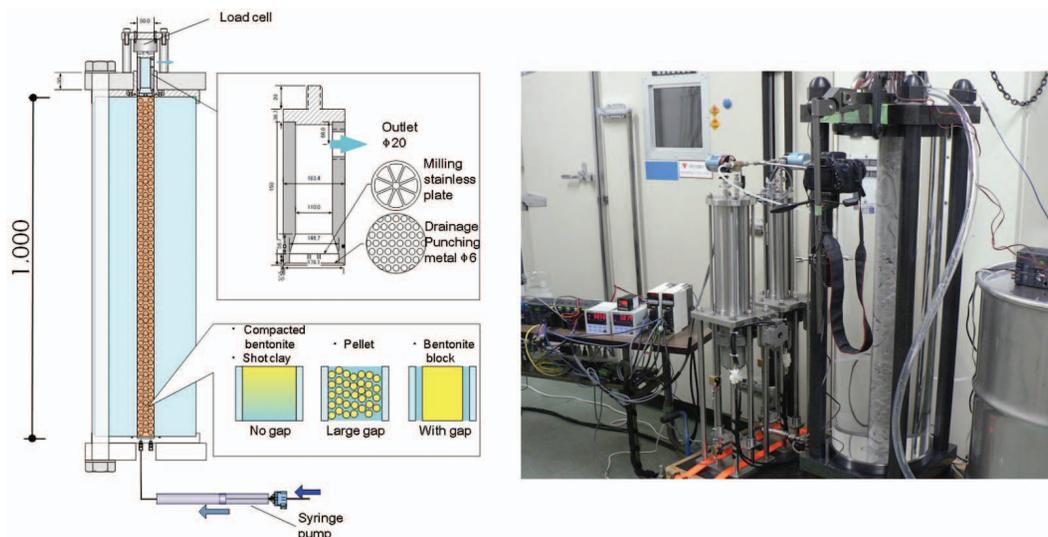


FIG. 2. Schematic drawing of the larger scale experiment and the two sets of syringe pumps.

the inside diameter was 110 mm and height 50 mm; porous stone was arranged at the bottom of the cell in order to distribute water from a plane surface. Twelve drainage gutters with diameter of 6 mm were situated at the top of the acrylic cover plate in order to maintain the advection field, and they were arranged at every 30° around the circumference with a diameter of 135 mm. For the larger scale experiment, the outside diameter was 300 mm and height 1000 mm in a massive acrylic cell; a hole with diameter of 50 mm and height of 1000 mm was opened inside the acrylic cell. For drainage, a

thin stainless sheet of perforated metal with open holes of diameter 5 mm was attached on the bottom side of the load cylinder in order to maintain the advection field (Fig. 2). Distilled water or saline water of 0.5 M NaCl was fed by two sets of syringe pumps in order to control the constant inflow rate. The maximum inflow rate of 0.1 l/min was based on the report of SKB (SKB, R-11-14). When the inflow rate needed to be changed to 0.01 l/min, it could be exactly controlled. During the experiments, the formation of piping, the self-curing ability of bentonite and sedimentation were observed, and water pressure, inflow of water, swelling pressure, total weight of eroded material and its time were measured.

TABLE 1. Grain diameter and chemical components of silica sand.

Type	No. 3 (mm)	No. 5 (mm)
Grain diameter	2.4–1.2	0.8–0.3
Type	No. 3 (wt.%)	No. 5 (wt.%)
SiO ₂	94–36	93–96
Al ₂ O ₃	2–4	2–4
Fe ₂ O ₃	0.1–1	0.1–1
Water	0–0.2	0–0.2

The test specimens

The buffer specimens were Na-type bentonite blocks, compacted bentonite and pellets. Each bentonite block and compacted bentonite consisted of 70 wt.% Kunigel V1 and 30 wt.% silica sand. Silica sand consisted of two types with different grain diameters; these were called nos. 3 and 5, and each grain diameter and chemical composition is shown in Table 1. The bentonite pellets consisted of 100 wt.% Kunigel V1. Table 2 summarizes the main characteristics of the bentonite specimens and experimental condition. These specimens are representatives of buffer construction methods,

TABLE 2. Characteristics of bentonite materials and experimental conditions.

Experiment	Case	Objectives	Type of buffer material	Volume ratio of gap (%)	Bulk dry density (*) Initial d. d. (Mg/m ³)	Type of liquid	Max. water pressure (MPa)	Flow rate (l/min)
Small scale experiments	1	Pipe evolution	Buffer block with gap	10	1.6 (1.916*)	Saline water	3	0.1
	2	Sedimentation	Mixed large and small pellets	10–40	1.600	Distilled water	3	0.1 → 0.001
	3	Self curing ability	Buffer block	0.41	1.594	Distilled water	3	0.1
	4	Pipe convergence	Mixed large and small pellets	10–40	1.595	Distilled water	3	0.1
	5	Position of piping	Mixed large and small pellets	10–40	1.500	Distilled water	3	0.1
	6	Mass of erodin and of its time	Mixed large and small pellets	10–40	1.471	Distilled water	3	0.01
	7	Initial inflow rate	Mixed large and small pellet	10–40	1.465	Distilled water	3	0.005
	8	of piping			1.49			0.001
Larger scale experiments	9	Initial inflow rate of piping	Buffer block with large pellet	10–40	Pellet: 1.074 Block: 1.601 Average: 1.348	Distilled water	3	0.1
	10	Pipe convergence	Buffer block with mixed large and small pellets	5–20	Pellet: 1.531 Block: 1.595 Average: 1.563	Distilled water	3	0.1
Larger scale experiments	11	Position of piping	Buffer block with gap	10	1.6 (1.936*)	Distilled water	3	0.1 → 0.0001
	12	Self curing ability	Large pellet	40	11	Saline water	3	0.1
	13	Pipe evolution	Buffer block with gap	10	1.6	Distilled water	0.2 → 0.5 → 1.0 → 2.0 → 2.5 → 3.0	0.001 → 0.05
	14	Sedimentation	Compacted buffer with no gap	0	1.6 (1.936*)	Distilled water		

such as bentonite block arrangement, pellet filling, bentonite compaction and spraying of bentonite.

For the small-scale experiments, 10 tests were conducted. In each case, the inflow rate was controlled by the two sets of syringe pumps and the pressure of distilled water or saline water was measured. In case 1, a bentonite block with 5 mm gap was used, and saline water of 0.5 M NaCl with 0.1 l/min was fed into it. The objective of case 1 was to investigate the piping process to consider how the pipes evolve in the critical flow condition, and how the sedimentation of silica sand occurred. The initial bulk dry density of the bentonite block was 1.936 Mg/m³. After swelling and sealing the gap, the dry density of the bentonite block was 1.6 Mg/m³. In case 2, a mixture of large and small pellets was used, and distilled water was fed into them. The inflow rate was initially 0.1 l/min, and changed to 0.01 l/min after 12 h, and to 0.001 l/min after 15 h. The objective of case 2 was to study the relationship between inflow rate and self-curing ability of the bentonite pellets. The bulk dry density of the mixture of large and small pellets after swelling was 1.6 Mg/m³. In case 3, six pin holes were arranged artificially inside and outside the bentonite block, and distilled water with inflow rate of 0.1 l/min was fed into it. The objectives of cases 3 and 4 were to study whether or not pipes converged into one pipe. In case 3, four pin holes were set in the interface around the acrylic cell and two pin holes were set inside the bentonite block. In case 4, five pin holes were initially set inside the bentonite block.

In cases 5, 6, 7 and 8, the initial inflow rates were 0.1, 0.01, 0.005 and 0.001 l/min of distilled water respectively, and were fed into the mixture of large and small pellets. The aim of cases 5–8 was to find the initial constant inflow rate which would cause piping, and especially in case 5, the relationship between the mass of erosion and its timing. In case 9, a half circle of the bentonite block and a large pellet were arranged in the acrylic cell, and 0.1 l/min of distilled water was fed into it. After swelling, the dry density of the bentonite block and large pellet was 1.595 and 1.074 Mg/m³ for each. The average dry density was 1.348 Mg/m³. In case 10, a half circle of the bentonite block and the mixture of the large and small pellets was arranged into the remaining space, and 0.1 l/min of distilled water was fed into it. After swelling, the dry density of the bentonite block and the mixture of large and small pellets was 1.591 and 1.531 Mg/m³ for each.

The average dry density was 1.563 Mg/m³. The objectives of case 9 and 10 were to study whether pipes would occur at the interface between the bentonite block and pellet or at the interface between the acrylic cell and pellet.

For larger scale experiments, four cases were conducted to confirm whether the same phenomena as in the small-scale experiments could be found, such as piping, erosion, sedimentation and self-curing. In case 11, a large bentonite pellet with an average diameter of 20 mm was used, and distilled water was fed into it. The inflow rate of distilled water was changed from 0.1 l/min initially, to 0.01, 0.001 and 0.0001 l/min after certain time intervals. The objective of case 11 was to investigate how pipes evolved in the flow conditions, how sedimentation of silica sand evolved and when self-sealing would occur. The bulk dry density of the bentonite block was 1.1 Mg/m³. In case 12, a bentonite block with a gap of 2.5 mm between the acrylic cell and the bentonite block was used, and distilled water was fed into it. The inflow rate of distilled water was changed from 0.1 l/min initially, to 0.01, 0.001 and 0.0001 l/min after certain time intervals. The objective of case 12 was the same as in case 11. In case 13, a bentonite block with a gap of 2.5 mm between the acrylic cell and the bentonite block was used, and saline water of 0.5 M NaCl was fed into it. The inflow rate of saline water was constant at 0.1 l/min. The objective of case 13 was to investigate how pipes evolved and, how sedimentation of silica sand evolved. In case 14, bentonite was compacted within the cell at every 5 mm layer and continued up to the top surface of the acrylic cell, and the water pressure of distilled water was controlled from 0.2 MPa to 0.5, 1.0, 2.0, 2.5 and 3.0 MPa at certain time intervals by two sets of syringe pumps. There was no gap between the compacted bentonite and acrylic cell. Water inflow was changed initially from 0.001 l/min to 0.05 l/min. The objective of case 13 was to study whether piping would occur when the water pressure increased from 0.2 MPa to 3.0 MPa. The water pressure of 3.0 MPa is equivalent to the groundwater pressure at 300 m depth.

Small scale experiments

Case 1: Bentonite block fed by saline water (0.5 M NaCl) with an inflow rate of 0.1 l/min (Fig. 3). Initially, saline water was fed from the

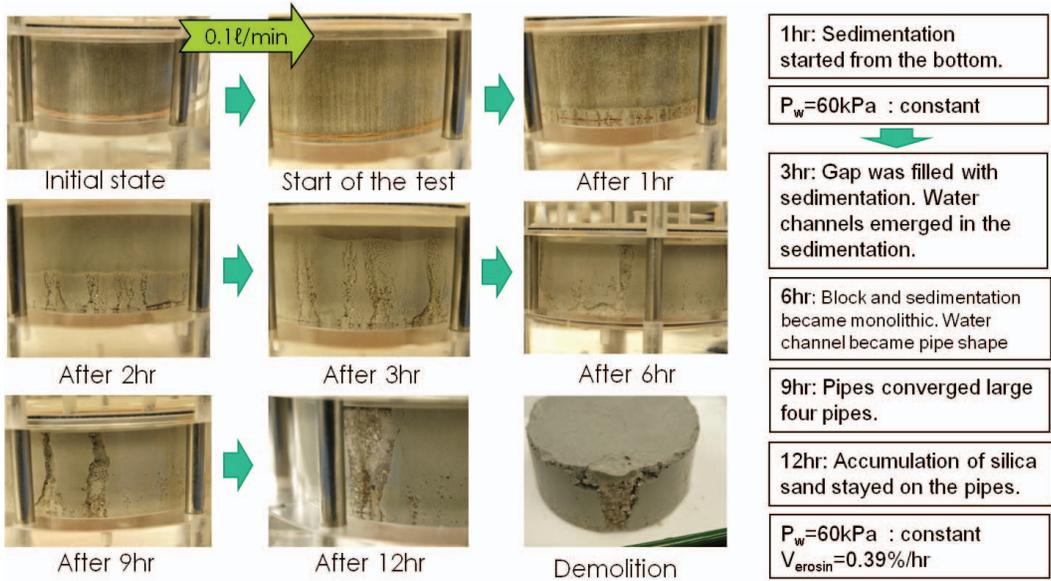


FIG. 3. Case 1; the piping and erosion experiment using bentonite block fed by saline water with inflow rate of 0.1 l/min.

bottom of bentonite block with an inflow rate of 0.1 l/min. After 1 h of saline water feeding, the bentonite block swelled, and the sedimentation of the accessory mineral bentonite started from the bottom side, and then the gap between the bentonite block and the acrylic cell was partly buried. The feeding water pressure was 60 kPa (Fig. 4). After 3 h, the gap was filled with sediment, and the water channels emerged in the sediment. Inside of the water channels, silica sand was washed away and accumulated on the surface. After 6 h, the bentonite block and sediment became monolithic, and the water channels became pipe-shaped. As the force of erosion is larger than that of swelling pressure, there was no evidence that the pipe could be sealed. The silica sand sedimentation seemed to protect the self-sealing.

After 9 h, some pipes were sealed and converged on four larger pipes. The water pressure was constant at 60 kPa. After 12 h, the specimen was dismantled and the accumulation of silica sand on the surface of the four pipes was observed. The erosion mass was 36.940 g against the initial dry mass of 758.1 g. The percentage of erosion was 4.873% and the erosion velocity was 0.39 %/hour.

Case 2: The mixture of large and small pellets fed by distilled water with an inflow rate changed from 0.1 l/min to 0.001 l/min (Fig. 5). Initially,

distilled water was fed from the bottom of the mixture of large and small pellets with an inflow rate of 0.1 l/min. After 15 minutes of distilled water feeding, many of the small water channels emerged. After 30 min, they converged on a few channels. After 1 h, they became larger than before. After 3 h, they converged on one pipe. A small and flat cavity emerged at the bottom edge. The water pressure was a constant 25 kPa (Fig.4). After 6 h, the pipe became larger because erosion progressed on the surface of the pipe. The cavity at the bottom

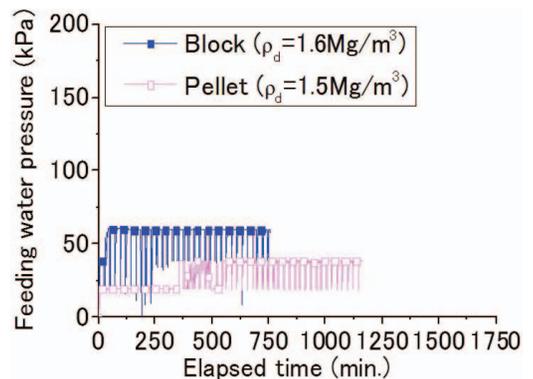


FIG. 4. Feeding water pressure and elapsed time for bentonite block and the mixed large and small pellets.

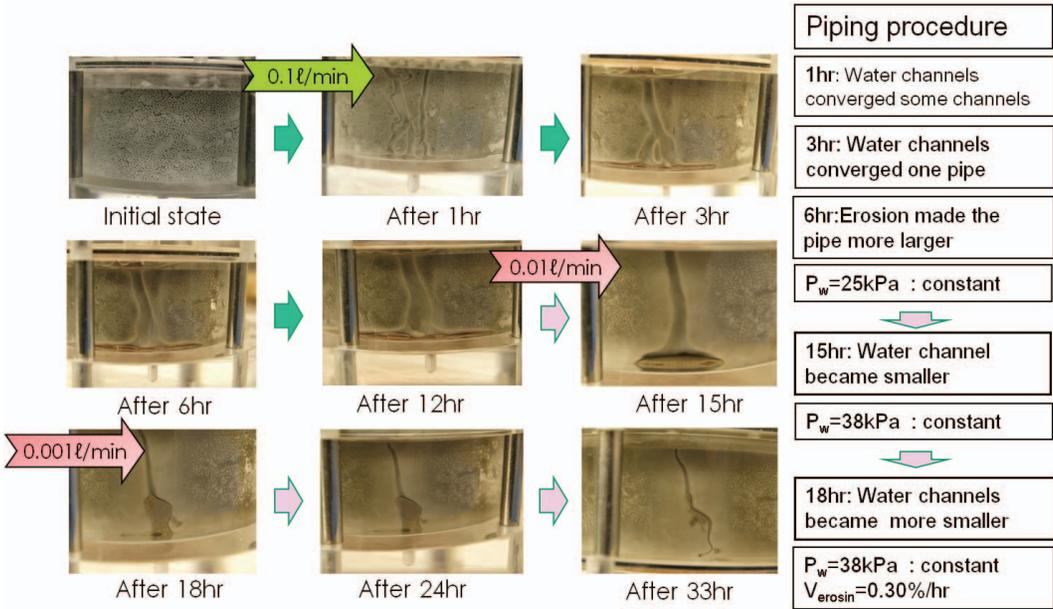


FIG. 5. Case 2; the piping and erosion experiment using the mixed large and small pellet feds by distilled water with inflow rate changed from 0.1 l/min to 0.001 l/min.

edge extended in a circumferential direction. The water pressure was changed to 38 kPa. After 12 h, the pipe tended to become larger and the cavity

enlarged in a vertical direction. The inflow rate was changed from 0.1 l/min to 0.01 l/min after 12 h. After 15 h, the width of the pipe became smaller

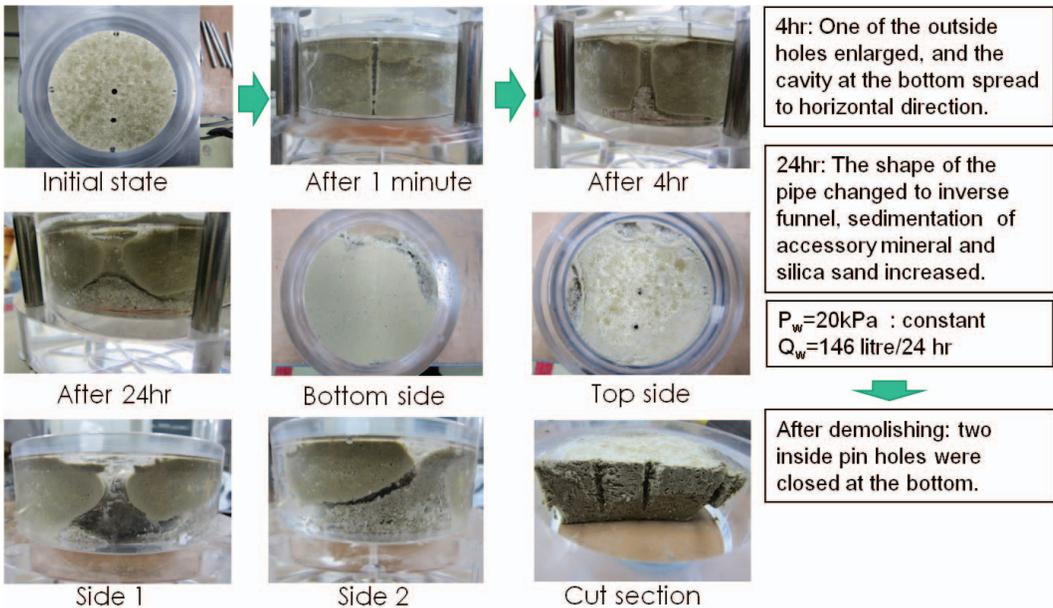


FIG. 6. Case 3; the position where piping emerged using bentonite block fed by distilled water with inflow rate of 0.1 l/min. Initial state was four outside pin holes and two inside pin holes.

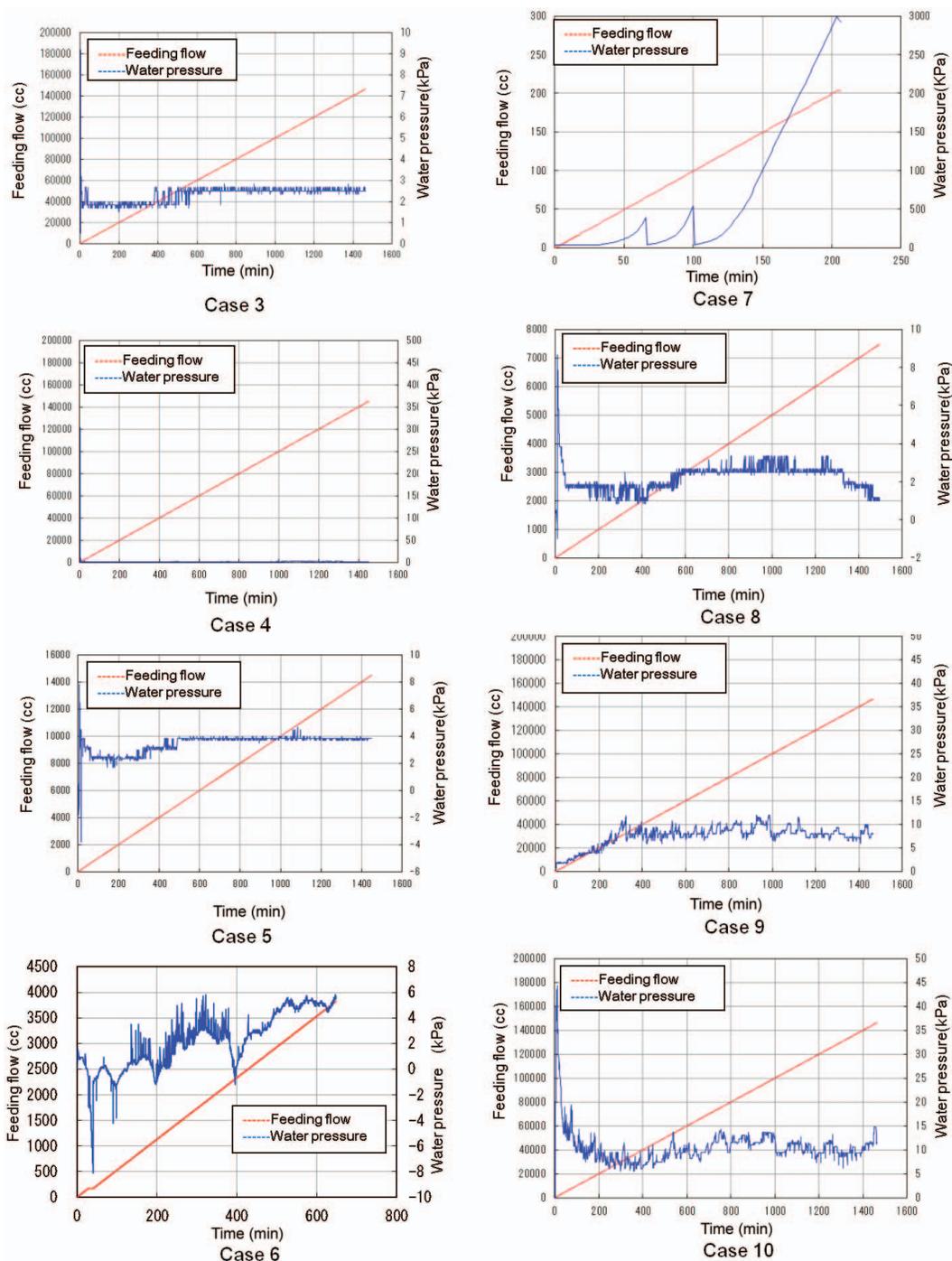


FIG. 7. Relation between feeding flow and water pressure.

because the swelling pressure exceeded the feeding water pressure of 38 kPa (Fig. 4). The cavity at the bottom became small and concentrated to a small elliptical shape. The inflow rate was changed from 0.01 l/min to 0.001 l/min after 15 h. After 18 h, the width of the pipe became smaller and the elliptical shape of the cavity became enlarged in the vertical direction, and then the sedimentation in the bottom pushed upwards. The water channel tended to be closed and the water pressure was a constant 38 kPa (Fig. 4). The mass of erosion was 42.910 g against the initial dry mass of 746.0 g. The percentage of erosion was 5.752% and the erosion velocity was 0.30%/hour.

Case 3: Six pin holes (two inside and four outside) were arranged artificially in the bentonite block, and distilled water with inflow rate of 0.1 l/min was fed into it (Fig. 6). After 4 h of feeding of distilled water with an inflow rate of 0.1 l/min, one of the outside four pin holes became a large pipe. The cavity at the bottom edge extended in a circumferential direction where the accessory mineral and silica sand were sedimented. After 24 h, the pipe became large and the shape changed to an inverse funnel in which the amount of accessory mineral and silica sand increased. At the same time, the accessory mineral flowed to the upper side. The sedimentation seemed to protect the

self-sealing of the bentonite. After dismantling the specimen, the two inside pin holes were closed at the bottom. The water pressure was constant at a low value of 2 kPa and the total amount of water fed was 146 litres after 24 h (Fig. 7).

Case 4: Five pin holes were arranged artificially inside the bentonite block, and distilled water with inflow rate of 0.1 l/min was fed into it (Fig. 8). The result was the same as case 3; after 2 h of distilled water feeding with an inflow rate of 0.1 l/min, one pipe emerged at the interface between the acrylic cell and bentonite block, and the accessory mineral and silica sand started to form sediment at the bottom of the large pipe. After 24 h, the width of the pipe became larger and the pipe at the bottom spread until half of the lower area was covered by sediment of the accessory mineral and silica sand. The sedimentation seemed to protect the self-sealing of bentonite. After dismantling the specimen, the five inside pin holes were closed at the bottom. The water pressure was constant at a very low value of 2 kPa and the total amount of water fed was 145 litres after 24 h (Fig. 7).

Case 5: The mass of erosion and its time were measured using a mixture of large and small pellets fed by distilled water with an inflow rate of 0.1 l/min (Fig. 9). After one day of distilled water feeding with an inflow rate of 0.1 l/min, a pipe

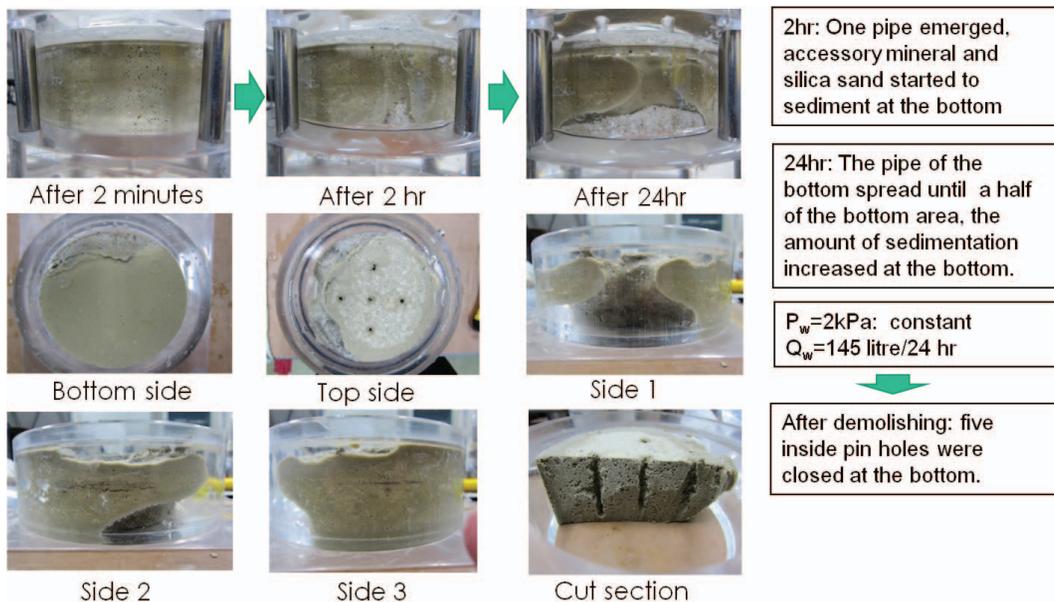


FIG. 8. Case 4; the position where piping emerged using bentonite block fed by distilled water with inflow rate of 0.1 l/min. Initial state was five inside pin holes.

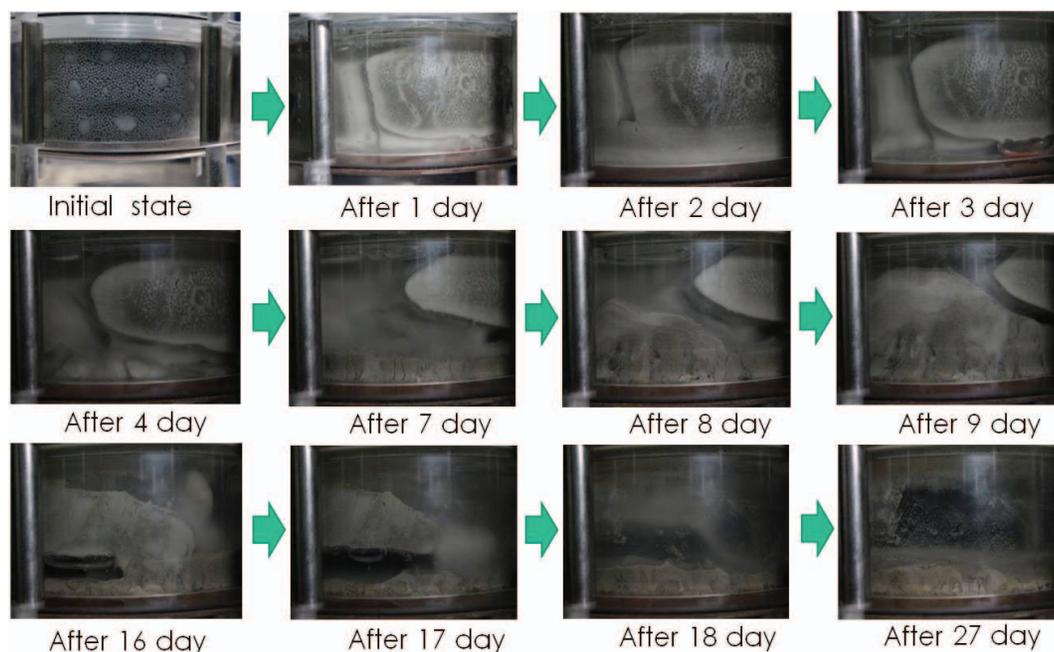


FIG. 9. Case 5; measurement of total mass of erosion and of its time using the mixture of large and small pellets with inflow rate of 0.1 l/min.

emerged at the interface of acrylic cell and pellet, and the pipe at the bottom edge extended in a circumferential direction. The colour along the pipe

turned light grey and it showed the beginning of swelling. After two days, the accessory mineral Kunigel V1 formed sediment at the bottom of the

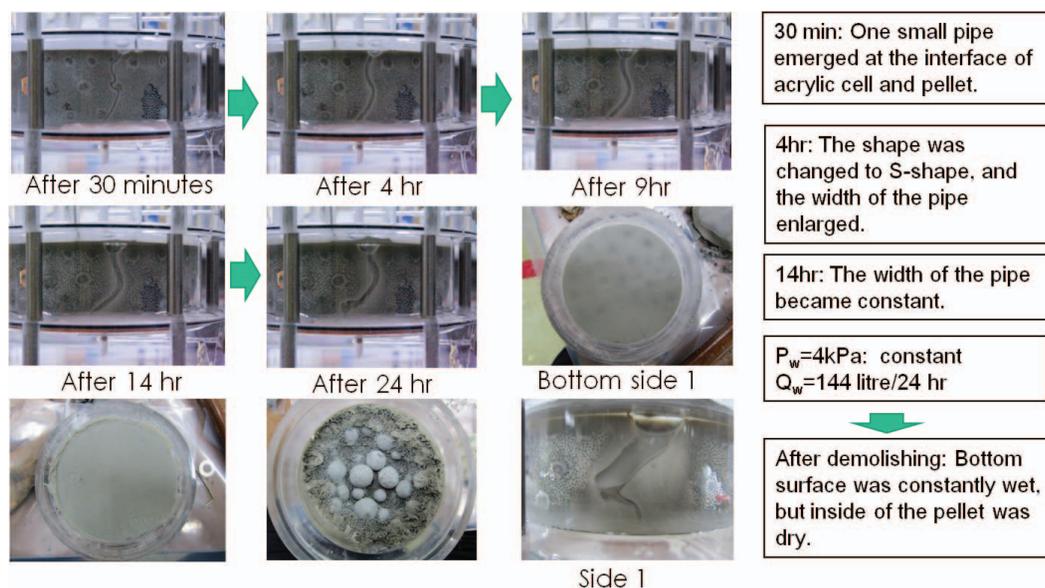


FIG. 10. Case 6; experiment with constant inflow rate which caused piping. Distilled water was fed with inflow rate of 0.01 l/min.

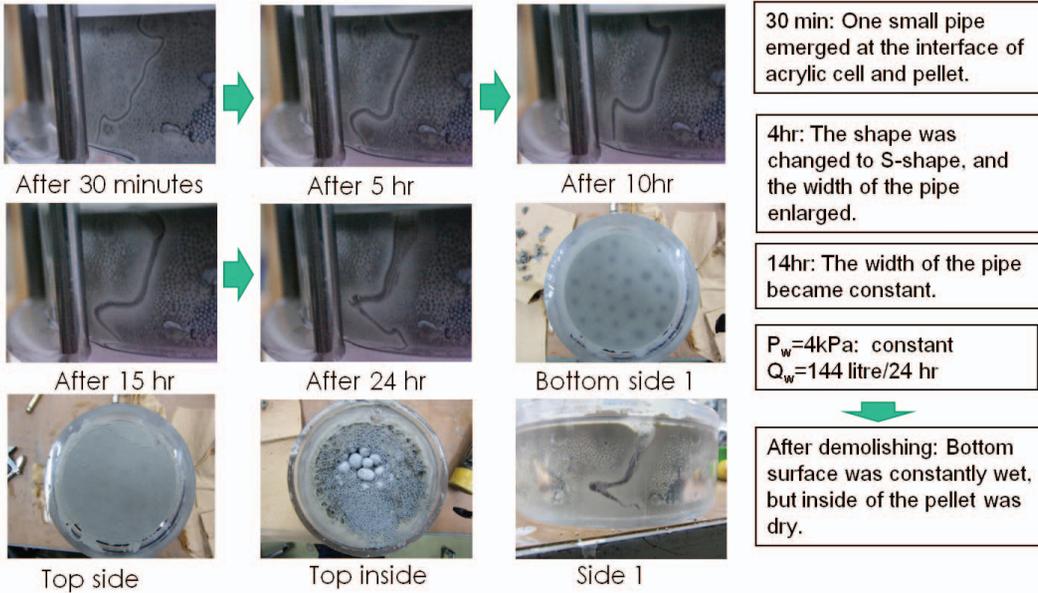


FIG. 11. Case 7; experiment with constant inflow rate which caused piping. Distilled water was fed with inflow rate of 0.005 l/min.

the pipe and along the circumferential pipe. After 3 days, accessory mineral sedimentation started to diminish and the cavity at the bottom enlarged. After 4 days, the cavity continued to enlarge and at the

same time erosion continued. After 7 days, the cavity and erosion progressed. After 8 days, along the acrylic cell wall, a new mass of accessory minerals emerged. After 9 days, the sedimentation



FIG. 12. Case 8; experiment with constant inflow rate which caused piping. Distilled water was fed with inflow rate of 0.001 l/min.

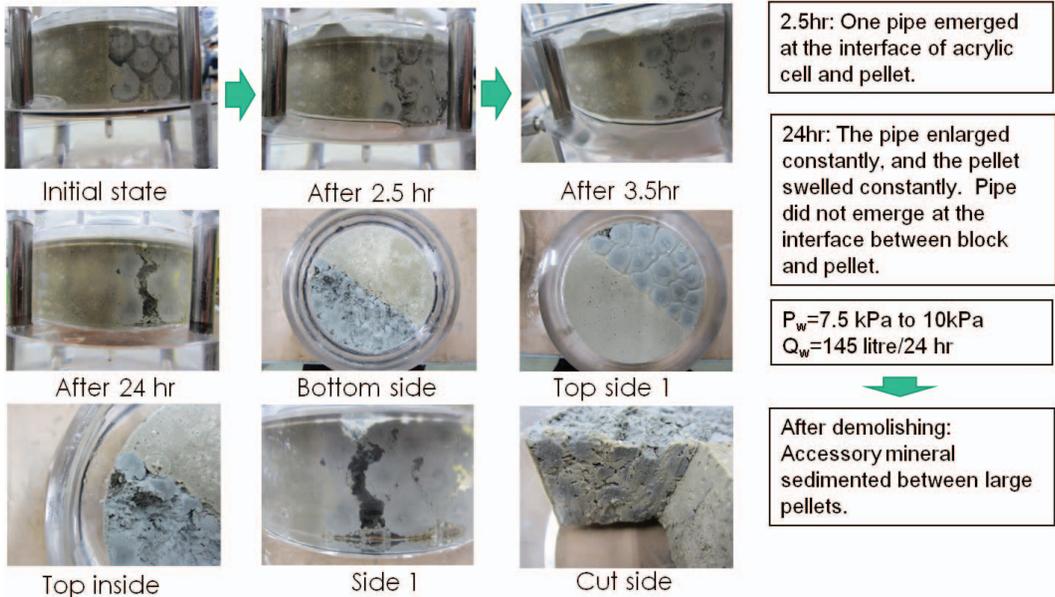


FIG. 13. Case 9; the position where piping emerged using bentonite block and large pellets fed by distilled water with inflow rate of 0.1 l/min.

developed in an upward direction. After 16 days, a part of the cavity emerged at the bottom, and the sedimentation divided into two parts. After 17 days, the cavity continued to enlarge. After 18 days, the

upper part of sedimentation started to diminish. After 27 days, almost all the sedimentation ceased, but a part of sedimentation rested at the bottom. The total mass of erosion was 612.8 g after 27 days.

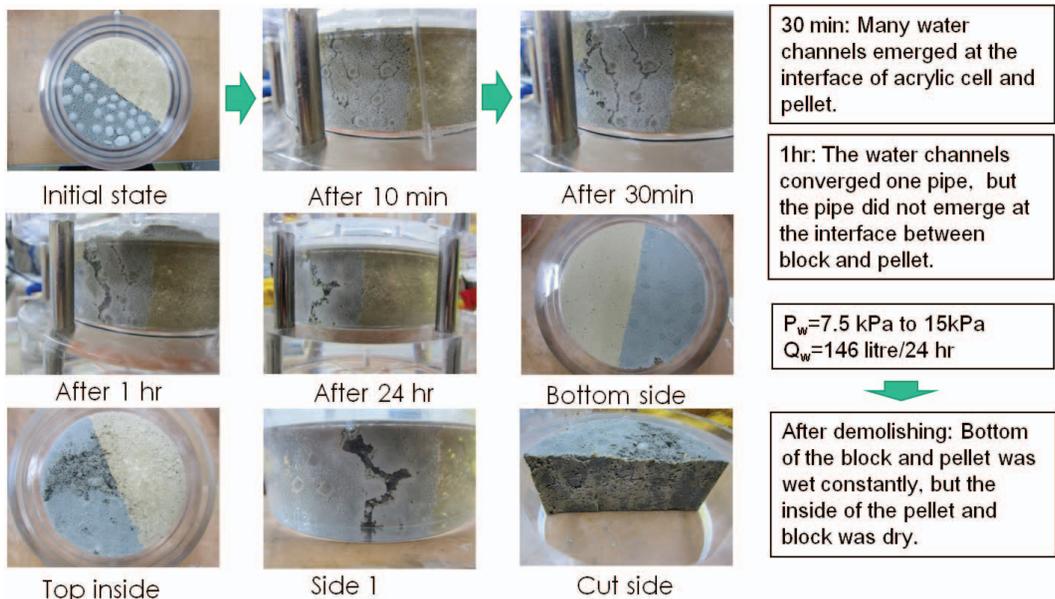


FIG. 14. Case 10; the position where piping emerged using the bentonite block and the mixture of large and small pellets fed by distilled water with inflow rate of 0.1 l/min.

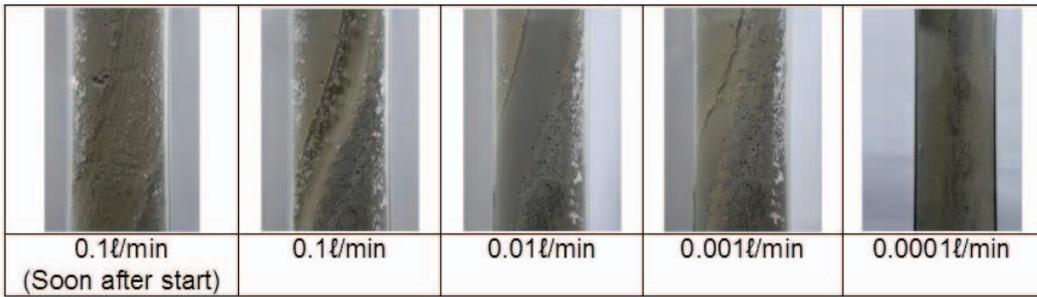


FIG. 15. Case 11. The movement of piping according to the inflow rate in the case of the bentonite block.

The water pressure was constant at a very low value between 0 kPa to 6 kPa, and the total amount of water fed was 3600 litres (Fig. 7).

Case 6: The large and small pellets fed by distilled water with an inflow rate of 0.01 l/min (Fig. 10). Initially, distilled water was fed into the bottom of the mixture of large and small pellets with an inflow rate of 0.01 l/min. After 30 minutes, one small pipe emerged at the interface of the acrylic cell and pellets. After 4 h, the shape changed to S-shaped, and the width of the pipe became enlarged. After 6 h, the width of the pipe continued to enlarge. After 14 h, the width of the pipe became constant. After dismantling the specimen, the outer sides of the pellets were found to be wet and the insides dry, and the bottom of the pellets was constantly wet. The water pressure was constantly very low at 4.0

kPa, and the total amount of feeding water was 144 litres for 24 h (Fig. 7).

Case 7: The large and small pellets fed by distilled water with an inflow rate of 0.005 l/min (Fig. 11). Initially, distilled water was fed from the bottom of the mixture of large and small pellets with an inflow rate of 0.005 l/min. After 30 minutes, one small pipe emerged at the interface of the acrylic cell and pellets. After 5 h, pipe meandered with complicated curves. After 24 h, the width of the pipe became enlarged. After dismantling the specimen, the outside of the pellets was found to be wet and the inside dry, and the bottom of the pellets was constantly wet. The water pressure was constantly very low at 2.5 kPa, and the total amount of feeding water was 7.4 litres for 24 h (Fig. 7).

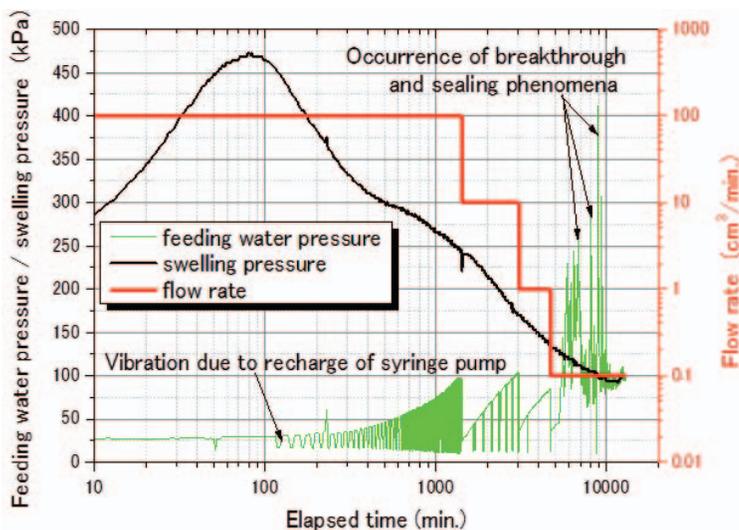


FIG. 16. The relationship between water pressure and inflow rate in the case of the bentonite block.

Case 8: The large and small pellets fed by distilled water with an inflow rate of 0.001 l/min (Fig. 12). Initially, distilled water was fed from the bottom of the mixture of large and small pellets with an inflow rate of 0.001 l/min. Pipes did not emerge at the the interface of the acrylic cell and pellets. After 3.5 h, swelling progressed constantly. After dismantling the specimen, the outside of the pellets was found to be wet and the inside was dry, and the bottom of the pellet was constantly wet. The water pressure changed varied from 0 kPa to 500 kPa for 2 h, and after 2.5 h, the pressure constantly increased to 3 Mpa (Fig. 7).

Case 9: The large pellet and bentonite block fed by distilled water with an inflow rate of 0.1 l/min (Fig. 13). Initially, distilled water was fed from the bottom of the large pellets and bentonite block with an inflow rate of 0.1 l/min. After 2.5 h, one pipe emerged at the the interface of the acrylic cell and large pellets. After 24 h, the pipe became enlarged and the large pellets swelled constantly. The pipe did not emerged at the interface of bentonite block and large pellets. After dismantling the specimen, accessory mineral sedimentation occurred between the large pellets. The water pressure varied from 5 kPa to 10 kPa constantly, and the total amount of water fed was 144 litres for 24 h (Fig.7).

Case 10: The mixture of large and small pellets and bentonite block fed by distilled water with an inflow rate of 0.1 l/min (Fig. 14). Initially, distilled water was fed from the bottom of the mixture of large and small pellets and bentonite block with an inflow rate of 0.1 l/min. After 30 minutes, many small water channels emerged at the the interface of the acrylic cell and pellets. After one hour, the water channels converged into one pipe. The pipe did not emerged at the interface of bentonite block and the mixture of large and small pellets. After 24 h, the bottom surface swelled constantly, but the

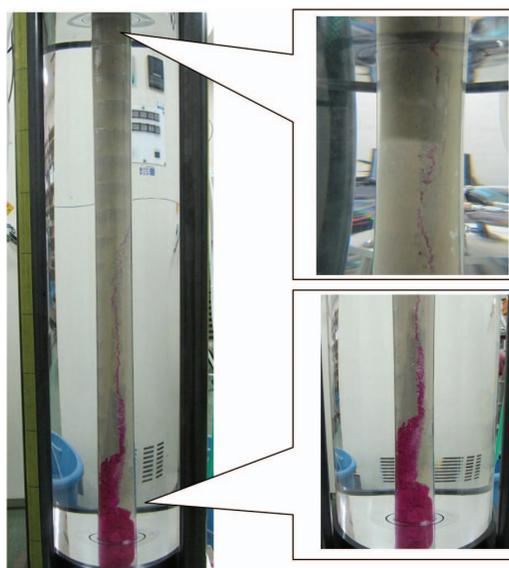


FIG. 17. The formation of piping and sedimentation by feeding of Rhodamine B in the case of the bentonite block.

inside of the pellets was dry. The water pressure varied from 7.5 kPa to 15 kPa, and the total amount of water fed was 146 litres for 24 h (Fig. 7).

Larger scale experiments

Case 1: Bentonite block fed by distilled water with an inflow rate from 0.1 l/min to 0.0001 l/min. Initially, distilled water was fed from the bottom of the bentonite block with inflow rate of 0.1 l/min. Soon after the start of experiment, water flowed constantly between the acrylic cell and bentonite block, and the gap was filled by swelled bentonite (Fig. 15), and the swelling pressure began at 250 kPa and increased to a maximum value of 475

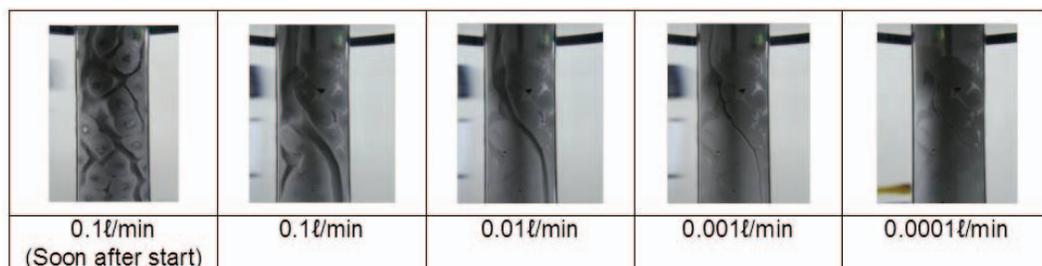


FIG. 18. Case 12. The process of piping according to the inflow rate in the case of the large pellets.

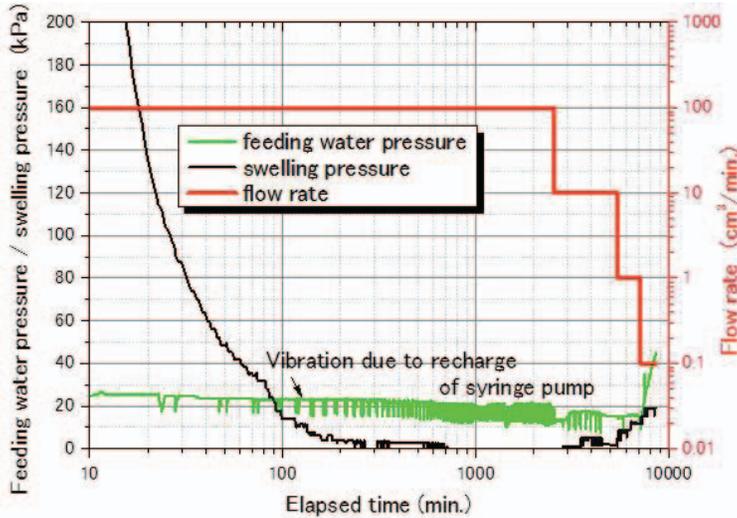


FIG. 19. The relationship between water pressure and inflow rate in the case of the large bentonite pellet.

kPa after 100 min (Fig. 16). After 3 h, a relatively wide and shallow water channel emerged at the gap between the acrylic cell and bentonite block; both edges of the pipe were continuously moving and the fine accessory minerals of Kunigel V1 were eroding. After 20 h, the width of the pipe became narrow, and the depth of it became deeper. The water pressure increased from 25 kPa to 100 kPa until 25 h. After 25 h, the inflow rate was changed to 0.01 l/min, the width of the pipe became wider, but the depth became shallower. The water pressure

increased from 25 kPa to 100 kPa over 50 h. After 50 h, the inflow rate was changed to 0.001 l/min, the depth of the pipe became shallower, and only the movement of the edges of the pipe could be seen. After 80 h, inflow rate was changed to 0.0001 l/min, and the water channel extinguished. The water pressure varied until it reached 400kPa. At this flow rate, the self-sealing effect of bentonite emerged. The swelling pressure decreased from 475 kPa to 100 kPa from 100 min to 7 days. After the experiment, Rhodamine B was fed into the

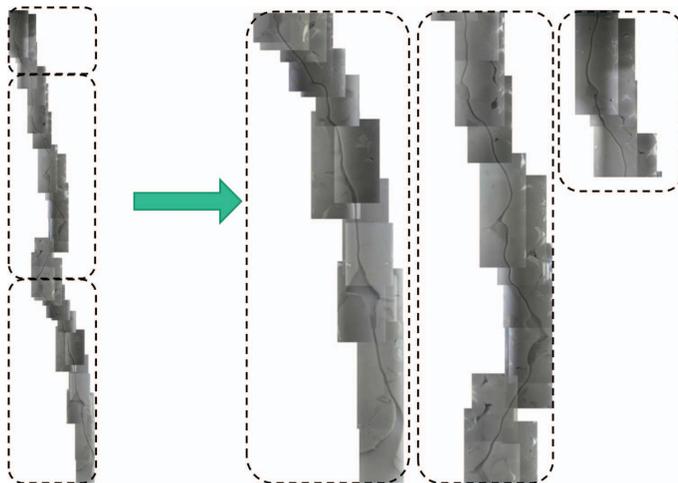


FIG. 20. The formation of piping in the case of the bentonite pellet.

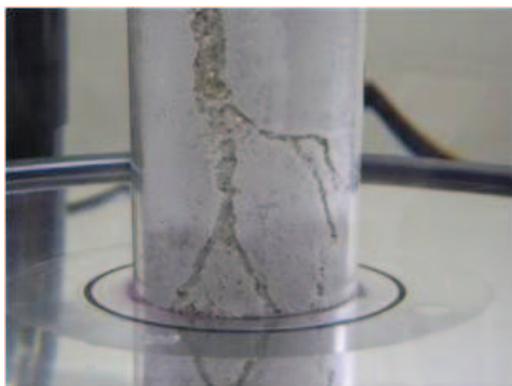


FIG. 21. The formation of water channels at the bottom of the bentonite block.



FIG. 22. The formation of sedimentation by silica sand. The light grey part is the sedimentation of no. 5 silica sand.

specimen. It was found that in the upper part of the acrylic cell, water channels converged into one pipe. But in the lower part of the cell, an accumulation of silica sand was found (Fig. 17).

Case 12: Large bentonite pellets fed by distilled water with an inflow rate from 0.1 l/min to 0.0001 l/min. Initially, distilled water was fed from the bottom of the large pellet of bentonite with an inflow rate of 0.1 l/min. Soon after the start of the experiment, a few pipes emerged. After 42 h, the pipes appeared to converge on one pipe (Fig. 18). The water pressure changed gradually from 25 kPa to 15 kPa (Fig. 19) and the swelling pressure decreased from 200 kPa to 5 kPa after 3 h. After 45 h, the inflow rate was changed to 0.01 l/min; the pipes converged into one pipe, and the width of the pipe became smaller and the depth

shallower. The water pressure decreased gradually around 20 kPa, and the swelling pressure was almost 5 kPa. After 90 h, the inflow rate was changed to 0.001 l/min; the width of water channel became more smaller and only a simple line could be seen. After 120 h, the inflow rate was changed to 0.0001 l/min and the water channel extinguished. The water pressure went up quickly from 15 kPa to 40 kPa. At this flow rate, a self-sealing effect emerged. The formation of piping in case of the large bentonite pellet is shown in Fig. 20.

Case 13: Bentonite block fed by saline water of 0.5 M NaCl with inflow rate of 0.1 l/min to 0.0001 l/min. Initially, saline water of 0.5 M NaCl was fed from the bottom of the bentonite block with



FIG. 23. Water splashed from sediment as jet water flowed making a turbulent flow.

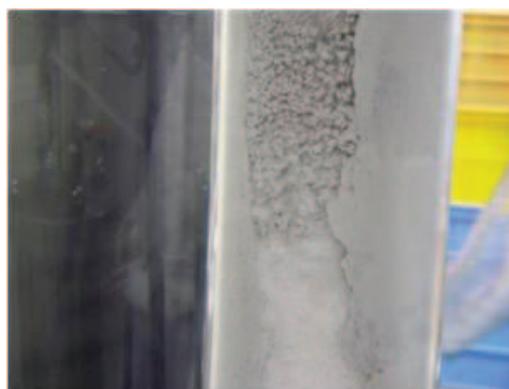


FIG. 24. Fine components of montmorillonite coagulated and rotated by the flow in the upper part of the cell.

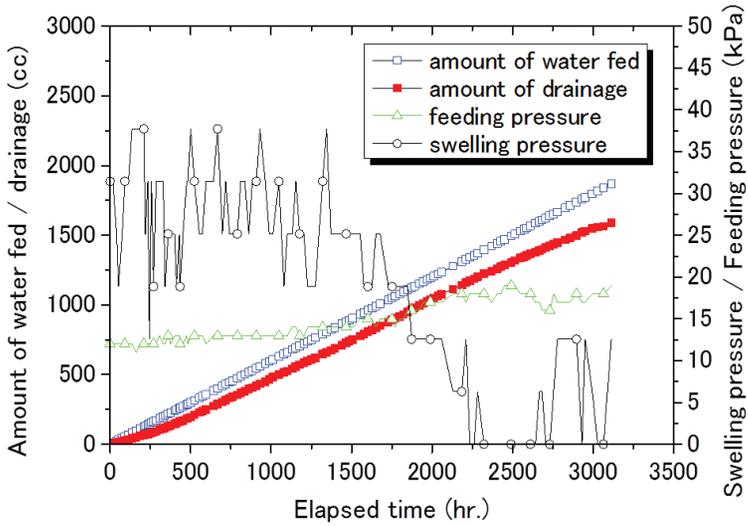


FIG. 25. The relationship of water pressure and inflow rate in the case of the bentonite block fed by saline water of 0.5 M NaCl.

an inflow rate of 0.1 l/min. Soon after the experiment began, many small water channels emerged at the bottom part of the specimen (Fig. 21). After one hour, the water channels converged on a single relatively wide pipe, and then sedimentation of two types of silica sand started with so-called grade 3 and grade 5 material. The sediment composed of relatively large dark grey coloured particles was silica sand grade 3, and the fine particles of light grey material was silica

sand grade 5. After 3 h, sedimentation of silica sand reached half height in the specimen (Fig. 22). The saline water appeared to pass through the silica sand sediment and water splashed from the top, making a turbulent flow (Fig. 23). In the upper part of the cell, fine components of montmollironite coagulated and were rotated by the flow (Fig. 24). The water channel did not close when the inflow rate reduced to 0.001 l/min. The swelling pressure changed from 20 kPa to 37.5 kPa for 60 days, and

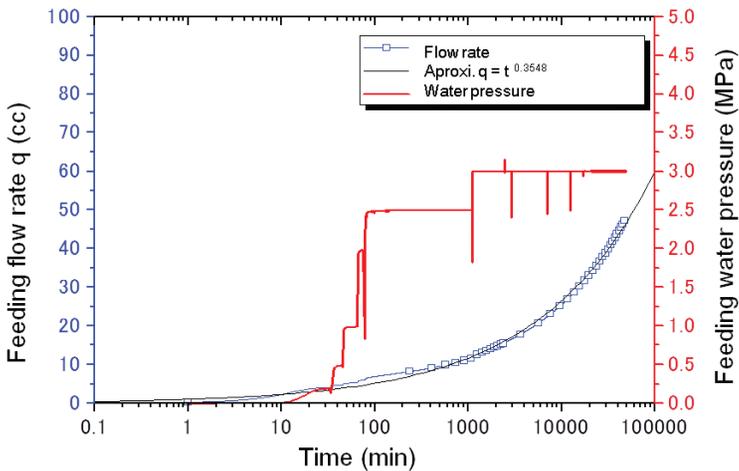


FIG. 26. The relationship between water pressure and inflow rate in the case of compacted bentonite fed by distilled water.

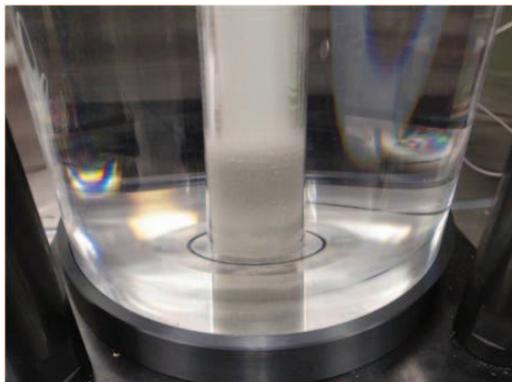


FIG. 27. The swollen part of the compacted bentonite.

the water pressure gradually increased from 15 kPa to 20 kPa (Fig. 25).

Case 14: Compacted bentonite fed by distilled water with feeding water pressure from 0.2 MPa to 3.0 MPa. The distilled water was fed from the bottom of the compacted bentonite with controlling water pressure increasing gradually from 0.2 MPa to 3.0 MPa. The water pressure of 3.0 MPa is equivalent to a repository depth of 300 m. The inflow rate was changed from 0.001 l/min to 0.05 l/min. During the experiment, no clear piping was observed (Fig. 26). In the bottom part of the specimen, the saturated part was dark grey and the non-saturated part was light grey; the contrast is

very clear (Fig. 27). This means that at the beginning of the experiment, the velocity of saturation is faster than that of diffusion of bentonite in the saturated part. The velocity of saturation will decrease with time.

RESULTS

The results of ten cases of small-scale experiments and four cases of larger scale experiments on piping and erosion phenomena using an Na-type bentonite block of 70 wt.% Kunigel V1 and 30 wt.% silica sand, and pellets of 100 wt.% Kunigel V1, are compiled in Table 3.

Piping and erosion occurred in the mixed large and small pellets which consists of 100% Kunigel V1 when the inflow rate of distilled water was more than 0.005 l/min. The position where these phenomena occurred is the interface between the acrylic cell and bentonite material. In the initial phase of piping, a few water channels emerged, but they converged into one channel after a few hours.

Even though the block was arranged next to the pellets, piping and erosion did not occur at the interface between block and pellets. Self-curing occurred in the block or large pellets when the inflow rate of distilled water was less than 0.0001 l/min. Although the water pressure during the piping and erosion is a maximum of 100 kPa for the bentonite block, and 40 kPa for the large and small bentonite pellets. Considering that the swelling

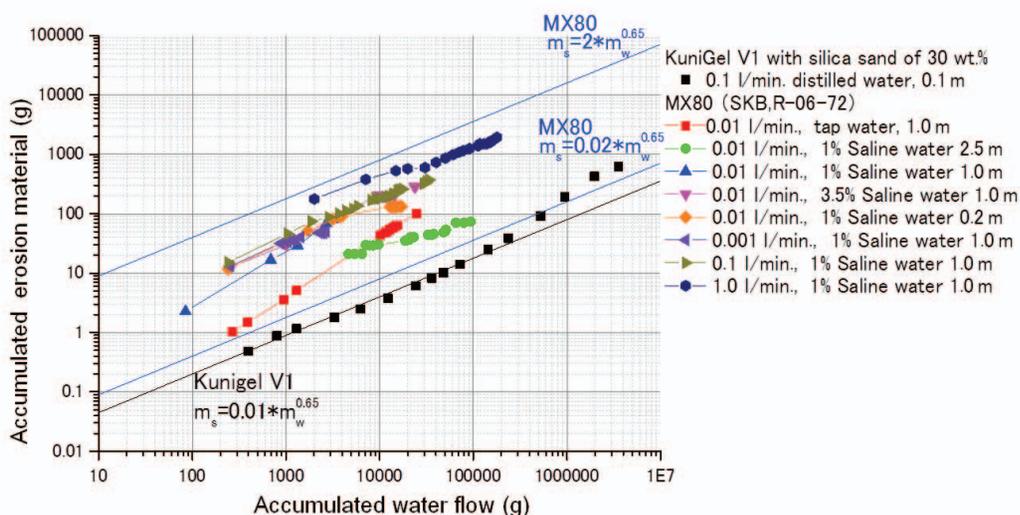


FIG. 28. Erosion results of MX80 compared with Kunigel V1.

TABLE 3. Piping and erosion experiments on Na type bentonite in Japan.

Experiment	Case	Type of buffer material	Type of liquid	Flow rate (l/min)	Piping and erosion	Sedimentation	Water pressure (kPa)	Where to occur?
Small scale experiments	1	Buffer block with gap	Saline water	0.1	○	○	60	acrylic cell
	2	Mixed large and small pellets	Distilled water	↓ 0.1 ↓ 0.01 ↓ 0.001	○	△	25 38 38	acrylic cell
	3	Buffer block	Distilled water	0.1	○	○	2.5	acrylic cell
	4	Mixed large and small pellet	Distilled water	0.1	○	○	2.5	acrylic cell
	5	Mixed large and small pellet	Distilled water	0.1	○	○	1→5	acrylic cell
	6	Mixed large and small pellet	Distilled water	→ 0.01	○	×	2.5	acrylic cell
	7	Mixed large and small pellet	Distilled water	→ 0.005	○	×	2.5	acrylic cell
	8	Buffer block with large pellet	Distilled water	→ 0.001	×	×	3000	acrylic cell
	9	Buffer block with large pellet	Distilled water	0.1	○	×	7.5	acrylic cell
	10	Buffer block with mixed large and small pellet	Distilled water	0.1	○	×	7.5→15	acrylic cell
Larger scale experiments	11	Buffer block with gap	Distilled water	↓ 0.1 ↓ 0.01 ↓ 0.001 ↓ 0.0001	○	○	25→100 25→100 40→80 40→300 25→20	acrylic cell
	12	Large pellet	Distilled water	↓ 0.1 ↓ 0.01 ↓ 0.001 ↓ 0.0001	○	×	17.5 17.5 17.5 17.5→45	acrylic cell
	13	Buffer block with gap	Saline water	0.1	○	○	12.5→20	acrylic cell
	14	Compacted buffer with no gap	Distilled water	0.001→0.05	×	×	200→ →2000→ →3000	acrylic cell

pressure of the bentonite block of same type in full saturation is around 700 kPa, piping and erosion occur at one tenth of the swelling pressure.

Piping and erosion did not occur in compacted bentonite with no gap, which consisted of 70 wt.% Kunigel V1 with 30 wt.% silica sand, when the inflow rate of distilled water was less than 0.001 l/min.

In order to compare the mass of erosion of Kunigel V1 in case 4 to that of MX80, the accumulated mass of erosion is plotted in Fig. 28 (SKB, R-08-135). The black squares show the mass of erosion for 70 wt.% Kunigel V1 with 30 wt.% silica sand, and it ranks lowest border of the MX80's. The accumulated amount of erosion of Kunigel V1 with 30 wt.% silica sand with inflow rate of 0.1 l/min is less than that of MX80 with tap water of 0.01 l/min or that of MX80 with 0.01 l/min of saline water. The reason is that the silica sand takes a role of binding material in Kunigel V1 and it makes harder to cause erosion than MX80.

When saline water of 0.5 M NaCl flows into the bentonite block with an inflow rate of 0.1 l/min, sedimentation as well as piping and erosion occur. The accessory minerals are separated from the bentonite block, and then the surface of no. 5 and no. 3 silica sand are washed away because of the ionic strength of Cl, and finally they form sediment on the surface of the channel. This channel could not be sealed in spite of the self-sealing function of montmorillonite.

DISCUSSION

If the allowable inflow rate is defined on the above experiments on Na type bentonite of Kunigel V1, the optimum inflow rate will be 0.001 l/min. But more experiments using saline water are required in order to obtain precise data for piping and erosion phenomena with different inflow rates. Moreover, as these results are derived from small-scale and larger scale experiments, they are not representatives of full-sized tests.

CONCLUSION

The project is still ongoing and more experiments will be carried out. However, some preliminary conclusions can still be drawn:

Piping will occur if there is an inflow of water of 0.1l/min and in the gap between acrylic cell and buffer materials, such as the bentonite block or pellets. The water pressure during the piping and erosion was under 100 kPa. This means that the swelling pressure of fully saturated bentonite could not be expected in the early stage of saturation. If the silica sand is contained in the bentonite block, the experiments show that the sedimentation protects the self-curing function of montmorillonite. This means that the water pathways with high hydraulic conductivity might exist for a considerable time. This has to be considered in the design and engineering as well as in the long-term assessment. Piping will not occur, when the inflow rate is less than 0.001 l/min, or the gap is filled with bentonite by compaction or spraying methods.

Finally the piping and erosion phenomenon are based on the boundary conditions that maintain advection. To protect against these phenomenon it is necessary to reduce the water in flow rate into deposition holes and tunnel to less than 0.001 l/min or to stop the water movement within a deposition hole by using a temporary plug in the deposition hole. These counter-measures and also water-management should be intensively investigated in Japan.

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