Laboratory measurement by geotechnical centrifuge of long-term behavior in a model of vertical emplacement concept with tunnel at a deep geological disposal repository

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ABSTRACT: We carried out the centrifuge model test to evaluate the long-term behavior during the resaturation surrounding the deep geological disposal repository. The centrifuge model is the vertical emplacement concept repository and 1/50-size, and the sedimentary rock is drilled a single disposal tunnel and hole, and then the model-overpack, Na-type bentonite buffer, and backfill material are placed in. And the test was conducted at 50 G with the effective stress of 3 MP for equivalent to about 200 years based on centrifugal similarity law. As a result, the displacement of the overpack was measured to be several times larger than that of the tests without the backfill material and disposal tunnel. In addition, it was confirmed that the buffer significantly expanded to the disposal tunnel after the test and visual confirmation. Test results implied that the displacement of the overpack is affected by the stiffness of the backfill material.

Keywords: Deep geological disposal repository, Long-term THM behavior, Centrifuge model test, Geomechanical interaction.

1 INTORODUCTION

The high level radioactive waste (HLW) disposal repository in Japan will be built in deeper than 300 m in the underground (JNC, 2000). The vitrified waste is enclosed in a metallic overpack. It is then packed, surrounded by buffer material made of clay bentonite, into a disposal hole drilled deep into the bedrock. The near-field is composed of such a heterogeneous composite. In the near-field, various processes will occur under the effect of heat from the waste, rock stress and underground water. This thermal-hydraulic-mechanical (THM) transition will dominate and continue for hundreds of years in the initial construction, operation, and closure stage. These states are transition period of artificial disturbance and resaturation, and phenomena dominates THM, mechanically unstable.

Long-term behavior in the near-field is finally evaluated by numerical analysis. In order to improve the reliability of the numerical analysis, it is necessary to validate the numerical analysis by comparing it with test results. To validate the numerical analysis, Nishimoto et al. (2016) conducted centrifuge model tests, which are time-acceleration tests based on the similarity law of static fields, and Sawada et al. (2017) compared the test results with those of the numerical analysis.

Nishimoto et al. (2016) conducted centrifuge model tests using a 1/30-size model of a vertical emplacement concept consisting of a single model-overpack, ring- and cylinder-shaped buffers, and a cylindrical sedimentary rock mass. The overpack and buffers are placed in the bore hole drilled in the rock mass. The tests were conducted in a centrifugal force field at 30 G for up to about 3 months (equivalent to about 200 years of real time), with confining pressure (correspond to ground stress) as a parameter. The results first revealed experimentally that the long-term behavior in the near-field was changed by the geomechanical interaction between the deformation stress of the bedrock/disposal hole and the swelling behavior of the buffer depending on the depth of the disposal repository and the stiffness of the bedrock. On the other hand, the tests by Nishimoto et al. (2016) used a model without disposal tunnels and backfill material. Therefore, the effect of the interaction between the tunnel and the backfill material on the displacement of the overpack and the swelling behavior of the buffer may differ from previous test results.

In this study, we conducted centrifuge test to evaluate the long-term behavior in the near-field using a model including the disposal tunnel and backfill material.

2 CENTRIFUGE MODEL TEST

2.1 *Centrifugal similarity law in the static field*

The behaviors expected in the near-field can be attributed to two-phase mixtures that consist of the rock/soil and pore fluid if the centrifugal model is the same material as the prototype. In a centrifugal model test, by subjecting $1/N$ scale model to N times the earth's gravitational/centrifugal acceleration (G) based on a centrifugal similarity law in a static field (where N is the scale factor and gravity/centrifuge acceleration level), the following are true: (1) the stress-strain behavior of a specimen in the model will be identical to that in the prototype, and (2) the equivalent elapsed time for the migration of underground water that satisfies Darcy's law, the stress due to consolidation and swelling, and the distribution of elastic strain can be shortened to $1/N^2$, compared with the full-scale elapsed time (Table 1) (Taylor, 1995). For instance, the behaviors for about 200 years can be simulated in about 30 days using a 50 G centrifugal force field. This study treats the behaviors of the near-field as occurring in a static field.

Table 1. Similarity law of the centrifugal model test.

Physical properties	Model/Prototype	Similitude
Gravity (Centrifugal force)	g_m/g	N
Length	l_m/l	$1/N$
Area	A_m/A	$1/N^2$
Volume	V_m/V	$1/N^3$
Stress	σ_m/σ	1
Young's modulus	E_m/E	1
Elastic strain	$(\varepsilon_e)_m/(\varepsilon_e)$	1
Temperature	T_m/T	1
Viscosity of pore fluid	$(\eta_w)_m/(\eta_w)$	1
Flow velocity of pore fluid	u_m/u	N
Time	t_m/t	$1/N^2$

'm' of index shows the 'model'.

2.2 *Geotechnical centrifuge and centrifugal model of near-field*

We used the geotechnical centrifuge of CRIEPI that enables us to perform a long-term operation of up to 6 months with a maximum payload of 1.5 ton up to 100 G (Nishimoto et al., 2016) (Figure 1). Therefore, the long-term behaviors in the near-field can be simulated in the short term on the basis of the centrifugal similarity law. The main features of the centrifuge are shown in Figure 1.

The near-field model including disposal tunnel and backfill material which is 1/50-size proposed by Ogata et al. (1999) and Kanagawa et al. (1999) (Figure 2a). The model consists of a single model-overpack, ring- and cylinder-shaped compacted buffers, backfill material in the tunnel and a cube-shaped sedimentary rock mass (Figure 2b).

The overpack and buffers are placed in the bore hole drilled in the rock mass. The overpack is 16-mm diameter by 37 mm height, and 6.16 Mg/m^3 density. The buffer and backfill material are made by compacting a Na-bentonite powder (Kunigel-V1), after it was oven-dried at 110 °C for 24 h. Overall volume of the buffer is about 32 mm in diameter by about 76 mm in height, and the initial dry density is 1.74 Mg/m^3 (the dry density after swelling is 1.55 Mg/m^3, including the swelling-filled gap between the overpack, the rock mass and the bentonite). The backfill material consisted of a mixture of 30% Na-bentonite and 70% silica sand and directly compacted in the tunnel to a density of 1.4 Mg/m^3. The rock mass is a cube-shaped with 300 mm on each side. The disposal tunnel is 100-mm diameter, and the disposal borehole in the tunnel is 56.7 mm in diameter by 127 mm in height. As rock mass, we selected Tage tuff because it is one of the most popular sedimentary rocks in Japan assuming the repository composed of sedimentary soft rock. And it is easily obtainable and shows values close to the average uniaxial compressive strength of soft rocks shown in the report of JNC (2000). The physical properties of the tuff in the laboratory tests are about 2.9 GPa (dry) and 1.2 GPa (wet) in the Young's modulus of the uniaxial compressional test, about 1.72 Mg/m^3 (dry) and 2.00 Mg/m^3 (wet) in the density, and about 10^{-11} m/s in the permeability (Nishimoto et al., 2016).

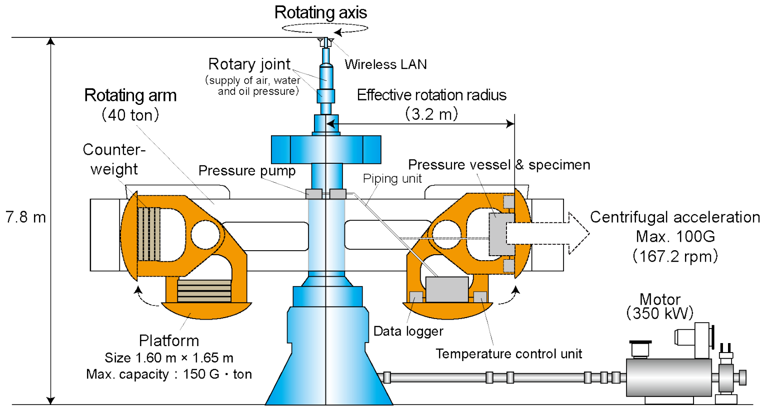
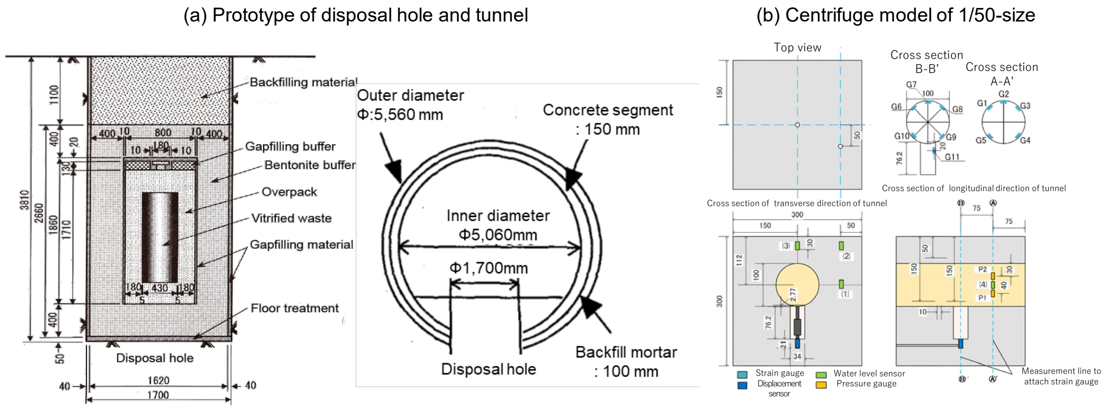


Figure 1. Schematic of geotechnical centrifuge.


(a) Prototype of disposal hole and tunnel

(b) Centrifuge model of 1/50-size

Figure 2. Target of repository (a), and centrifuge model and sensor layout (b).

2.3 *Test condition*

The test was conducted at a centrifugal force field of 50 G for about one month, assuming a repository of about 300 m-underground (effective stress of 3 MPa at the top of the disposal hole in the tunnel), with a confining pressure of 4 MPa given by the pressure vessel, and a pore pressure of 1.07 MPa at the bottom of the model and 0.92 MPa at the top of the model under drainage conditions. This is the equivalent of a 15 m difference in hydraulic head for a model height of 30 cm by the static similarity law. The confining and pore pressures were determined based on the limitations of the vessel's pressure resistance. For the viscosity of the pore fluid η_w, we used distilled water, because it is satisfied at 1:1 between the model and the real object in terms of the similarity law of the static centrifugal force field. The heat generated by the waste was not considered in this test (boundary temperature is constant at 25°C). We measured the pore water level in the rock mass, strain of disposal tunnel wall and vertical displacement of overpack in the buffer in the test.

3 RESULT AND DISCUSSION

The results of the centrifuge model test are shown below. In figs, positive and negative values for the displacement of the overpack indicate heave and settlement and are shown in equivalent values (50 times larger than the measured values). And the positive and negative values of strain indicate expansion (tensile) and compression. The lower and upper horizontal axis shows the equivalent time and the test elapsed time. The origin was defined as the zero time when water injection started after the centrifugal acceleration reached 50 G. The measured values were also set to zero. Unless otherwise noted, the equivalent time and value are used in the text.

3.1 Pore water level

Figure 3 shows the temporal change in the output voltage of the pore water level sensor. This sensor is a simple sensor solidified with epoxy resin using a pair of electrodes, which are stainless steel plates with size of 5 mm×10 mm and thickness of 0.1 mm. When pore water in the model reaches the sensor, the electrodes are energized, and a voltage of 6 V is output.

The pore water level sensor, WL (1) (Figure 1b) installed in the rock mass at a height of 190 mm (9.5 m in actual scale) from the bottom of the model outputs 6 V at a time equivalent to 154 years. This indicates that pore water has permeated up to this height. The test was conducted for about 700 hours (equivalent to about 200 years), but the pore water did not reach the top of the model. Based on the energization time of the WL (1), the penetration rate of pore water in the rock mass was calculated to be 1.95 x 10^{-9} m/s. However, this is not a representative value because only one water level sensor value was obtained from the measurement.

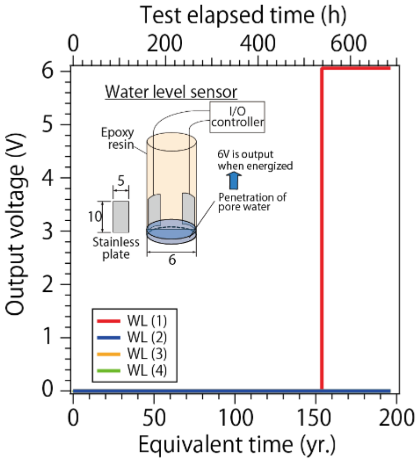


Figure 3. Temporal change in output voltage of pore water level sensor.

3.2 Strain of disposal tunnel wall (rock mass)

The results for strain gauges G1 to G5 (Figure 1b) mounted in the tunnel are shown in Figure 4.

Except for G3, the strains for G1-G5 began to increase gradually immediately after the start of the test. The reason why the behavior of G3 differs from that of the other symmetrically placed gauges is undetermined. G1 and G2 continued to increase gradually. In contrast, G4 and G5 continued to increase rapidly from about 100 years passed. These changes in strain can be attributed to the decrease in effective stress due to penetration of pore water.

Based on the penetration rate determined by the water level sensor, the time for water to reach G4 and G5 is estimated to be about 120 years, and the height of G1 and G3 is estimated to be about 180 years. It is implied that the penetration of pore water and the change of strain are generally congruent.

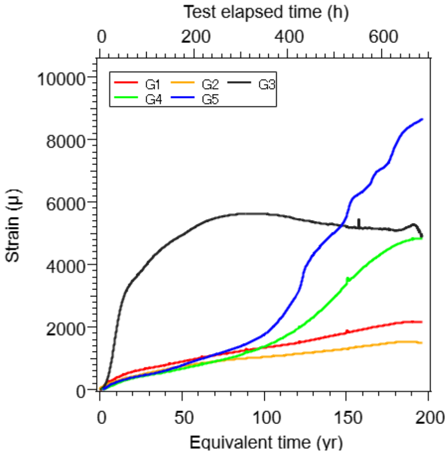


Figure 4. Temporal change in strain of tunnel wall.

3.3 *Vertical displacement of overpack*

Figure 5 shows temporal change in the vertical displacement of the overpack in this study with the result of Nishimoto et al. (2016) under similar effective stress condition (see next section for details). The displacement of the overpack is qualitatively considered to behave as follows; swelling of the buffer located below pushes the overpack upward, and when the pore water reaches the buffer and backfill material located in the upper part, it is pushed back by the swelling pressure and settles. The settlement was observed at the beginning of the test, but the overpack began to rise after about 27 years, and then settled rapidly again after about 54 years. The settlement was about equivalent to 7.2 mm. The overpack began to rise again after about 66 years and rose to 17.4 mm at about 130 years. It then began to rise rapidly, and eventually rose to 74.6 mm. At the end of the test (equivalent to about 200 years), the displacement had not converged.

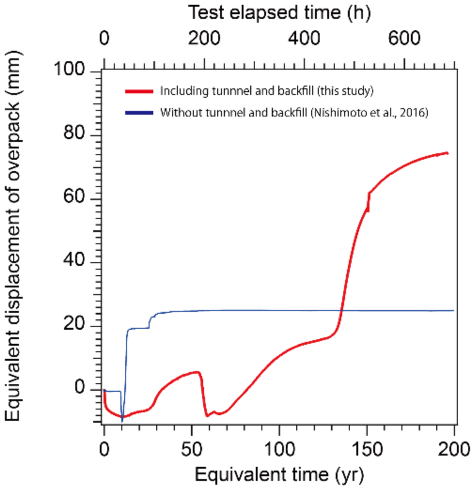


Figure 5. Temporal change in the vertical displacement of the overpack.

3.4 Condition in the tunnel after the test

Compared to the condition of Nishimoto et al. (2016) that the top of the buffer is loaded at confining pressure without the tunnel and the backfill material, the heave of the overpack in this study was several times larger. Therefore, we removed the backfill material after the test and observed inside the tunnel. Figure 6 shows the condition inside the tunnel after the test, and it is observed that the buffer inside the disposal hole has expanded significantly into the tunnel. The displacement of the overpack is larger than that of Nishimoto et al. (2016) due to this expansion. The measured height of the overhang was about 10 mm from the top end of the disposal hole. This corresponds to an expansion of approximately 50 cm in actual size. However, the actual expansion is considered to be smaller than this because it was observed where the self-weight in a centrifugal force field and the confining pressure of the pressure vessel were unloaded. In contrast to previous studies without tunnels and backfill, this test suggests that, at least, depending on the initial density of the backfill and buffer material, the buffer may expand into the tunnel, and that not small density changes may occur in the buffer of the disposal hole.

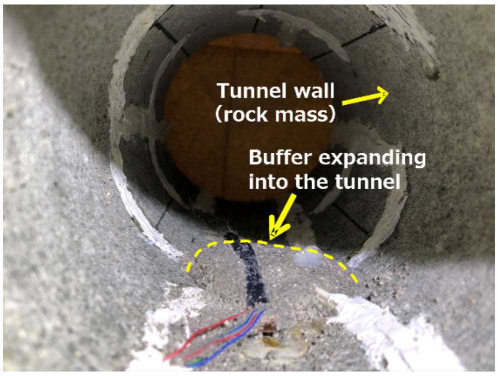


Figure 6. Conditions in the tunnel after the test.

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