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Elution and Containment of Harmful Substances in Construction-Generated Soil: A Case Study of Oshikado Tunnel, Japan

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Elution and Containment of Harmful Substances in Construction-Generated Soil: A Case Study of Oshikado Tunnel, Japan

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Abstract. In recent years, there has been an increasing number of cases in Japan where countermeasures against environmental pollution caused by natural heavy metals contained in soil and wastewater generated during construction work have become a problem. For example, when arsenic, which is often used, exceeds 0.01 mg/L, which is the criterion in the elution test, the generated soil is covered with low-permeability (permeability coefficient $\leq 1 \times 10^{-6}$ cm/s) soil mixed with bentonite to prevent heavy metal leakage. Although the impact on the surrounding environment is predicted in the design of such a disposal site, it does not accurately reflect the behavior of leachate in the embankment and the elution characteristics of heavy metals. Therefore, in this study, for the purpose of optimal design of the disposal site, the distribution of heavy metals in the embankment, behavior of leachate, and elution amount of heavy metals were investigated, and a numerical analysis method using the advection-dispersion equation was examined. In addition, a large column test using soil at the site was conducted to reproduce the site. The parameters related to the permeation characteristics obtained from the column test agreed with the field test; however, the unit elution amount, which is a parameter related to the elution characteristics, was 7.5 times that of the field test. This result indicates the possibility of overestimating the elution amount of heavy metals in the test modeling of the disposal site.

1. Introduction

In Japan, it is necessary to appropriately manage and dispose of excavation scraps containing naturally derived heavy metals generated in construction work. Effective remediation methods include covering with a poorly permeable material such as bentonite mixed soil or an impermeable sheet [1,2]. The impermeable sheet has an excellent water-impervious function; however, there it may be damaged during construction which generates problems. In contrast, because bentonite has swelling properties, self-healing properties can be expected even if cracks occur. Therefore, bentonite is often mixed with soil and applied [3,4]. Impact prediction is important in designing an embankment to dispose of contaminated soil and establishing an accurate prediction method will help rationalize the design. In this study, in the excavation embankment of the Oshikado tunnel where containment measures were taken with bentonite mixed soil, part of the top of the embankment was temporarily exposed. Further,



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the elution of heavy metals was observed and simulated by numerical analysis using the advection - dispersion equation. At the site, the following information were confirmed as necessary for the numerical analysis:

- 1) Monitoring of rainfall and leachate
 - 2) Boring survey in embankment (distribution of heavy metals)
 - 3) In situ unsaturated permeability test (identification of parameters in analytical model)
- An attempt was made to reproduce the site using a column test with soil at the site.

2. Monitoring rainfall and leachate at excavation embankment

The Oshikado tunnel is located on National Highway 340, which is the main road in Iwate Prefecture, and bypasses the Oshikado Pass. In this study, arsenic exceeding the criteria value was detected in the preliminary survey; therefore, all excavated soil was covered with bentonite mixed soil. The amount of embankment was approximately 180,000 m³. Figure 1.1 shows the floor plan of the drainage facility at the embankment, and Figure 1.2 shows the vertical cross-section of the embankment. At the main embankment, after the excavated soil has been filled, the excavated soil is exposed without capping a part of the top of the embankment (approximately 970 m²) to accept the residual soil generated by the subsequent pavement work. Rainfall from the exposed part infiltrated the embankment, and the amount of leachate was observed. The amount of permeation into the embankment was calculated assuming a water collection range of approximately 1,790 m².

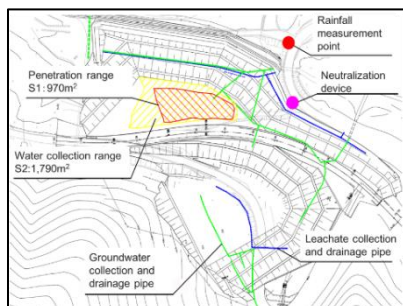


Figure 1.1. Top view of drainage facility in excavation embankment.

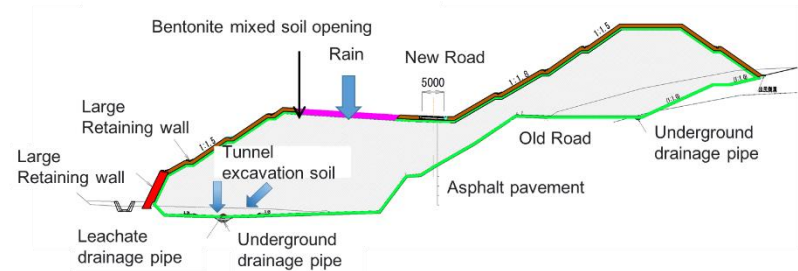


Figure 1.2. Longitudinal cross-section of the excavation embankment.

Figure 2.1 shows an example of the changes in rainfall and leaching water over time. The leachate increased on the day of the maximum rainfall of 41 m³/h then disappeared, the leachate gradually decreased, and the rainfall flowing in from the exposed part was discharged 13 days later. Figure 2.2 shows the changes in cumulative rainfall and cumulative leaching during the measurement period. The cumulative rainfall was delayed by the number of drainage days, the moving average was taken for 13 days, and the amount of leachate (64 m³) inside the embankment before the measurement was added as the estimated infiltration amount. The estimated infiltration and cumulative leachate were in good agreement.

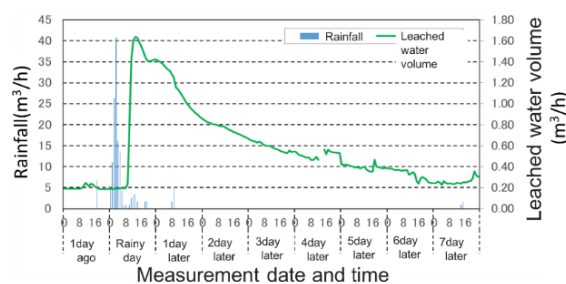


Figure 2.1. Changes in rainfall and leaching water.

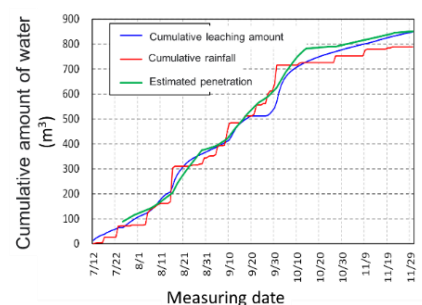


Figure 2.2. Changes in cumulative.

3. Boring survey in the embankment

A boring survey was conducted at five locations on the embankment to investigate the distribution of heavy metals in the embankment. The water level in the hole was not present at any point. The boring core was sampled at 50 cm intervals, and a short-term dissolution test^[5] was performed. Table 1 shows the average elution amount of arsenic in the boring core and the ground. The maximum arsenic concentration was 0.034 mg/L, and the average value was 0.010 mg/L. The average value was approximately the same for the ground and the boring core; however, the coefficient of variation was 1.000 for the ground and 0.440 for the boring core, and the variation was smaller for the boring core. It is probable that the heavy metals that were unevenly distributed in the ground were dispersed during excavation, transportation, and embankment work.

Table 1. Mean concentration and standard deviation.

		Ave. (mg/L)	SDI	COV
<div>Ground</div> <div>Boring core</div>		0.008	0.008	1.000
	Ave.	0.010	0.004	0.440
	B1	0.015	0.007	0.467
	B2	0.009	0.002	0.222
	B3	0.009	0.004	0.444
	B4	0.007	0.003	0.429
	B5	0.010	0.006	0.600

4. In situ unsaturated permeability test

4.1. Method

An unsaturated permeability test was conducted on-site to understand the behavior of the leachate and the eluted heavy metals inside the embankment. The test was carried out according to the local conditions using the in situ unsaturated hydraulic conductivity test method [6-8] by controlling the water injection pressure. In this test method, the time change of the soil moisture content in the ground was measured while supplying water (or natural precipitation) at a constant flow rate from the ground surface. Figure 3.1 shows the outline of the test equipment, and Figure 3.2 shows the measurement status. While injecting a constant flow rate into the closed lid installed on the ground surface with a metering pump, the change in moisture content volume was measured with a soil moisture meter. It also measures the changes in suction using the water potential sensor. The unsaturated parameter was identified from the measurement results.

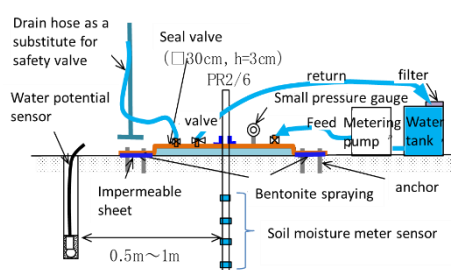


Figure 3.1. Outline of test equipment.

Figure 3.2. Measurement status.

4.2. Unsaturated hydraulic conductivity test results on the surface

Figure 4.1 shows the measurement results of the test in which water was supplied by the metering pump. The parameters of this measurement result were identified, and numerical simulations were performed using the van Genuchten model [9] (Eq. (2)), and the specific water permeability coefficient [10] (Eq. (3)) as the unsaturated infiltration characteristics in the penetration equation (Eq. (1)).

$$\mu \frac{\partial H}{\partial t} - \frac{\partial}{\partial x} \left(k_x \frac{\partial H}{\partial x} \right) - \frac{\partial}{\partial y} \left(k_y \frac{\partial H}{\partial y} \right) - \frac{\partial}{\partial z} \left(k_z \frac{\partial H}{\partial z} \right) - Q = 0 \quad (1)$$

$$\text{Effective saturation } S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} = \{1 + (\alpha \psi)^n\}^{-m} \quad (m=1-1/n) \quad (2)$$

$$\text{Permeability coefficient (Irmy type)} \quad k_r = S_e^\beta \quad (3)$$

Where H denotes the total head; μ denotes specific moisture capacity; k denotes hydraulic conductivity; Q denotes flow rate; Ψ denotes suction; α , β , m , and n are experimental constants; θ denotes volume moisture content; θ_s denotes saturated volume moisture content; and θ_r denotes residual volume moisture content. Figure 4.2 shows the contour of the pressure head. Comparing 5 min and 10 min after water injection, it can be confirmed that the pressure head just below the water injection range rises, and the saturation region expands. Next, the same test was carried out continuously for 13 h under natural rainfall conditions to identify the unsaturated parameters. Precipitation was up to 4 mm.

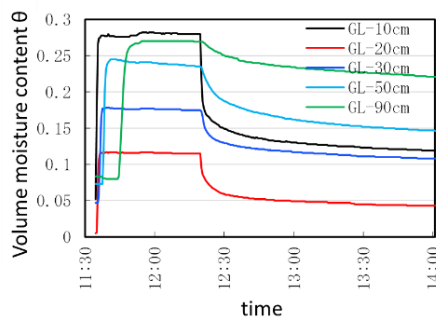


Figure 4.1. Measurement result.

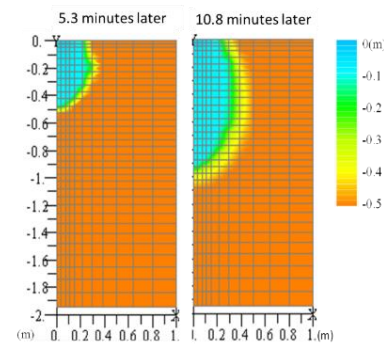


Figure 4.2. Pressure head contour.

4.3. Water injection test at the observation hole

4.3.1. Test method. The water injection and the rainfall condition tests in Section 4.2, were conducted on the surface layer, and it is necessary to verify whether the overall hydraulic conductivity of the disposal site can be evaluated. Therefore, the permeability characteristics inside the embankment were evaluated using the observation holes. Figure 5.1 shows the test method, and Figure 5.2 shows a photograph of the observation hole.

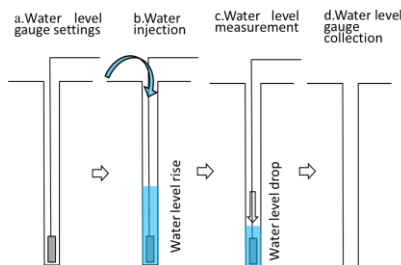


Figure 5.1. Test method



Figure 5.2. Photograph of the observation hole

4.3.2. Test results. Figure 6.1 shows the measurement results and numerical simulation results. The black line is the measured value, and the blue line is the analysis value, which indicates the change in the water level of the observation hole. The red line shows the change in the integrated value of the

water injection flow rate obtained from the analysis. Figure 6.2 shows the change in the contour of the pressure head in observation hole B2. Since the water was injected for 2.1 min, the water level increased, and after the water injection was stopped, it can be confirmed that the water level was lowered and spread laterally.

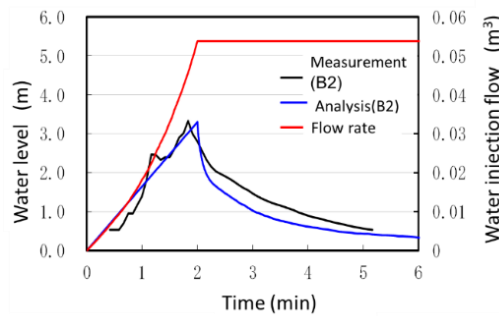


Figure 6.1. Measurement results and numerical simulation results.

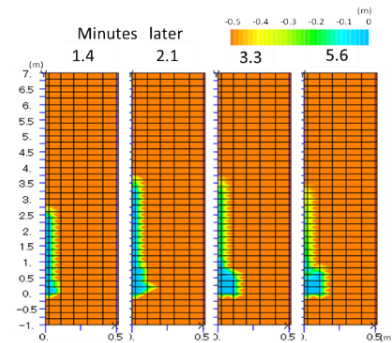


Figure 6.2. Pressure head contour.

4.4. Evaluation of unsaturated parameters

Table 2 shows the saturated hydraulic conductivity and unsaturated parameters identified in the surface water injection, rainfall, and observation hole water injection tests. In the observation hole test, the saturated hydraulic conductivity k_0 is smaller than in other tests. This is likely due to the difference in compaction between the surface layer and the inside. Regarding the unsaturated parameter coefficients, n , α , and β in Eqs. (2) and (3), the measurement results could be roughly evaluated to a certain extent, even if the same values were assumed regardless of the test method.

Table 2. Permeability and unsaturated parameters.

	k_0 (10^{-2} cm/s)	n	α	β	θ_r	θ_s
Surface water injection (See Figure 3.1.)	2.5~8.33	20	7~10	7	0.05	0.2~0.35
Surface rainfall	2.5~3.0	20	10	7	0.05	0.25~0.3
Observation hole	0.1~4.5	20	10	7	0.05	0.3

5. Column test

5.1. Outline of column test

A column test was conducted to evaluate the elution parameters that determined the amount of arsenic elution. Figure 7.1 shows the column elution test equipment. A column with a diameter of 30 cm was filled with excavation scraps to a height of 90 cm. Water was evenly injected from the top of the excavation slab with a sprayer, the leaching water from the bottom was collected, and the leaching flow rate, arsenic concentration, electrical conductivity (EC), and water temperature were measured. The leachate was stored in a sample bottle every 30 min, and the water quality was analyzed. The flow rate of the leachate was measured using an overturning basin flow meter. In addition, the volumetric moisture content and suction in the column were measured using the same procedure as the in situ unsaturated permeability test for unsaturated permeation characteristics.



Figure 7.1. Column elution test equipment.

5.2. Column test results of unsaturated osmotic water

Figure 8.1 shows the results of a particle size test of approximately 1 m³ of excavation scrap collected from the local embankment. Considering that the contact area and contact time between the shear particles and the leachate affect the elution amount, a preliminary test was conducted by changing the particle size of the waste to be filled in the column and the flow rate of the sprayed water.

Figure 8.2 shows the results of the preliminary test. From the preliminary test, the soil moisture content did not increase even when the flow rate was adjusted to a medium particle size. In contrast, the soil moisture content increased with a small particle size; however, no significant change was observed in the soil moisture content even when the flow rate was increased. Therefore, a test of the total particle size was carried out to confirm the relationship between the flow rate and the soil moisture content, and the particle size at which the soil moisture content changed was examined.

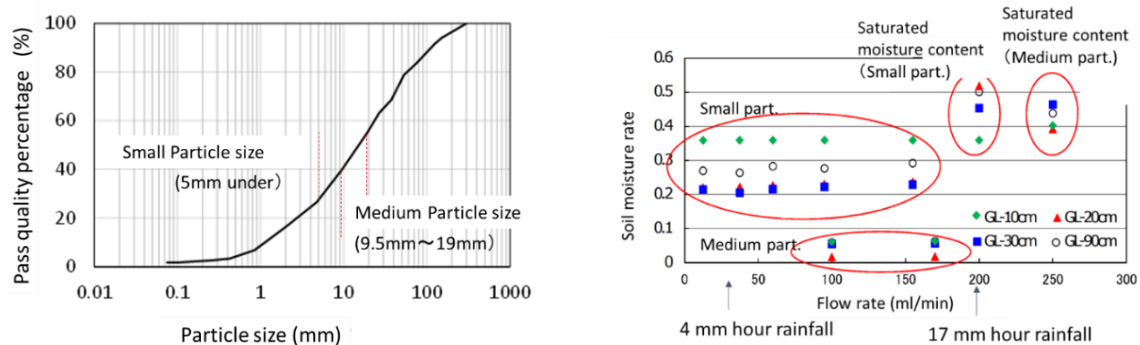


Figure 8.1. Particle size distribution of local excavation scraps.

Figure 8.2. Preliminary test results.

Figure 9.1 shows the change over time in the amount of arsenic eluted in the column test. The elution amount of arsenic with a total particle size of ≤ 80 mm) and a small particle size of ≤ 5 mm was overwhelmingly higher in small particles with poor permeability and was proportional to the contact area and contact time [11]. Consequently, arsenic concentration increased. If these can be evaluated as changes in the volume moisture content, they can be reflected in the analysis model.

The analysis value is the advection-diffusion equation of Eq. (4), and the arsenic concentration was formulated using Eq. (5) and (6).

$$\frac{\partial C}{\partial t} + u_x \frac{\partial C}{\partial x} + u_y \frac{\partial C}{\partial y} + u_z \frac{\partial C}{\partial z} - \frac{\partial}{\partial x} \left(D_x \frac{\partial C}{\partial x} \right) - \frac{\partial}{\partial y} \left(D_y \frac{\partial C}{\partial y} \right) - \frac{\partial}{\partial z} \left(D_z \frac{\partial C}{\partial z} \right) - q = 0 \quad (4)$$

$$q = q_a \times f(\theta, u, d) \quad (5)$$

$$f(\theta, u, d) = a \times (100 \times (\theta - b \times \theta_r))^c \times (\kappa + \lambda \times u) \quad (6)$$

Where C denotes arsenic concentration; u denotes flow velocity; D denotes the dispersion coefficient; q denotes the elution amount of heavy metals per unit volume; q_a denotes the unit elution amount of heavy metals; θ denotes the volume moisture content; θ_r denotes the residual volume moisture content; and d denotes the slip diameter (particle size distribution).

Based on the preliminary results, the parameters of the elution characteristics were determined, and a simulation was performed. Figure 9.2 shows the simulation results, and Table 3 shows the parameters used in the analysis. Analysis (1) applies the measurement results obtained in the field to the simulation of the column test, and Analysis (2) is the result of reviewing the parameters so that they fit into the column test.

The elution amount of arsenic per unit volume in the column test and the field differed. Analysis (1) covers the entire embankment field, and analysis (2) covers the inside of the column tester. The difference in scale may have caused the large difference in the elution amount q_a and the maximum elution amount q_{max} . The evaluation of this is something which must be considered in the future.

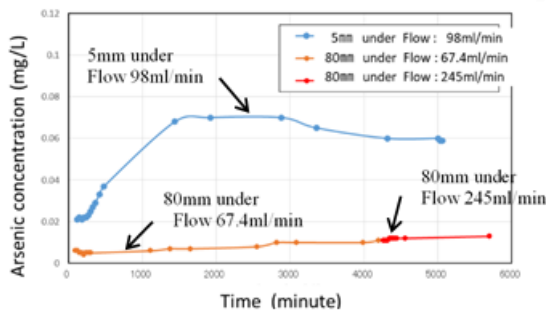


Figure 9.1. Time course of arsenic elution in column test.

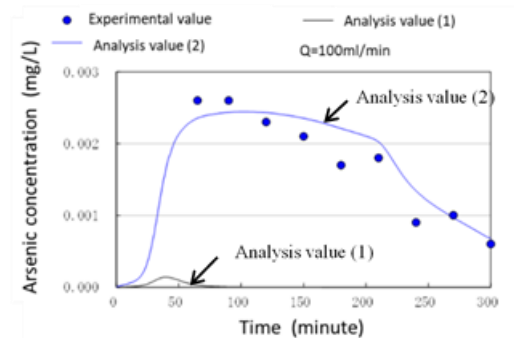


Figure 9.2. simulation results.

Table 3. Parameters used in the analysis

	a	b	c	κ	λ	q_a	q_{max}
Model analysis	0.008	0.5	1.0	1.0	0.5	0.008	0.008
Reproduction analysis	0.008	0.5	1.0	1.0	0.4	0.06	0.8

6. Conclusion

At the excavation embankment of the Oshikado tunnel, where the amount of arsenic elution exceeded the standard and contained bentonite mixed soil, rainfall was allowed to flow from the opening, the behavior of the leachate and the amount of arsenic elution were measured, and numerical simulation by advection analysis of variance was performed. In addition, a column test was conducted using the excavated soil in the field, and a numerical simulation was performed using the same analysis method. The parameters related to the permeation characteristics were the same in the field and column tests; however, the elution parameters were the elution amount, which was 7.5 times that in the field test and 100 times the maximum elution amount in the column test. This indicates that in a mock test modeling a disposal site, the amount of heavy metal elution may be overestimated. In the future, we will improve the elution characteristic prediction formula to ensure the phenomenon that occurs locally can be reproduced from the results of the column test.

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