Proceedings of the 21st ICSMGE, Vienna, Austria, 14 – 19 June 2026. Pistrol, Adam & Schweiger (eds.)
Published by: ÖGG, Austrian Society for Geomechanics, Salzburg, Austria, ISBN 978-3-9503898-4-5
https://doi.org/10.53243/ICSMGE2026-2347

Attenuation layer method for utilizing excavated soils and rocks with geogenic contamination

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ABSTRACT: Excavated soils and rocks with geogenic contamination are desirable for use as geomaterials with proper countermeasures, considering the level of contamination is relatively low. An attenuation layer method is proposed as a promising measure, while the design concept has not been established. This paper discusses the design of the attenuation layer method, reviewing prior research and conducting hydraulic conductivity tests. First, regarding mitigating rainfall infiltration, the effectiveness of the sandy soil with a hydraulic conductivity of even 10-5 m/s orders of magnitude is mentioned. Second, the importance of leaching tests is highlighted to clarify the target contaminants and estimate the leaching burden and kinetics. Thirdly, the way of determining the mixing ratio of the stabilizing agent is demonstrated based on the leaching tests. In addition to the review, hydraulic conductivity tests are conducted. When the solution containing 100 mg/L iron is permeated to the specimen of soil amended with a 5% stabilizing agent, hydraulic conductivity decreases approximately one order during pH is attenuated from 2.7 to 7-8. This result suggests that a travel time in the attenuation layer might become longer with pH attenuation, especially for strong acid-excavated soils, and it should be cared for when designing.

KEYWORDS: Leaching, sorption, column test, hydraulic conductivity, material recycling.

1 INTRODUCTION

Excavated soils and rocks, which are greatly generated from construction works, should be utilized as geomaterials to decrease the disposed materials for sustainable development (e.g., Magnusson et al. 2019; Katsumi, 2025). However, geogenic contamination in the soils and rocks may have a conservative influence on using such materials (e.g., Tabelin et al. 2018; Arima et al. 2024). If the soils and rocks fail to meet the set environmental standards, actions for contaminant control or disposal of such soils and rocks are usually implemented, while considering the leaching load and the nature of these materials, actions such as disposal or strict measures, might not be appropriate. In many cases, toxic chemicals leached in low concentrations that slightly exceed the mandated limits (e.g., Ito & Katsumi, 2020). Therefore, utilizing the soils and rocks under proper contaminant control conditions is highly recommended, rather than simply disposing of them.

To utilize excavated soils and rocks with geogenic contamination, countermeasures such as containment in an embankment, immobilization treatment, and installation of an attenuation layer have been considered. The attenuation layer, a soil layer with sorption capacity, has attracted attention as a unique concept from other methods (e.g., Tatsuhara et al. 2012; Gathuka et al. 2022; Kajiyoshi et al. 2024). The advantage of the attenuation layer method is the stable earthen structures constructed by simple compaction and cost efficiency, as shown in Figure 1. A typical attenuation layer material is clean host soil mixed with a stabilizing agent, such as magnesium oxide, to stabilize the contaminants and enhance the sorption capacity of the host soil. Effectiveness of the attenuation layer must be clarified to assure environmental safety.

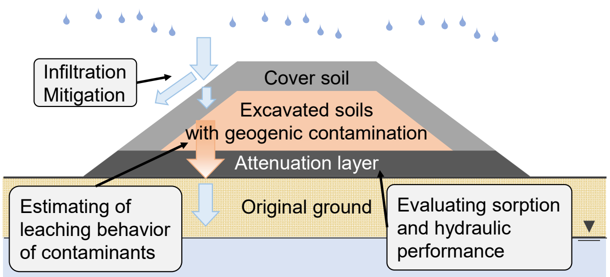

Figure 1. Schematic diagram of the attenuation layer method.

The attenuation layer method has several advantages in utilizing geogenic earthen materials, while its design method has not been fully established. Several studies have been conducted individually, and the linkage is missing. Therefore, this paper reviews the prior research and discusses the issues described in Figure 1. Besides reviewing, hydraulic conductivity tests were conducted to support the information for hydraulic performance.

2 ROLES OF COVER SOIL

The first step is installing the cover soil. The cover soil layer prevents scattering of the excavated soils with geogenic contamination and rainfall infiltration. Since reducing infiltration leads to a decrease in the volume of leachate with geogenic contamination, the cover soil design is crucial. Minamiguchi et al. (2022) investigated the effectiveness of infiltration mitigation by installing a cover layer with 1.6 m. The results suggested that if the sandy soil was used as the cover soil and its saturated hydraulic conductivity was 6.2 x 10^{-5} m/s, the infiltration ratio (infiltration to original ground/rainfall intensity) could be reduced by 80% by the surface runoff when rainfall intensity was 1 mm/hr. Furthermore, if the excavated soil layer was well compacted and its hydraulic conductivity was reduced, much infiltration was prevented because rainfall was permeated into the cover soil layer and drained. Even in sandy soil with a hydraulic conductivity of 10^{-5} m/s, rainfall infiltration can be suppressed by constructing a cover soil. Finally, as the drained infiltration volume increased, the saturation degree of the top of the slope increased. Therefore, this study suggested that some drain systems, such as the crushed rock layer, should be installed at the top of the slope.

3 ESTIMATING LEACHING BEHAVIOR OF GEOGENIC CONTAMINANTS

The second step is understanding the leaching behavior of geogenic contaminants. A leaching test based on the Soil Contamination Countermeasures Act is commonly conducted in Japan. However, this test method is a simple batch leaching test that was developed to originally evaluate artificial contamination but did not consider the characteristics of geogenic contamination (Katsumi, 2025). Therefore, several research have been conducted to simulate the leaching behavior closer to the in-situ conditions.

Effects of redox conditions, temperature, pro- and post-processing, etc. have been investigated by batch tests. Soils are originally placed under anaerobic conditions in the ground, while once they are excavated, they should be exposed to the air and then oxidized. Kamata & Katoh (2019) evaluated changes in arsenic (As) release, and their phases were investigated during the oxidation of framboidal pyrite (FeS_2) in marine sedimentary rock following exposure to the atmosphere. Batch leaching tests showed that atmospheric exposures over 14 days increased As release.

Temperature fluctuation is another important issue since the excavated soils are placed on shallow ground, such as the embankment. Kato et al. (2023) investigated the effects of temperature on leaching behavior using batch tests. As shown in Figure 2, more As and boron (B) in the excavated mudstone leached as temperatures rose, while the magnitude was at most 5 times. When the leaching concentration is estimated while considering the temperature effect, if the leaching concentration at room temperature is multiplied 5 times, that might be enough for the safe side evaluation.

Column leaching tests are expected to estimate leaching behavior more reasonably because they more closely represent the in-situ condition (Katsumi, 2025). Japanese Geotechnical Society (JGS) participated in ISO/TC190 on Soil Quality and took the initiative to establish the international standard on column leaching tests (International Organization for Standardization, 2019; Yasutaka & Sakanakura, 2022). Kato et al. (2021a) proposed that concentration profiles obtained from column tests are used to categorize between monotonous decreasing and other contaminants by using the shape of the curves, as shown in Figure 3. If the leaching concentration profiles diminish quickly, such as B, only short-term sorption performance may be required to the attenuation layer design, and the design can be simplified.

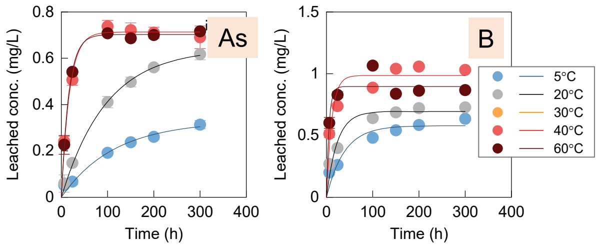

Figure 2. Temperature effects on leaching behavior of geogenic contaminants from excavated rocks (edited from Kato et al. 2023).

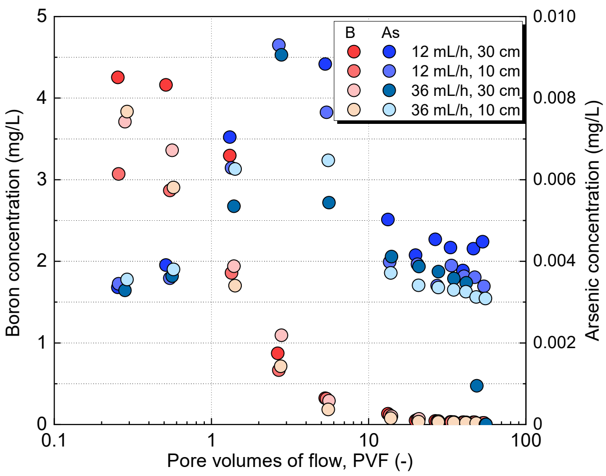

Figure 3. Different patterns of leaching concentration profiles between boron and arsenic (edited from Kato et.al. 2021a).

The conclusions of this chapter are shown. First, the target contaminants must be clarified. Second, the leaching burden, such as leaching concentration or amount, should be estimated. If the effects of redox conditions or temperature are not revealed, a few times more considerable burden should be considered so as not to underestimate. The leaching concentration is used for the boundary condition of the advection-dispersion analysis for predicting the solute transport at the attenuation layer, while the total leached amount is used to determine the required sorption performance of the attenuation layer and the amount of mixed stabilizing agent. Finally, whether the leaching diminishes quickly can be understood if the concentration profile is obtained.

4 EVALUATING SORPTION PERFORMANCE

The third step is evaluating the sorption performance of the attenuation layer. As shown in Table 1, various types of stabilizing agents are manufactured. The laboratory experiments confirm their effectiveness in terms of chemical or environmental engineering, while the applicability for the geostructures is still challenging. Nishikata et al. (2022) focused on the hydration reaction because water must be mixed when the soil-agent mixture is compacted to achieve a high compaction degree. As the hydration reaction proceeded, the sorption performance of some agents decreased. Therefore, if a long-term sorption performance is required, the agents not affected by the hydration might be desirable.

After selecting the stabilizing agent, the batch or column sorption test is conducted using a soil-agent mixture against the target contaminant to determine the mix proportion of the stabilizing agents. Manufacturers and suppliers have conducted the tests independently because no standardized methods exist. Therefore, the technical committee was launched to establish the standards for evaluating the sorption performance of geomaterials and stabilizing agents against contaminants. After a five-year discussion, Japanese Industrial Standards (JIS) for

Table 1. Major components and characteristics of stabilizing agents (edited from Nishikata et al. 2022).

Major components of agents	After water immersion
Layered double hydroxide (LDH)	No change
Iron hydroxide [$Fe(OH)_3$]	
Calcium sulfide ($CaSO_4$)	$CaSO_4$ disappeared with the hydration reaction.
Magnesium oxide (MgO)	MgO disappeared and magnesium hydroxide [$Mg(OH)_2$] was generated.

Table 2. Summary of the Japan Industrial Standards (JIS) for Evaluating the Attenuation Layer Material (cited from Katsumi. 2025).

Parameter	Condition
Particle size	< 4.75 mm (both soil and stabilizing agent)
Mixing ratio	3 – 30% (Mass of agent / Mass of soil)
Initial concentration	10 or 30 times higher than regulatory limits
pH	5.8 – 6.5 adjusted using HCl or NaOH
Liquid-to-solid ratio (L/S) for batch test	100, 250, 500, 1000, 2500, 5000, 10000 L/kg
Shaking condition for batch test	4 – 5 cm horizontal shaking with 200 rpm for 24 hours
Specimen for column test	5 cm diameter x 5 cm height
Permeation for column test	72 ± 6 mL/h Up to 400 L/kg

batch and column tests were finally established in 2025 (Japanese Industrial Standards, 2025; Katsumi, 2025). The essence is summarized in Table 2.

However, the limitation is the current evaluating method is revealed. Kato et al. (2021b) conducted column tests using the soil-agent mixture and showed that experimental results could not be well predicted using the advection-dispersion analysis. Since the agent's mineralogy is transformed by hydration reaction, the applicability of the conventional solute transport model is still challenging. Therefore, the required sorption performance and the mixed agent amount should be determined based on the total leached amount to not overestimate the sorption performance.

5 HYDRAULIC PERFORMANCE

Hydraulic performance is a crucial issue for the attenuation layer. If the solution passes through within too short a time, contaminants might not be captured. In contrast, if the solution cannot be drained from the attenuation layer, the system does not work.

This study conducted a steady head type hydraulic conductivity test, as shown Figure 4. Soils mixed with 5 wt.% of the stabilizing agent of Ca/Mg composite were compacted into the acrylic column (ϕ 5 cm × L 10 cm) with D_c = 95%. Then, the column was placed into the deaerator for 48 hours to make the specimen saturated. As the influent, distilled water, Fe = 10 or 100 mg/L acidity solution or on-site leachate was permeated with a hydraulic gradient. On-site leachate was collected from the embankment, where excavated soils and rock with geogenic contamination were filled in, and the solution contained Fe = 91.2 mg/L. As mentioned in Chapter 3, since the decomposition of FeS_2 is one of the primary mechanisms of the release of As, the acid solution containing Fe was applied herein. Effluents were regularly sampled, and hydraulic conductivities were calculated using the volume of the effluent and Darcy's Law. Then, hydraulic conductivities for 15ºC, k_{15}, were calculated based on the temperature of the effluents. The effluent's pH was measured using a pH meter (Horiba F-54).

Figure 5 shows the results of the hydraulic conductivity tests, and k_{15} of approximately 10^{-6} m/s was obtained when distilled water was permeated as the influent. In contrast, smaller k_{15} were obtained when Fe solution was permeated. Almost one or two-order smaller k_{15} were obtained compared to the distilled water case at 30 PVF. The effluent's pH profiles showed that acidity in the influent was neutralized. This result suggests that when acid pH is neutralized, the precipitation of $Fe(OH)_3$ might be generated, affecting the attenuation layer's hydraulic performance. When the attenuation layer is designed, the possibility of decreasing hydraulic conductivities should be considered, especially for strong acid-excavated soils.

6 PRACTICAL APPLICATIONS

Attenuation layer method has been gradually employed in construction projects in Japan (e.g., Kikuchi et al. 2017; Kajiyoshi et al. 2024), while its long-term performance has rarely been elucidated. Kajiyoshi et al. (2024) investigated the effectiveness of the attenuation layer method installed approximately 11 years after construction. Herein, excavated mudstone containing As was used as the material for the embankment, while soil mixed with a Fe-based stabilizing agent was used as the attenuation layer material. A borehole drilling in the embankment sampled the undisturbed core sample. Then, batch leaching tests evaluated the immobilized As fraction in the attenuation layer. The results revealed that the attenuation layer still had enough capacity to capture more As. In addition, geogenic contaminants, once captured in the attenuation layer, might be immobilized for at least 11 years, the reliability of the attenuation layer is supported. Therefore, environmental engineering approaches have verified the stabilizing agent's effectiveness. The remaining issue is the design concept of the embankment, including the attenuation layer.

Finally, the design concept of the attenuation layer summarized. First, the fundamental concept is to mitigate rainfall infiltration by the covered soil layer as much as possible. As illustrated in Chapter 2, the compacted soil layer performs low hydraulic conductivity. Even a sandy soil layer is effective.

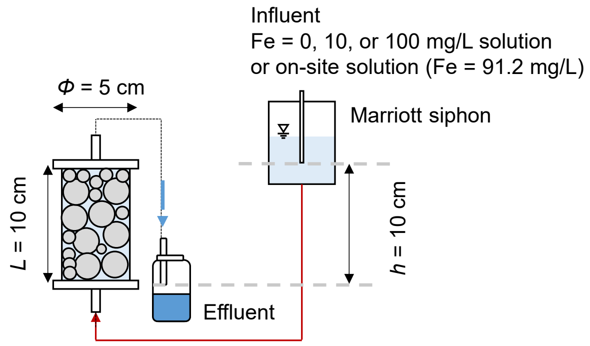

Figure 4. Schematic diagram of hydraulic conductivity tests.

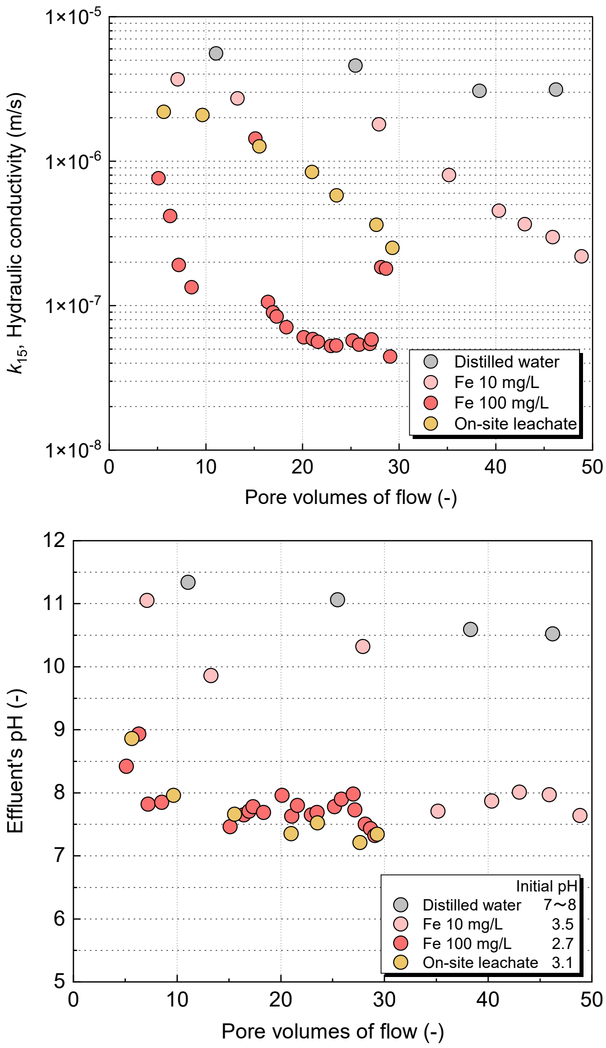

Figure 5. Profiles of hydraulic conductivities and effluent's pH for soil-stabilizing agent mixture with different solutions in this study.

The well-graded soil should be selected, and higher compaction degrees should be achieved. Herein, the attenuation layer can be considered as fail-safe. Namely, rainfall infiltration cannot be entirely prevented from entering the embankment if high-intensity rainfall is applied. The attenuation layer helps, especially in this case. Column leaching tests are better to be carried out to examine whether the leaching diminishes monotonously and quickly. Short-term sorption performance will be required for the monotonous decreasing chemicals, while long-term performance will be required for other toxic elements, which are expected to be leaching for a long time. As one of the long-term performances, the hydration of the stabilizing agent should be cared for. Therefore, the sorption performance of the stabilizing agent is desirable to be evaluated as per the newly established JIS methodology. Finally, suppose the acid drainage with a high ion-containing solution is expected to permeate into the attenuation layer. In that case, the decrease in the hydraulic performance should be taken care of because the drainage might accumulate into the attenuation layer, and the stability of the embankment might be decreased due to the elevation of the degree of saturation. If a decrease in hydraulic conductivity is expected, the attenuation layer might not be the optimum countermeasure.

7 CONCLUSIONS

This paper discussed the attenuation layer method design based on the findings' linkage to prior research. First, mitigating rainfall infiltration is fundamental in the attenuation layer method. Even sandy soil with hydraulic conductivity of 10^{-5} m/s orders of magnitude prevents the infiltration to some extent. Second, leaching tests are conducted to clarify the target contaminants, estimate the leaching burden, and understand the leaching behavior. Finally, the mixing ratio of the stabilizing agent is determined based on the required sorption amount calculated from the leaching tests. Since the hydration might affect the sorption performance, the stabilizing agent should be carefully selected, considering the leaching behavior of contaminants, leachate pH, and the expected infiltration rate.

Hydraulic conductivity tests were also conducted as part of this study. When the solution containing 100 mg/L iron was permeated to the specimen of soil amended with a 5% stabilizing agent, hydraulic conductivity decreased approximately one order during pH attenuation from 2.7 to 7-8. The travel time in the attenuation layer might become longer, especially for strong acid-excavated soils, and it should be taken into account when designing.

8 ACKNOWLEDGEMENTS

The authors acknowledge the support provided by the JSPS KAKENHI (Grant Nos. 22H00227 and 22K04309). This appreciation extends to Riho Ogata (former Kyoto University student) for her assistance with the hydraulic conductivity experiments.

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