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Technical Report

Seismic Reinforcement Methods for Small Earth Dams Using Steel-related Materials

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Abstract

Recently, small earth dams for agricultural reservoirs have been frequently damaged by earthquakes, and thus the reinforcement of dam bodies has become paramount. Nippon Steel Corporation has been working on research and development of the seismic reinforcement methods using steel sheet piles or slags. This report presents the outline of methods, major research achievements such as shaking table tests and field experiments, and some application examples.

1. Introduction

As Japan has been plagued by huge earthquakes like the Great East Japan Earthquake and by torrential rains in recent years, embankments of some of its agricultural small earth dams have broken and caused human casualties and damage to nearby facilities. For example, nearly 4000 small earth dams were reported to have been damaged in the Great East Japan Earthquake,[1] 28 small earth dams were reported to have collapsed in western Japan during the heavy rains of July 2018,[2] and 131 small earth dams, mainly in the Tohoku region to the Kanto regions, were reported to have been breached or damaged (14 breached and 117 damaged) in the 2019 East Japan Typhoon.[3] Under these circumstances, the Japanese government revised the small earth dam design guidelines[4] with the addition of seismic verification methods for level 2 seismic motions according to the lessons learned from the Great East Japan Earthquake and established the “Act on Special Measures Concerning Promotion of Disaster Prevention Works, etc., Related to Priority Agricultural Small Earth Dams for Disaster Prevention (enforced on October 1, 2020)”. Since then, the Japanese government has been promoting disaster prevention works in a concentrated and systematic manner.[5] Many of the small earth dams had their embankments built before the Edo period. The materials of the embankments have deteriorated since then. Some of the embankments have been left as built on soft ground and do not meet current seismic resistance standards. Some small earth dams have been repeatedly expanded. As a result, boundaries between different quality soil layers are formed in the transverse direction of their embankments. When heavy rains fall, such embankments are likely to seepage failures. Many small earth dams need repair or reinforcement. Small earth dams impound water indispensable for agriculture and daily life. When the entire embankment of a small earth dam is to be repaired, the water cannot be released from the dam for an extended period of time. If the dam is located in a valley, it is difficult to secure high-quality ground materials. Repair and reinforcement methods must be selected to suit regional characteristics.

Nippon Steel Corporation has been working on the development of steel sheet pile and slag methods as methods for repairing and reinforcing the embankments of small earth dams. The steel sheet pile method installs two rows of steel sheet pile walls at the center of the embankment of a dam to create a sturdy core. This core can retain the embankment height against an earthquake or torrential rain, protect the embankment from breakage, and prevent the impounded water from seeping downstream. The steel sheet pile method has been applied in Kochi Prefecture and Tottori Prefecture. With this method, the dam can be repaired or reinforced without drawing down the impounded water, the banking soil can be obtained in the required quantity, the adverse effect of muddy water on a surrounding sea area can be prevented, and a construction yard can be easily secured. The steel sheet pile method has been employed because it can solve problems that are difficult to solve with the conventional earth method.[6, 7] The slag method uses slag, which is a by-product of the steelmaking process, as a substitute when the lining method

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lacks in good-quality lining material. Due to its latent hydraulicity, the slag increases in strength and decreases in hydraulic conductivity with age. It is a material effective against the sliding and seepage failures of embankments.

In this report, we describe the characteristics and objectives of the steel sheet pile method and the slag method and introduce the effectiveness test results, on-site observation results, and application examples of these methods.

2. Research and Development of Small Earth Dam Reinforcement Method Using Steel Sheet Piles

2.1 Issues related to application of steel sheet pile method to small earth dams

The design method for the steel sheet pile method has been established for coastal embankments and has already been applied to them.[8] Small earth dam embankments differ from coastal embankments in that the impounded water constantly seeps through the embankment and forms a groundwater table. In an earthquake, the saturated zone below the groundwater table drops in strength and may cause the sliding failure of the embankment slope and the liquefaction of the embankment and the foundation ground.

Figure 1 schematically illustrates the seismic reinforcement effect of a small earth dam embankment by the steel sheet pile method. Steel sheet piles have high flexural rigidity to suppress ground deformation and watertightness to lower the groundwater level inside the embankment. Making use of these characteristics, the steel sheet pile method is considered capable of: (1) preventing the sliding failure from the crest of the embankment through the steel piles to the slope and (2) reducing the liquefaction-caused settlement of the embankment core to below the allowable settlement.

Few studies had been conducted on the application of the steel sheet pile method to small earth dam embankments. It was not clear whether or not the steel sheet pile method was effective in reinforcing the small earth dam embankments. Together with Kochi University and Eight-Japan Engineering Consultants Inc., Nippon Steel: (1) verified the effect of steel sheet piles in reinforcing the embankment and the foundation ground with respect to failure modes during earthquakes by a shaking table test and (2) assessed the impact of the steel sheet piles on the groundwater level in the embankment by an on-site observation. Through these initiatives, we proposed an impounded water modeling method concerning the analytical evaluation of design against level 2 seismic ground motions and summarized the results in the “Design Guidelines for Method of Reinforcing Small Earth Dam Embankments with Steel (First Edition)”.[9]

2.2 Research and development results of steel sheet pile method

(1) Verification of effect of steel sheet piles in seismically reinforcing embankment

A shaking table test was conducted in a gravity field to verify the effect of steel sheet piles in reinforcing the embankment with respect to the sliding failure of the embankment and the liquefaction of the embankment and the foundation ground. **Figure 2** shows the shaking table test.

In Series A[10] targeted at the sliding failure, embankments with a downstream slope gradient of 1:1.5 and susceptible to sliding failure were simulated in two cases. An embankment with the upstream slope covered with waterproof sheets was simulated in one case. An embankment reinforced with steel sheet piles was simulated in the other. The two embankments were compared according to whether the sliding failure occurred. The excitation waveform was that of the Nankai Trough Earthquake expected to strike Kochi Prefecture. In Series B[11] targeted at liquefaction, liquefied layers were considered to exist in the foundation ground. In one case, the embankment was not reinforced. In the other case, the embankment was reinforced with steel sheet piles. The embankments were compared according to whether they deformed and subsided with liquefaction. The excitation waveform consisted of 20 sinusoidal waves with a maximum acceleration of 6.0 m/s^2 and a frequency of 5 Hz.

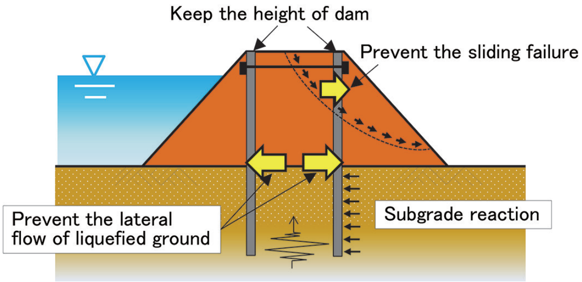


Fig. 1 Effectiveness of double sheet pile walls against earthquake

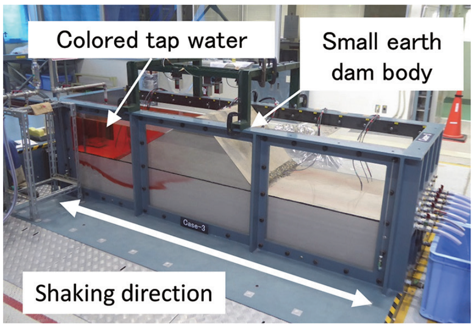
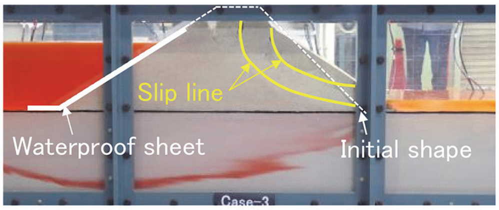


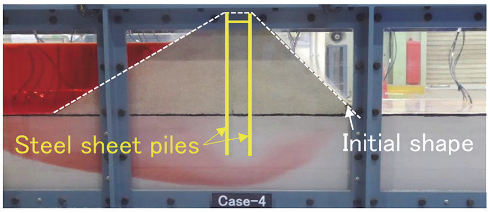
Fig. 2 State of the shaking table test

In each case, the geometric scale was $\lambda = 1/35$. The foundation ground and the embankment were modeled in a soil container and shaken in the horizontal direction. The steel sheet piles were simulated with steel plates with a rigidity equivalent to that of 25H to 50H hat-type steel sheet piles. The impounded water was simulated with colored tap water. The models were vibrated after they were stably permeated with the colored tap water.

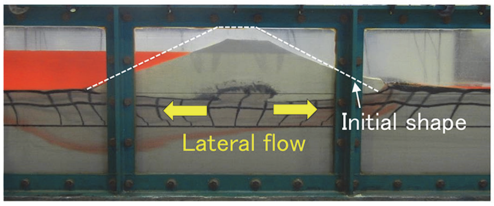
Figure 3[10, 11] shows the residual deformation of the embankment after shaking. In Series A, a sliding failure occurred from the crest to the slope of the embankment in the case where the upstream slope of the embankment was covered with waterproof sheets, but no sliding failure occurred in the case where the embankment was reinforced with steel sheet piles. This is probably because the shear rigidity of the steel sheet piles suppressed the formation of a slip surface across the steel sheet piles. In Series B, the liquefied layers laterally moved and the embankment greatly subsided in the case where the embankment was not reinforced. In the case where the embankment was reinforced with the steel sheet piles, the two rows of steel sheet pile walls and the ground between the two rows of steel sheet pile walls deformed negligibly and the steel sheet piles subsided less than 1 mm on the model scale. It is considered that the steel sheet piles restricted the ground flow between the two rows of steel sheet pile walls and stabilized the embankment core. In this way, it was clarified that the reinforcement of the embankment by the steel sheet pile method prevents the failure of the small earth dam embankment even under severe vibration conditions.



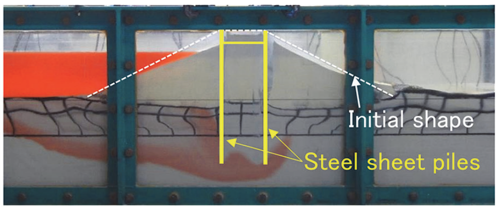
(a) Waterproof sheet (Series A)



(b) Steel sheet pile method (Series A)



(c) Non reinforcement (Series B)



(d) Steel sheet pile method (Series B)

Fig. 3 Deformation after shaking table tests[10, 11]

(2) Application of steel sheet pile method and evaluation of groundwater level by on-site observation

There is a previous study[12] in which the groundwater level in the embankment reinforced by the steel sheet pile method was evaluated by a model test and numerical analysis. There are no cases where the groundwater level was actually observed in small earth dam embankments reinforced by the steel sheet pile method. At actual construction sites, however, there are factors that are difficult to model by experimentation and numerical analysis, such as the unevenness of the embankment and the effect of existing structures such as bottom conduits. Furthermore, when steel sheet piles are driven into hard ground such as in valley earth dams, excavation with an earth auger is sometimes used. In such a case, water seepage may occur from below the bottom of the steel sheet piles. Therefore, we observed the impounded water level and the groundwater level on the site of a small earth dam reinforced by the steel sheet pile method.[13, 14]

The small earth dam is located in the mountain area of Kochi Prefecture. It is relatively large with a crest height of about 15 m and a storage capacity of about 20000 t. It is designated as a priority dam for disaster prevention. Reinforcement of the dam embankment by earth work was also studied, but for reasons of material availability, the steel sheet pile method was applied instead for the first time in Japan. The embankment is made of sandy soil and is highly permeable. A leaning-type retaining wall is installed on the slope on the downstream side. Holes were bored at the center of the embankment (between the two rows of steel sheet pile walls) and on the downstream side. Guide pipes were connected to the steel sheet piles. Water gauges were inserted into the bored holes and the guide pipes and were used to measure the groundwater level. **Figure 4** shows how the on-site observation was conducted.

Fig. 4 State of on-site observation

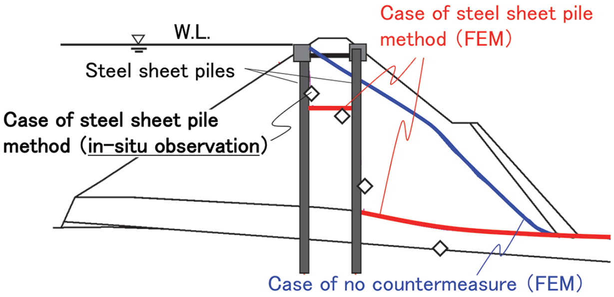


Fig. 5 Groundwater levels assessed by numerical analysis and on-site observation[13)]

Figure 5[13)] shows the groundwater level observed in the steady state and the groundwater level estimated by seepage flow analysis before and after the installation of the steel sheet piles. The groundwater level observed at the site was relatively close to the groundwater level after the installation of the steel sheet pile and estimated by seepage flow analysis. The gradient was different, however. The observed groundwater level was lower than the groundwater level estimated by seepage flow analysis before the installation of the steel sheet piles. The water cutoff performance of the steel sheet piles probably helped to lower the groundwater level. These results showed that the effect of excavation by the earth auger was small and that the steel sheet piles exhibited water cutoff performance on the actual construction site and contributed to the reduction of the groundwater level. We investigated the quality of the impounded water and the underground water in the embankment and confirmed that the impounded water did not leak through below the bottom of the steel sheet piles.

2.3 Application results of steel sheet pile method

In 2018, the steel sheet pile method was applied to the small earth dam embankment described in the previous section for the first time in Japan[15)] and has gradually spread since then. Among the application examples up to now, there is a case where steel sheet piles were installed without drawing down the water as shown in **Fig. 6**. It has been confirmed that the steel sheet pile method can be applied to small earth dam embankments difficult to reinforce without drawing down the water to avoid adverse effects on agricultural activities in surrounding areas.

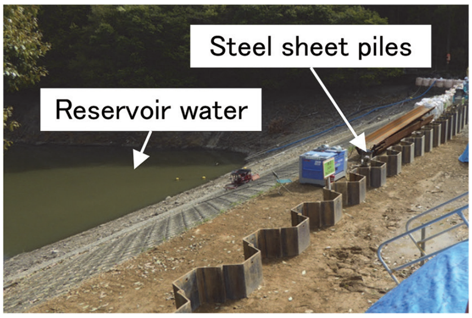


Fig. 6 Construction site where the steel sheet pile method was adopted

3. Research and Development of Steel Slag Method for Reinforcing Small Earth Dam Embankments

3.1 Overview of slag method and issues related to its application to small earth dam embankments

Among the small earth dam embankment repair methods, the most common method is the lining method.4) The lack of high-quality lining material to be used as impervious lining material has become a social issue in promoting earthquake resistant projects for small earth dams. On the other hand, steel slag is a by-product of steel production, is abundantly generated, and has been used in the sectors of roads, ports and harbors, etc. We are expanding the application of slag as a useful resource that contributes to the Sustainable Development Goals (SDGs). For example, we developed the simple pavement material "KATAMA™ SP (special)" by taking advantage of the latent hydraulicity of granulated blast furnace slag and steel slag. KATAMA™ SP is used as a weed control measure and for forest maintenance roads,16) among other purposes. In the development of KATAMA™ SP, we clarified the strength and solidification mechanism of steel slag in the research and development stage of steel slag as a simple pavement material. We have not yet clarified: (1) the long-term latent hydraulic properties (strength and water permeability) of steel slag, (2) characteristics of steel slag when used as embankment structure material, and (3) seismic resistance of small earth dam embankments constructed by using steel slag as a substitute lining material. Together with the National Agriculture and Food Research Organization, Nippon Steel has worked to clarify the technical issues (1) to (3). Research results are described in the following sections.

3.2 Research and development results of slag method

(1) Long-term latent hydraulicity properties of mixed slag (strength and water permeability)

First, to clarify the long-term strength and water permeability of steel slag, we conducted an unconfined compression test and hydraulic conductivity test by changing the curing conditions and periods.

The test material was produced by mixing steel slag and water granulated blast furnace slag. It is hereinafter referred to as mixed slag. The steel slag is aged and has a maximum grain size of 31.5 mm. The iron slag has a maximum dry density of 2.431 g/cm^3 and an optimum water content of 8.0%. To clarify the effect of different curing conditions on latent hydraulicity, slag specimens were air cured, spray cured, and water cured, respectively, and were then tested. For spray curing, the specimens were passed through tap water every three days. The specimens were completed with a dry density of 2.1 g/cm^3 and a loose compactness of 86%. Unconfined compression test results are shown in **Fig. 7**17) and hydraulic conductivity test results are shown in **Fig. 8**.17) We found that the chemical reaction between water and slag in the air sprayed specimens has an effect on the unconfined compression strength for up to 56 days and an effect on the water hydraulicity for up to 28 days. With spray curing and water curing, we found that because water was supplied to the specimens even at 336 days, the specimens increased in strength and decreased in hydraulic conductivity.

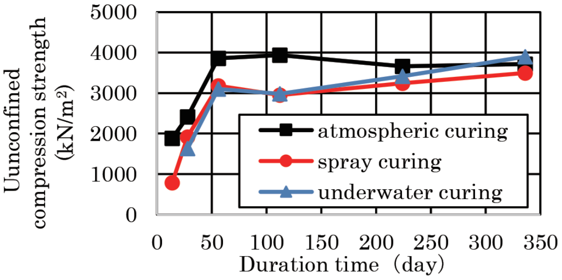


Fig. 7 Time histories of unconfined compression strength17)

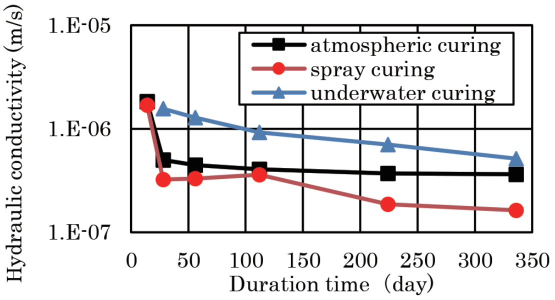
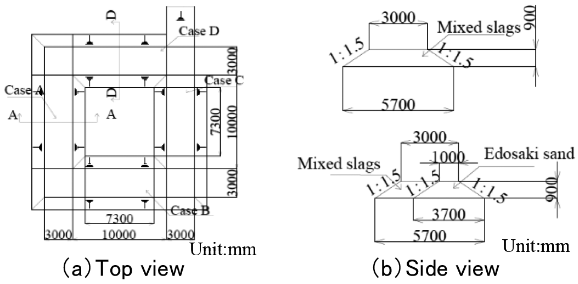


Fig. 8 Time histories of hydraulic conductivity17)



(a) Top view (b) Side view

Fig. 9 Outline drawing of banking test18)

(2) Characteristics of mixed slag as embankment structure material

To examine the applicability of the mixed slag to embankment structures, among other things, we next conducted a banking test. The banking test is schematically shown in **Fig. 9**.18) The mixed slag was adjusted to an optimum moisture content, spread with a backhoe (heaped capacity of 0.8 m^3), graded, and compacted with a vibrating roller (4 t), a hand guide roller (0.6 t), and a plate compactor. The bank was then sprayed with water to an optimum water content ratio of +2% by considering evaporation and underseepage. The finished thickness per layer is 150 mm. After the completion of the banking test, the bank was cured for 2 weeks. A water filling test was then conducted. The bank was supplied with tap water at a constant rate. A drainage pump was used to keep the water level constant at a height of 10 cm from the crest.

Table 1[18] shows the field density test results for the second, fourth, and sixth layers in each case. In all cases, the compaction degree was 90% or more. It can be seen that embankments can be easily built in the same way as is done by the method of using the simple pavement material. **Figure 10**[18] shows the change with time of hydraulic conductivity in each case. The hydraulic conductivity decreases as the material increases in age in all cases. When the hydraulic conductivity at two weeks is compared with that at eight weeks, it is lower by about one order of magnitude. This is probably because the pores of the slag are filled with calcium silicate hydrate and carbonate produced by the latent hydraulicity of the mixed slag. **Figure 11**[18] shows the change with time of the pH of raw water and impounded water. In the initial stage of the impoundment, the pH of the impounded water is different by more than 1 from that of the raw water. As the time after the impoundment increases, the pH difference between the raw water and the impounded water decreases. This is due to the elution of alkali ions as the latent hydraulicity of the slag appears. It is suggested that the elution amount of alkali ions from the slag decreases with time.

These test results clarified that the constructability of embankments with the mixed slag is high, that the latent hydraulicity is exhibited, and that the effect of the pH on the impounded water is small.

Table 1 Field density test results[18]

	Rolling times	Banking materials	Degree of compaction (%)			
			2 layers	4 layers	6 layers	Avg.
Case A	4	Mixed slags	94.6	92.8	98.9	95.4
Case B	2	Mixed slags	94.2	94.8	92.3	93.8
Case C	6	Mixed slags	96.2	94.6	92.2	94.3
Case D	4	Mixed slags Edosaki sand	93.7	97.5	99.8	97.0

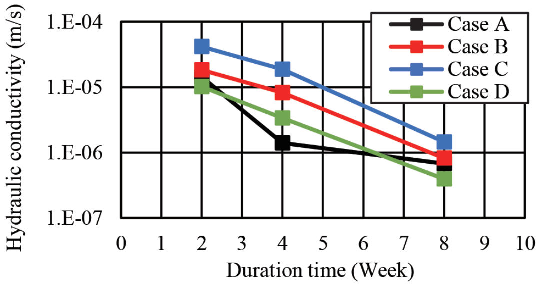


Fig. 10 Time histories of hydraulic conductivity[18]

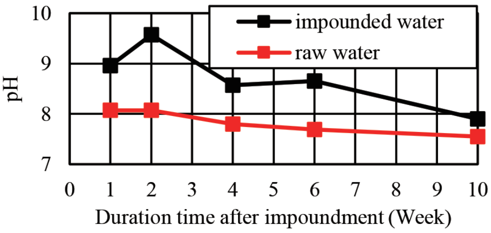


Fig. 11 Time histories of pH[18]

(3) Seismic resistance of embankment built from mixed slag used as substitute lining material

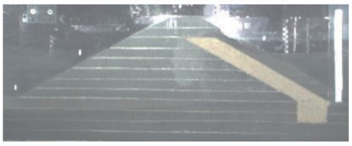
Lastly, we conducted a centrifugal loading test to clarify the seismic resistance of small earth dam embankments built of the mixed slag as a substitute lining material. The test was performed in a 40 G centrifugal field. The soil container was made of aluminum and was 1.35 m wide by 0.45 m high by 0.40 m deep. The Asama sand was used as ground material and embankment material. The Kasama clay and the mixed slag were used as lining materials. The input waveform was that of the east-west component of the Nankai Trough waveform in Nishio City, Aichi Prefecture. **Figure 12**[19] shows the cross sections of the models after the tests. When the embankment was not reinforced, the upstream slope failed by sliding and bulged in the middle. On the other hand, in the case of the lining method (Kasama clay), shallow collapse occurred in the surface layer of the upstream slope, but settlement or sliding failure did not occur at the crest. When the embankment was lined with the mixed slag, the results obtained were similar to those obtained when the embankment was lined with cohesive clay (Kasama clay). **Figure 13**[19] shows the acceleration responses of the embankment core and the embankment slope lined with the Kasama clay and the embankment lined with the mixed slag. When the embankment was lined with the Kasama clay, the phase difference in the acceleration response is small between the core and the lined slope of the embankment. Similar tendencies were obtained when the embankment was lined with the mixed slag. It is thus evident that the mixed slag vibrates together with the fill material in an earthquake.

The test results showed that use of the mixed slag as lining material suppresses the deformation of the embankment during vibration as compared with the case where the embankment is not reinforced. It was also shown that the lining material and the fill material behaved integrally. The mixed slag lining method is thus found to be an effective earthquake resistant method.

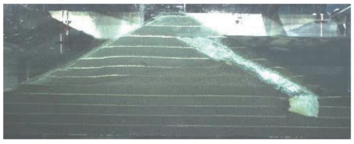
3.3 Summary

As evident from the test results described above, we solved the technical issues discussed in Section 3.2 and showed the possibility of using the mixed slag as a substitute lining material in an inclined cutoff zone. A future issue is to verify the applicability of the mixed slag lining method to existing small earth dam embankments

(a) Non reinforcement

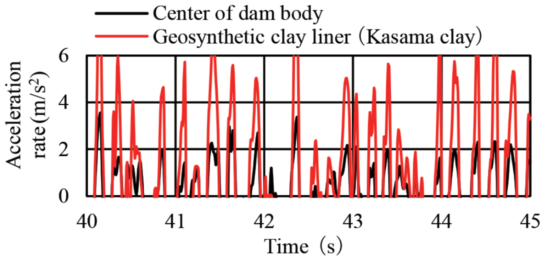


(b) Geosynthetic clay liner (Kasama clay)

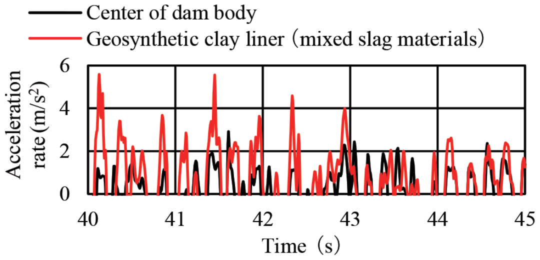


(c) Geosynthetic clay liner (mixed slag materials)

Fig. 12 Deformation after shaking table tests[19]



(a) Geosynthetic clay liner (Kasama clay)



(b) Geosynthetic clay liner (mixed slag materials)

Fig. 13 Time histories of response accelerations19)

through testing there.

4. Conclusions

In this report, we have described the verified effectiveness of the steel sheet pile method and the slag method as seismic reinforcement measures for small earth dam embankments and have introduced the areas where the two methods can be employed according to their characteristics. We compiled a seismic design guide for the steel sheet pile method9) through joint research with Kochi University. We are pushing ahead with the application of the steel sheet pile method to small earth dam embankments so that it can be recognized as an effective earthquake resistant method for small earth dams on a nationwide basis.

When the government revised small earth dam reinforcement guidelines titled “Small Earth Dam Maintenance”4) in 2016, it emphasized the need to fully consider the effect of a dam collapse on downstream areas and set importance classes for small earth dams according to the effect of their breaches on downstream areas. If a small earth dam is located upstream of major roads, railroads, houses, and other facilities that have an extremely serious impact on human life and property, it is designated AA, the most important class, and is required to limit its damage when it is struck by level 2 earthquake ground motions. From the viewpoint of downstream impacts, it is important to take measures not only for collapse in earthquakes, but also for seepage failure in heavy rainfalls, sliding failure of the slope due to rainfall seepage, and breach originating from slope erosion due to overtopping. To promote research and development to meet on-site needs, the government launched a 2021 to 2025 five-year program entitled “Development of Functional Diagnosis and Repair and Reinforcement Evaluation Technologies Toward Proper Maintenance and Management of Small Earth Dams”. The program aims at the development of technologies for evaluating repair and reinforcement methods to secure safety performance during earthquakes as well as torrential rainfalls.20) The two methods developed and promoted by Nippon Steel as described in this technical report No. 130-06 are also promising as measures against heavy rainfalls. The steel sheet pile method installs steel sheet pile walls to prevent seepage flow into the embankment. When the slope is damaged by rainfall seepage or overflow, the embankment core surrounded by the double steel sheet pile walls can retain the embankment height and prevent embankment breaches. The slag method can prevent seepage failures and sliding failures by reinforcing the embankment with highly impervious materials. We will strive to have the steel sheet pile method and the slag method officially recognized through collaboration with the government, promote the two methods as methods for repairing and reinforcing small earth dam embankments against earthquakes and heavy rainfalls, and thereby contribute to national resilience.

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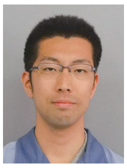
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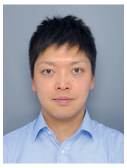
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