

Experimental study about recovery of bearing capacity against train load by reconstruction work of embankment damaged by rainfall

Takaki Matsumaru, Taketo Sato

Structure Technology Division, Railway Technical Research Institute, Japan, matsumaru.takaki.35@rtro.or.jp

ABSTRACT: In recent years, a lot of railway embankments have been damaged due to severe rainfall. In the case where the restart of the operation of railway is strictly required, the emergency reconstruction works are conducted, and large-scale soilbags are often used in the works. However, the stability and the characteristics of settlement of the damaged and reconstructed embankments have not been studied efficiently. In this study, the rainfall infiltration and loading tests of damaged and reconstructed embankments were performed. From these studies, it was revealed that the stability of the reconstructed embankments was recovered if the support and drainage of the sandbags was sufficient. Furthermore, it was confirmed the stability analysis of the damaged embankment and emergency reconstructed embankment successfully reproduced the tendency obtained by the experiments.

KEYWORDS: Embankment, seepage, reconstruction, sandbag, settlement.

1 INTRODUCTION

In recent years, there have been an increasing number of cases of railway embankments being damaged by heavy rainfall due to the rainy season, typhoons, and even linear rain bands in the summer. When heavy rainfall exceeds the rainfall limitation value for operation of railway, the operations are suspended and inspections of the line are carried out before resuming operations (Kajitani et al. 2012). When a certain damage to the embankment is confirmed, the necessity for reconstruction works is considered. If the damage is not large, train operations are resumed by preventing rainfall seepage with sheets as shown in Figure 1 (a), etc. However, if some kind of restoration is required and restart of operations must be resumed quickly, emergency reconstruction works are conducted. The decision on whether or not to resume operations and to restore largely depends on the experience of the inspectors. Furthermore, since the performance of the damaged embankment and the emergency reconstructed embankment has not been evaluated, there is a possibility that restoration will be carried out on embankments that do not actually require restoration, or that the structure of the emergency restoration will be excessive. In addition, large sandbags are often used for emergency restoration as shown in Figure 1 (b), but they cannot be used as permanent structures for railway embankments and should be removed, which means that permanent restoration after emergency restoration is very time-consuming. Although studies about seismic performance (Miyagawa et al. 2013, Mori et al. 2016) and manuals for design and construction have been prepared for restoration structures, no studies have been conducted focusing on the resistance against severe rainfall.

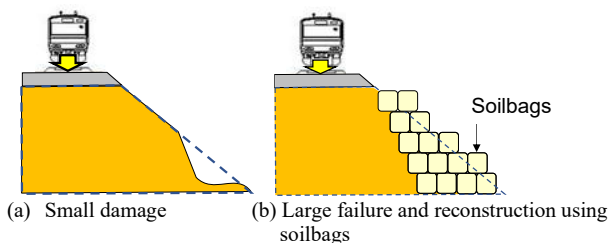


Figure 1. Illustration of scale of damage of railway embankment due to rainfall.

In this study, we conducted model experiments to confirm the train support performance of embankments damaged by rainfall and embankments that were temporarily restored, by carrying out load tests after rainfall sprinkling, to determine the stability of the embankments when train operations are resumed, for which there is a concern. We also conducted tests

on structures in which the large sandbags were not removed after emergency restoration, to verify the change in performance from the time of emergency reconstruction. Furthermore, the validation of the experimental results was examined by the stability analyses focusing on the damaged embankment and the emergency reconstructed embankment.

2 TEST OF DAMAGED EMBANKMENT

2.1 Experimental conditions

Rainfall infiltration and loading experiments were conducted on a 1/6-scale embankment model, in order to investigate the resistance of the embankments against train loads for the case of collapse. Figure 2 shows an illustration of the embankment used in the experiments. The height of embankment was 0.67 m and the gradient of the slope was 1:1.5. The crushed stone was provided at the top of the embankment with 0.1 m layer. The material of the embankment was Inagi sand. The material properties are shown in Table 1.

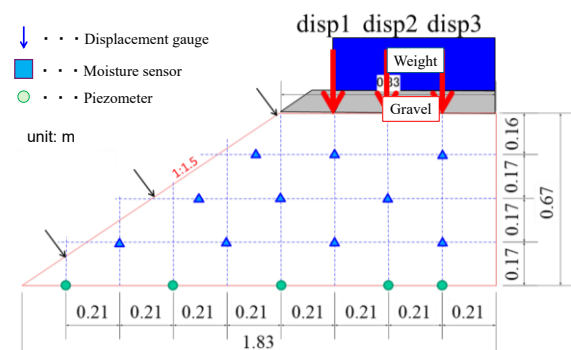


Figure 2. Illustration of model embankment.

Table 1. Material properties of Inagi sand.

Soil particle density	2.72 g/cm ³
Natural water content	19.4 %
Maximum dry density	1.72 g/cm ³
Optimal water content	16.2 %

Three cases of experiments were conducted for evaluating the behaviors of damaged embankments. In Cases 1 and 3, the degree of compaction D_c of approximately 80% were considered, and in Case 2 D_c of 87% was prepared. Though the design standard for railway earth structures (R.T.R.I., 2007) requires 90 % or more for new embankments, a lot of embankments constructed before the publication of the standards do not satisfy the values. In Cases 1 and 3, this

situation was considered. Table 2 shows the permeability coefficient, internal friction angle and cohesion obtained from laboratory tests of Inagi sand. From the permeability test in laboratory using embankment material, the permeability coefficient differs by one order of magnitude between Cases 1 and 3 and Case 2, and Case 2 is somewhat stronger in terms of strength.

Table 2. Permeability coefficient and strength parameters of Inagi sand.

	Cases 1 and 3	Case 2
	$D_c = 80\%$	$D_c = 87\%$
Permeability coefficient	$2.98 \times 10^{-4} \text{ m/s}^2$	$2.98 \times 10^{-5} \text{ m/s}^2$
Internal friction angle	32.4 degree	34.1 degree
Cohesion	0	4.6 kPa

The amount of rainfall was set at 30 mm/h in all three cases. Sprinkling rainfall causes collapse of the embankment in stages and loading tests for applying train loads were conducted at the timing of small, medium, and large collapses, based on the collapse shapes of the embankment as shown in Figure 3. In Cases 1 and 2, the load was applied as soon as preparations for loading after sprinkling rainfall. On the other hand, in Case 3, taking into account the time required for inspections and other procedures until the resumption of actual train operation, the load was not applied immediately after rainfall sprinkling was stopped. A delay of about an hour and a half was considered in this test. The applied load was set at 774.2N, which is equivalent to the actual EA load (R.T.R.I., 2023) of 170kN applied to the top of the embankment.

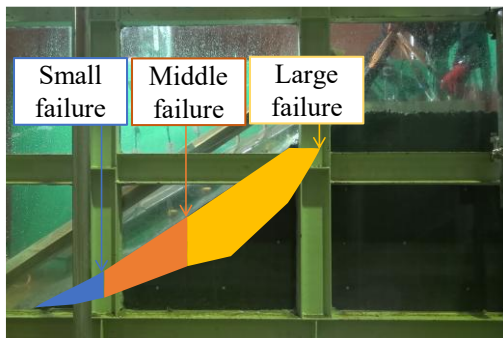


Figure 3. Failure pattern of embankment.

2.2 Results and discussions

Though the timing of the collapse of the embankment differed for each case, the total amount of rainfall was 143 mm in Case 1, 179 mm in Case 2, and 175 mm in Case 3. Figure 4 shows the water level and distribution of the degree of saturation in the embankment for each case when the large scale of failure was observed. In all cases, the degree of saturation increased and the water level was also formed. The water level and the degree of saturation rose more in Case 2 than in Cases 1 and 3 because the embankment density in Case 2 is higher, resulting in a smaller permeability coefficient, and the embankment strength is higher. There was no significant difference in the water level and degree of saturation between Cases 1 and 3.

Figure 5 shows the settlement at the top of the embankment when the train load was applied in accordance with the collapse scale of small, medium, and large in Cases 1 to 3. In Cases 2 and 3, the settlement of the embankment was small regardless of the collapse scale. However, in Case 1, the settlement of the embankment at the top increased when the train load was applied, even when the collapse scale was small.

In particular, the difference from Case 3 was that there was no significant difference in the distribution of degree of saturation and water level as shown in Figure 4 (a) and (c), so it is assumed that there was a difference in the distribution of the degree of saturation between the two cases above the soil moisture sensor installation positions. From these results, it is considered that the degree of compaction and the distribution of the degree of saturation in the embankment affect the settlement at the top when the train load acts. In the case of an embankment with a small degree of compaction, even if the collapse surface does not reach the ballast, it is possible that the stability against the train load will not be sufficient if the degree of saturation at the top of the embankment is high immediately after rainfall.

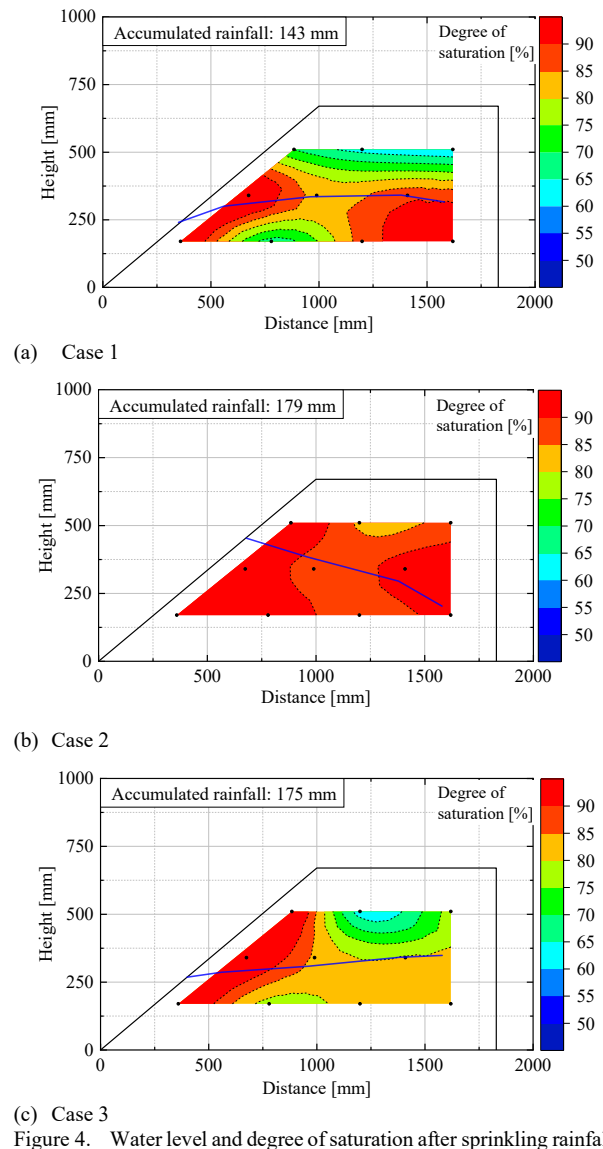


Figure 4. Water level and degree of saturation after sprinkling rainfall.

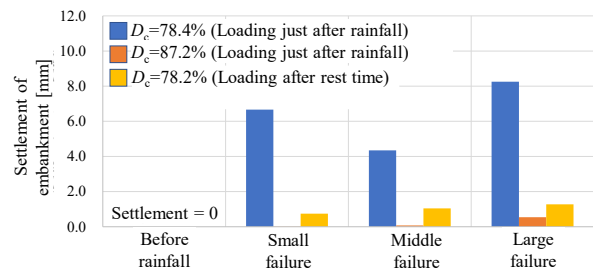


Figure 5. Relationship between scale of failure and settlement.

2.3 Validation of stability analysis for evaluating failure due to rainfall

The applicability of the method of stability analysis was examined through the simulation of the rainfall sprinkling and loading test in Case 1. In the stability analysis, the circular slip method was adopted in consideration with the water level obtained from experiments. For the strength parameters of the embankment, the internal friction angle and the cohesion as shown in Table 2 were used. For the case evaluating the stability of unsaturated embankment, the cohesion depends on the value of the degree of saturation (R.T.R.I., 2007). However, a lot of regions where collapse occurred were under the water level, so the cohesion was determined as constant value obtained from saturated triaxial tests.

Figure 6 shows the comparisons of slip surfaces obtained from experiments and stability analyses. Though the circular slip from the analyses were a little bit deeper than those of the experiments, the shapes were similar. Furthermore, in the stability analysis, the stabilities of the damaged embankments under the applied load were also evaluated. From the analyses, the stabilities of the embankments were still kept after the occurrence of failure, so the analyses coincided with the tendencies obtained from series of tests.

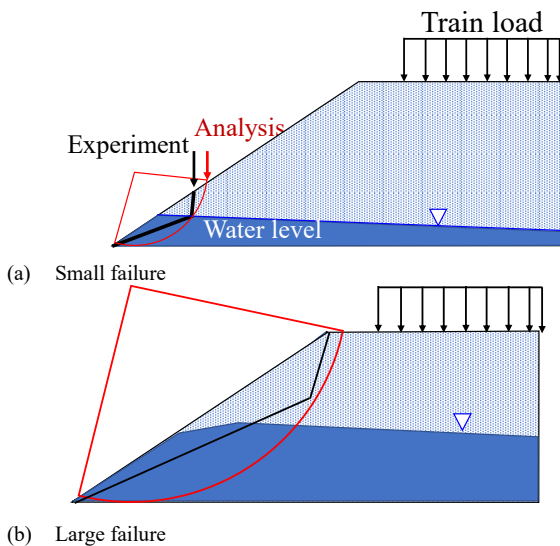


Figure 6. Result of stability analysis using circular slip method.

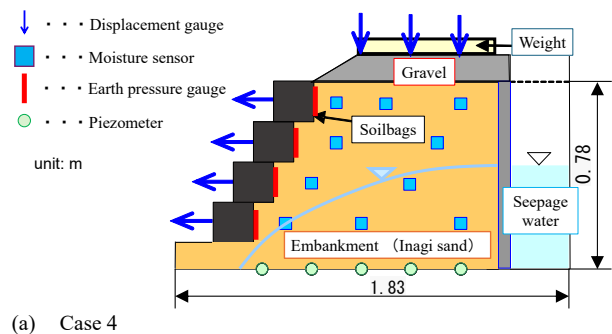
3 TEST OF EMERGENCY RECONSTRUCTED EMBANKMENT

3.1 Experimental conditions

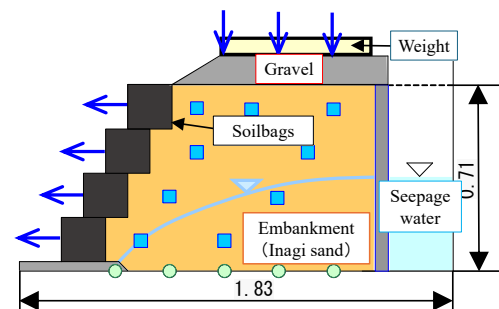
Rainfall sprinkling and loading tests similar that shown in Chapter 2 was conducted on the embankment temporarily reconstructed using large sandbags, in order to confirm the stability of the embankment when the train loads were applied, assuming the resumption of train operation. The model embankment was 1/6 scale, with a height of 0.78 m in Case 4 and 0.71 m in Case 5.

The model embankment was constructed using Inagi sand, as in the test in Chapter 2, and the degree of compaction was targeted at approximately $D_c=80\%$, as in Cases 1 and 3. Two cases of tests were carried out in this experiment, and the difference between the cases was in the preparation conditions for the support ground below the sandbags, as shown in Figures 7 (a) and (b). In Case 4, the same Inagi sand as the embankment was used, whereas in Case 5, crushed stone was used in order

to increase the bearing capacity at the bottom of the sandbags and improve drainage from the sandbags. In both cases, five rows of $\phi 20$ mm drainage pipes were installed in the depth direction of the support ground to lower the water level behind the sandbags, making it easier for water to drain outside the embankment. To measure the earth pressure, the sandbag model was made of mortar to ensure reaction force, and an earth pressure gauges and load cells were installed. The mass and size were made to be 1/6 of the actual size, and the sandbag model is a square with one side measuring 17 cm. Since friction between the back embankment and the sandbags was thought to be important in the rainfall sprinkling and loading tests, the friction coefficient of the model sandbag was adjusted to that of an actual large one, and the fabric of the sandbag was attached with adhesive to five sides of the sandbag model except for the front side. The sandbags were arranged in a single row after a stability study against the load was conducted in advance. In the rainfall sprinkling and loading experiment, first, without rainfall, the water level in the embankment was raised by supplying water from the tank installed behind the embankment while maintaining the water level at 400 mm, and then rainfall of 30 mm/h was applied from the rainfall sprinkler to increase the degree of saturation in the embankment. This assumes a situation in which the railway embankment collapses due to rainfall, and then emergency reconstructions are made with large sandbags, and then rainfall occurs again, causing the increase of the water level and degree of saturation in the embankment. After rainfall sprinkled, the weight was applied to simulate the load of a train. In addition, if the settlement of the embankment top and the horizontal displacement of the sandbags that occur after loading are small, the load was increased to grasp the deformation of the embankment and sandbags.



(a) Case 4



(b) Case 5

Figure 7. Illustrations of the model embankments.

3.2 Results and discussions

The tests for both cases were carried out over 2 to 3 days, with infiltration from the back and rainfall sprinkling being interrupted at night. In the test for Case 4, the water level in the

water tank behind the embankment was kept at about 400 mm, and when the accumulated rainfall after the start of sprinkling reached about 30 mm, a large collapse occurred in the embankment, centered on the location of the large sandbags above the second tier, as shown in Figure 8. Although it can be judged that the rainfall resistance has improved compared to the experiments mentioned in Chapter 2, it is considered that the stability against rainfall is not sufficiently secured. The water level in the embankment at the time of the collapse was about 150 mm at the position closest to the sandbags shown in Figure 7 (a), and it is assumed that pore water pressure was also acting on the bottom sandbags, even though a drainage pipe was installed.

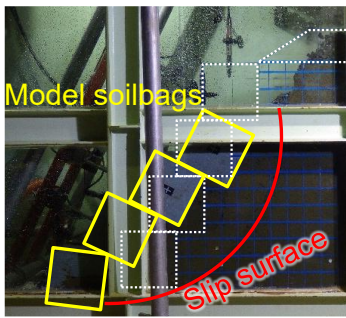


Figure 8. Photos of damaged embankment in Case 4.

On the other hand, in the test of Case 5, the water level from the backfill was set to about 400 mm, and a total amount of rainfall of 317 mm was applied with a rainfall intensity of 30 mm/h, but the embankment did not collapse due to seepage water from the backfill and rainfall. Based on the test result of Case 4, although the rainfall resistance of the embankment was improved by restoration using sandbags, it is thought that in order to ensure sufficient stability, it is necessary to ensure the bearing capacity at the bottom of the sandbags and to lower the water level at the back of the sandbags. Figure 9 shows the water level and degree of saturation in the embankment immediately before the loading test after rainwater sprinkling. The degree of saturation remained at about 50% near the surface of the embankment, but as the water level reached about half the height of the embankment, an increase in degree of saturation was observed above the water level.

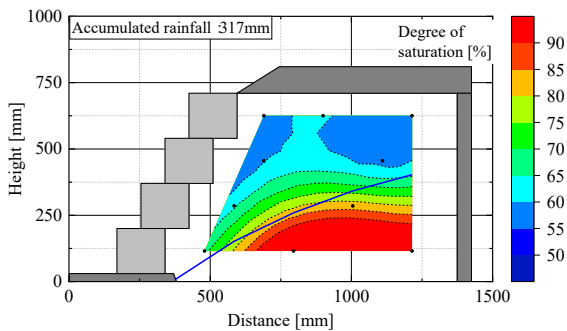
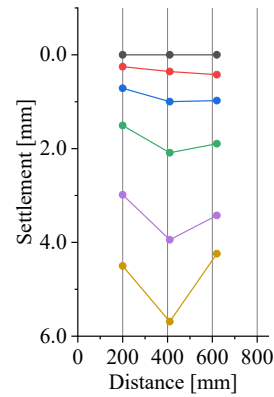


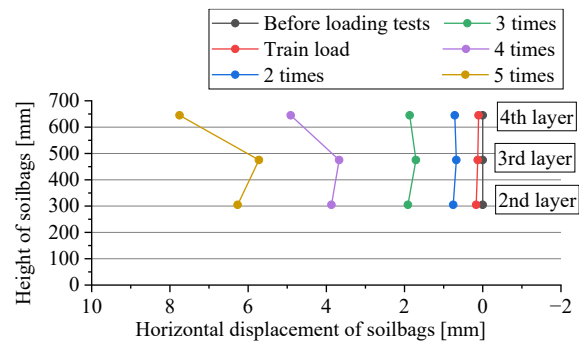
Figure 9. Water level and degree of saturation in Case 5.

Figure 10 shows the distribution of vertical displacement at the top of the embankment and horizontal displacement at each sandbag when the train load was applied, in the test of Case 5. The horizontal axis of vertical settlement means the distance from the shoulder of the embankment. The load was applied up to a level equivalent to five times the train load. Even when the load was twice the train load, the settlement at the top of the embankment was about 1 mm, and the displacement towards the front of the sandbags was also kept to less than 1 mm. When the load was subsequently increased, the vertical

displacement at the top and the horizontal displacement of the sandbags increased, and the same level of bulging occurred throughout the sandbags up to a load of about three times the train load. When the load was increased beyond four times the train load, the bulging of the top sandbag became obvious, with a maximum displacement of about 8 mm. However, even when the load was five times the train load, the embankment did not collapse.



(a) Settlement at top of embankment



(b) Horizontal displacement of soilbags

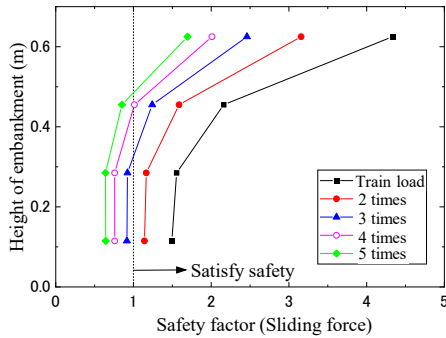
Figure 10. Settlement of embankment and lateral displacement of soilbags.

3.3 Stability analysis about equilibrium of earth pressure of soilbags

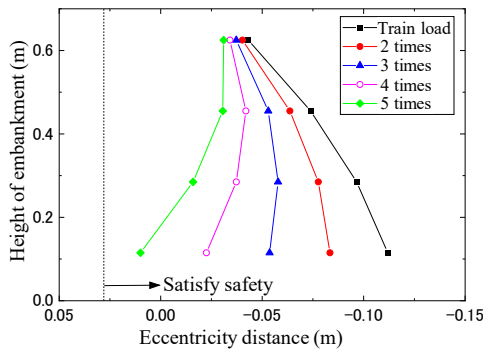
When embankments are damaged by rainfall, emergency reconstruction works using large sandbags are often performed by stacking the sandbags in a way that recreates the shape before the damage, but in this experiment in Cases 4 and 5, only a single row of sandbags was used in this experiment. To verify that this structure is stable, a stability analysis against sliding was calculated using the stability analysis method shown in reference. In this analysis, the stability of the earth pressure acting to each soilbag was examined. The friction coefficient between soilbags and embankment material was determined as $\mu=0.7$ considering the study by Matsuoka et al. (2004).

Figure 11 shows the calculated results for the safety factor about sliding force and the eccentricity against tipping obtained by stability calculation at the overturning moment for each applied load. The results show that there is no significant eccentricity against overturning moment even when a load up to five times the train load is applied, as shown in (b). However, when a load equivalent to more than three times the train load is applied, the safety factor about sliding force for the large sandbags in the bottom two tiers falls below 1. The horizontal displacement of the sandbag position obtained in the experiment as shown in Figure 10 was large in the second tier from the bottom, while the safety factor obtained by calculation

becomes smaller from the bottom tier, suggesting that sliding displacement occurs from the bottom tier of sandbags. In the experiment of Case 5, high-quality crushed stone was laid under the sandbags, and it is thought that the friction between the crushed stone and the sandbags suppressed the displacement of the bottom tier of sandbags. Although there are differences in the deformation modes of the sandbags as described above, as shown in Figure 10, in the experiment, when the load was more than three times the train load, there was an increase in the amount of settlement at the top of the embankment and the horizontal displacement of the sandbags themselves. It is confirmed that the horizontal displacement of the sandbags in response to the increase in the applied load in the experiment is expressed in the stability calculation as a decrease in the safety factor against sliding.



(a) Sliding force



(b) Overturing moment

Figure 11. Safety factor obtained from stability analysis.

4 TEST OF PERMANENT RECONSTRUCTED EMBANKMENT

4.1 Experimental conditions

Rainfall sprinkling and loading tests were conducted on the embankments that had been temporarily restored using large sandbags, with the aim of covering the front of the sandbags with soil to make the structure permanent without removing the sandbags. The experimental case was Case 6, and the illustration of the model embankment is shown in Figure 12. The front side of the sandbags was covered with the same Inagi sand as the backfill of the sandbags, with a slope of 1:1.2 and the degree of compaction of $D_c=80\%$. In order to improve drainage on the covered soil side as well, crushed stone was laid up to the height of the second step between the bottom of the embankment and the sandbags.

In the rainfall sprinkling and loading test, as in experiment Chapter 3, no rainfall was applied in the first stage, and the water level in the embankment was raised by supplying water with maintaining the water level at a height of 400 mm from a

water tank prepared behind the embankment. Next, with the water level raised, a rainfall intensity of 30 mm/h was applied to increase the degree of saturation in the embankment. Finally, with the water level raised to 600 mm, the rainfall intensity was increased in the order of 30 mm/h, 48 mm/h, and 78 mm/h. The accumulated rainfall reached 330 mm, roughly the same as in experiment Chapter 3. Then, the loading test was conducted, and the load of up to five times the train load was applied.

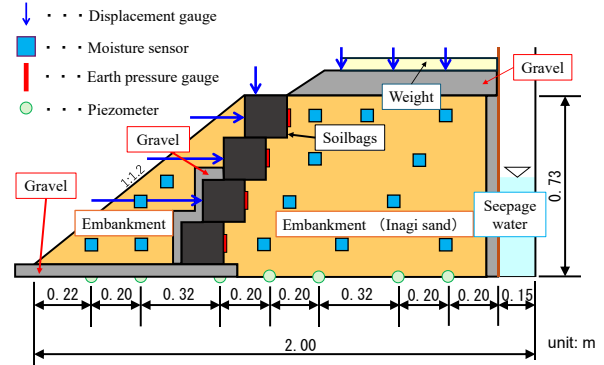


Figure 12. Illustrations of the model embankment in Case 6.

4.2 Results and discussions

During the period when infiltration water and rainfall were applied, some erosion of the slope surface was observed when the rainfall intensity was increased, but there was no debris flow from the slope due to a rise of the water level in the embankment, and no behavior that would cause the covered embankment to collapse even with the accumulated rainfall that would cause the embankment to collapse without countermeasures. From this result, it was confirmed that the stability during rainfall has been improved by the proposed structure, including the embankment part on the front side covered with soil.

Figure 13 shows the water level and distribution of degree of saturation in the embankment after rainfall sprinkling. As with the emergency reconstructed embankment shown in Figure 9, there is a tendency for the water level to gradually decrease from the embankment behind the sandbags toward the crushed stone layer, and no water level is formed in the covered embankment in front of the sandbags. The crushed stone layer at the bottom of the sandbags acts as a drainage blanket, and the increase in degree of saturation of the covered embankment on the front side is also suppressed to about 70%. In the damaged embankments in Cases 1 to 3, as shown in Figure 4, increases in water levels and degree of saturation were observed even near the slope. However, this was not the case in the reconstructed embankments, and it is believed that no remarkable changes occurred in the front of the embankment that was covered with soil.

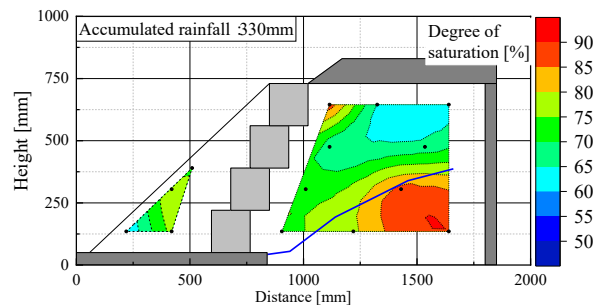
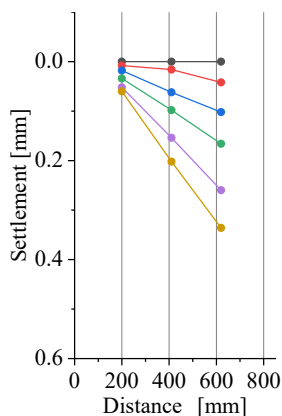
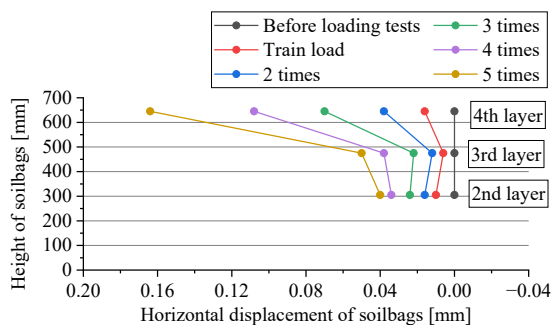


Figure 13. Water level and degree of saturation in Case 6.

Figure 14 shows the distribution of horizontal displacement at each 4 and vertical displacement at the top of embankment when the train load was applied. Focusing on the horizontal displacement of the sandbags, the horizontal displacement occurring throughout the sandbag model in this reconstructed structure was small, and even in the top sandbag, which showed the largest horizontal displacement, it was about 1/50 of that in the emergency reconstructed embankment of Case 5 as shown in Figure 10. In addition, the increase in horizontal displacement was further reduced in the second and third sandbags, and it is considered that the embankment covering the front side of the sandbags had an effect of reducing displacement. The distribution of settlement of the top of embankment occurred almost uniformly in the emergency reconstructed embankment but occurred greatly near the back of the model embankment in this reconstructed structure. This is thought to be because in this reconstructed structure, the horizontal displacement of the sandbag was reduced, so the top of embankment near the slope shoulder was less likely to settle, and the area near the back of the embankment, where the degree of saturation had increased due to the influence of the water of the backfill, was more likely to settle. The amount of settlement that occurred in this reconstructed embankment was approximately 1/10 of that in the emergency reconstructed embankment. A comparison of the horizontal displacement of the sandbag model and the settlement of the top of the embankment showed that the displacement was reduced by covering the front of the sandbags with embankment.



(a) Settlement at top of embankment



(b) Horizontal displacement of soilbags

Figure 14. Settlement of embankment and lateral displacement of soilbags.

5 CONCLUSIONS

In this study, the stability of embankments damaged by rainfall and their reconstructed structures at the time of resumption of

train service was examined by conducting rainfall sprinkling and loading tests on model embankments. From the series of tests, the following results were obtained.

- 1) A series of tests on damaged embankments revealed that the train support capacity of embankments is highly dependent on the degree of saturation and density of the embankment. Loose embankments with a high degree of saturation may not be able to provide sufficient train support capacity. Additionally, the experimental results successfully reproduced by stability analysis using circular slip method.
- 2) From the tests on embankments that had been temporarily repaired using large sandbags, it was confirmed that the ground beneath the sandbags was stable and drainage was ensured, the embankment would be sufficiently stable even under train loads. This tendency was also reproduced by the stability analysis considering the equilibrium about the earth pressure of soilbags.
- 3) The test on the permanent reconstructed embankment, which was covered in front with soil without removing the large sandbags, showed that there was no significant increase in the water level or degree of saturation, and no remarkable deformation occurred. It was also confirmed that deformation due to train loads was suppressed compared to the emergency reconstructed embankment, thereby improving performance.

In this study, only the resistance against rainfall was studied through the rainfall infiltration test and loading test. For the usage as railway embankment, the settlement characteristics caused by cyclic loading due to trains should be also studied. Furthermore, the seismicity was also studied because some previous studies mentioned that the reconstructed embankment using soilbags showed reduce of seismic resistance.

REFERENCES

- Kajitani, N., Togari, A., Seki R. and Tomori, M. 2012. The method of train operation control against rainfall with new rainfall hazard index, *Geotechnical Engineering Magazine*, 60(3), 20-23.
- Matsuoka, H., Sihong Liu, Hasebe, T. And Shimao, H. 2004. Deformation-strength properties and design methods of soilbag assembly, *Journal of Japan Society of Civil Engineers*, 764, 169-181.
- Miyagawa, S., Kubo, T., Mori, Y. and Miyatake, H. 2013. Examination of efficient corresponding method to large scale embankment disaster, *Geosynthetics Engineering Journal*, 28, 45-52.
- Mori, Y., Miyatake, H., Kubo, T. and Inoue, G. 2016. Study on new restored technology for large-scale sediment disaster, *Journal of Japan Society of Civil Engineers, Ser. F4 (Construction and Management)*, 72(4), I_77-I_87.
- Railway Technical Research Institute 2007. *Design Standards for Railway Structures and Commentary (Earth Structures)*.
- Railway Technical Research Institute 2023. *Design Standards for Railway Structures and Commentary (Basic Principles and Bridge)*.