Rainfall infiltration characteristics of railway embankments based on field monitoring

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Abstract

Soil structures, such as embankments, accounting for 80% of railways in Japan, are prone to damage from natural disasters and consequent long-term suspension of operations. The risk of railway operation is mostly evaluated based on statistical results such as past rainfall and disasters. However, the increasing frequency of heavy and prolonged rainfall makes it necessary to review existing risk management methods. To grasp the signs of slope failure due to rainfall from changes in volumetric water content and utilize it to determine train operation regulations, we are examining a new method for evaluating the process of destabilization of the surface layer of railway embankments by visualizing the rainfall infiltration characteristics via the application of the continuous observation technology, which has been proven on natural slopes and expressway slopes. Specifically, as a primary stage of our research, field monitoring of rainfall and volume moisture content in embankments and natural slopes where surface collapse is of concern were performed. Continued observations were made for more than one year from October 2020. A behaviour similar to the infiltration process from the equilibrium state at IQS to the rise of the saturation zone obtained in the results of the model slope experiment was observed. Additionally, in the model slope experiment, inflow from the upper part of the slope (including the track), which was not assumed as an experimental condition, to the surface layer of the embankment was observed. The conclusions were limited, but based on the observation results and ground survey, cases were observed where the difference in permeability due to the compaction of the upper soil structure, including the railroad track, compaction of the embankment, and different stratum composition, affects the time and direction of rainfall infiltration, and it was suggested that the rainfall infiltration characteristics can be visualized.

Keywords: railway embankments, field monitoring, volumetric water content

1. Introduction

The percentage of soil structures among civil engineering structures in Japanese railways exceeds 80%, and these structures were made long time ago. They were manually constructed without construction machinery and good quality embankment materials were not utilized. Therefore, it is considered that many of the embankments do not exhibit sufficient performance and quality when compared to the embankments constructed in recent years (Kojima, K. 2014). The disaster risks for train operation of railway soil structures include fallen trees, earthquakes, and sediment collapse due to heavy rains, as shown in **Table 1**. Although the frequency of fallen trees is high, the recovery time until removal is short, and the degree of impact is small. A large earthquake has a significant impact on train operation when it occurs. However, seismic retrofitting work is conducted on important routes where the frequency of occurrence is low and the load of passenger transportation is high. Conversely, the frequency of sediment collapse has increased due to torrential rains and long rains in recent years, and even a surface collapse with a small amount of collapsed soil leads to train obstruction and train derailment. Hence, the degree of impact is high and the risk of disaster is increasing. Furthermore, in the case of

Table 1: Disaster risks of railway soil structures

Disaster	Frequency	Impact on trains	Proactive measures
Fallen tree	High	Small	Logging / fixation
Large earthquake	Low	Big	Embankment seismic retrofitting
Sediment collapse	Medium **→ High**	Big	**Difficult to take measures**

Table 2: Characteristics of railway embankment

	Railway	Expressway
Construction age	Since the 1870s	Since the 1960s
Embankment superstructure (Rain penetration)	Crushed stone (easy)	Pavement (difficult)
Impact during a disaster	Can't detour and has a big impact	Detour to general road is possible

sediment inflow to the track due to the collapse of the slope at the top of the railway, train operation can be resumed by removing the inflowing sediment as an emergency measure. However, in the case of embankment collapse, it is necessary to reconstruct the ground, and the time to restoration tends to be long. **Table 2** shows a comparison of the characteristics of railway embankments with those of expressways. Railways are old, and tracks are not paved. Hence, rainwater easily penetrates and there is no detour route. Therefore, it exhibits a feature which has a large impact on users in the event of a disaster.

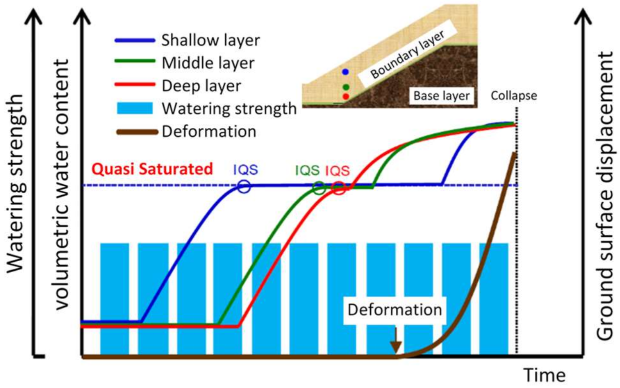

Figure 1: Relationship between infiltration characteristics, IQS, and deformation due to watering based on the model slope experiments (Koizumi et al 2021)

Japanese railway soil structures are usually visually inspected every two years, and the soundness is judged by a qualitative judgment example based on past disasters. The judgment on start and release of train operation restrictions for rainfall is conducted by comparing the observed rainfall with a rain gauge installed along the railway line wherein the standard rainfall is determined for each area based on regional characteristics such as topography and disaster history. In this manner, the soundness evaluation and operation regulation of railway slopes are judged based on empirical rules obtained from rainfall history and collapse history. The process of rainfall infiltration and saturation zone formation, which are the causes of collapse, cannot be quantitatively understood. Furthermore, the process and timing leading to the collapse are unknown, and the validity of the soundness evaluation of the railway slope and the operation regulation is unclear. In recent years, torrential rains that exceed the amount of experienced rainfall and long rains over a wide area have occurred. This in turn has led to disasters before the start of operation regulations, and in certain cases, the danger can be overlooked or the safe side can be selected excessively. Additionally, the train operation can be stopped for a long time, and the convenience of passengers can be impaired. In Japan, there are high social demands for safe operation and on-time operation, and a review of management methods is required.

Based on previous studies on natural slopes and expressway slopes (Koizumi et al. 2021), the surface displacement of the slope is expected to occur after the volumetric water content, at all depths of the collapsed soil, reaches the Initial Quasi Saturated volumetric water content (hereinafter referred to as IQS). By monitoring the time when the volumetric water content reaches IQS, it is possible to predict the deformation due to rainfall. Specifically, IQS shows the water content in a pseudo-saturated state in which the inflow and outflow of water at any point on the slope are temporarily balanced. As shown in the schematic diagram in **Figure 1**, based on the results of the model slope experiment, after the volumetric water content reaches IQS in order from the depth closest to the ground surface, the volumetric water content rises again in order from the deepest depth due to the rise in the saturation zone starting from the boundary layer. After reaching on-site saturation, the effective stress inside the embankment decreases due to the generation of pore water pressure, which increases the probability of collapse.

To grasp the signs of slope failure due to rainfall from changes in volumetric water content and utilize it to determine train operation regulations, we are examining a new method for evaluating the process of destabilization of the surface layer of railway embankments by visualizing the rainfall infiltration characteristics via the application of the continuous observation technology, which has been proven on natural slopes and expressway slopes. In this study, we describe the field monitoring results of rainfall and volumetric water content at two railway embankments with different topography, where surface collapse is a concern. The results were obtained by this method, and we discuss the probability of visualizing rainfall infiltration characteristics based on differences in local ground characteristics.

2. Outline of field monitoring site and observation method

Figure 2 shows the location map of observation site A. The observation site is located at the foot of the mountain range, and it is a one-seat section parallel to the coastline. It is an old embankment that was opened on a single

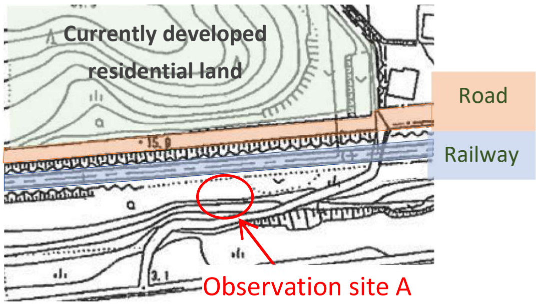

Figure 2: Location map of Observation site A

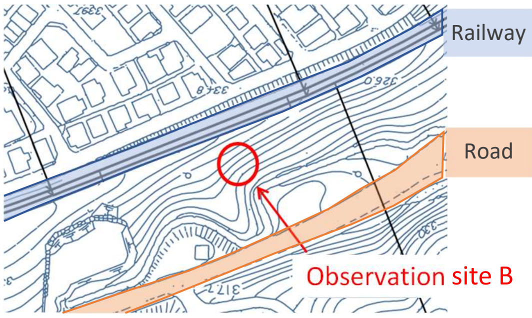

Figure 3: Location map of Observation site B

track in the latter half of the 1800s. Furthermore, it was double-tracked in the early 1900s with the embankment on its stomach. In the past, multiple surface collapses due to heavy rain occurred on the surrounding embankments. When it rains, spring water is observed in the foot of the slope, and there is concern with respect to the deformation and collapse of the soil mass. Field monitoring started in October 2020.

Figure 3 shows the location map of observation site B. It is located in the mountainous area, and it is a half-cut half-bank section. It was opened as a single track in the 1920s, and it was double tracked in the 1960s. The neighbouring embankment collapsed on the surface due to heavy rain several years ago. When it rains, spring water is observed in the foot of the slope, and small-scale collapses occurred in the middle of the slope in the past. The observation site is on the middle of the slope and is close to the natural slope, and field monitoring was started in October 2020.

Figure 4 shows the field monitoring system. The observation equipment was a soil moisture meter, a rain gauge, and a inclinometer, and various data were recorded on the cloud server at 15-min intervals using the LPWA communication method. The communication device and sensor are powered by dry batteries, and the battery replacement frequency was approximately once every 6 months.

To grasp the sedimentation condition of the local ground and plan the installation position of the soil moisture meter, we conducted the Portable Dynamic Cone Penetration test (PDCP), which is one of the simple methods for relatively investigating the softness of soil. As shown in **Figure 5**, the PDCP is a type of sounding that obtains the softness of the ground from the number of hits, Nd, required to freely drop a hammer, with a mass of 5000 g, from a height of 500 mm and penetrate the tip of the rod by 10 mm. **Figure 6** shows some of the PDCP results. At both observation sites A and B, the softness of the ground changes at Nd = 10, and the intrusive resistance value tends to increase from the depth at which Nd > = 10. Therefore, there is a probability that the permeability of the ground can significantly change in this part and become the boundary layer for rainfall infiltration. Specifically, the fluctuation of the intrusive resistance value is larger at the observation site B than at the observation site A. Therefore, it is judged that it has a clearer boundary.

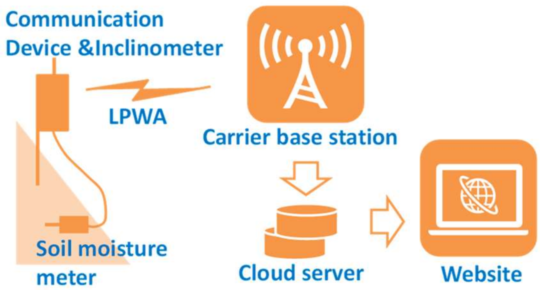

Figure 4: Field observation system

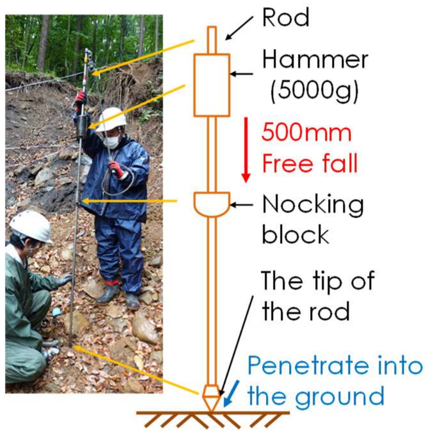

Figure 5: Overview of PDCP

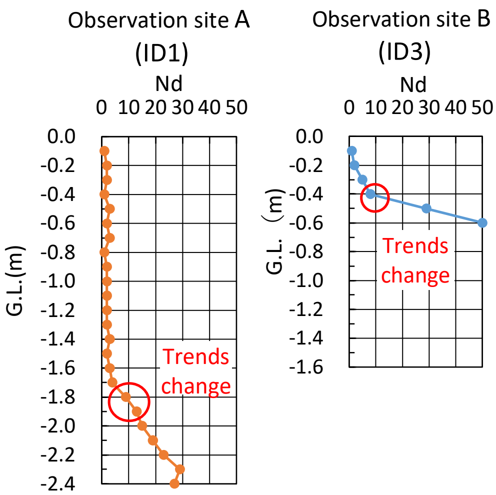

Figure 6: Nd value at Observation sites A and B

Figure 7 shows the cross-sectional shape of observation site A, geological boundary connecting Nd <10, and installation status of soil moisture meters. **Table 3** lists the typical physical characteristics of the field-collected sample, and **Figure 8** shows grain size accumulation curve. The soil moisture meter is placed by focusing on the difference in soil quality and softness. The surface soil layer is coarse-grained soil with a wide grain size and low permeability, and the in-situ compaction degree Dc is 80% or less (Ishikawa et al. 2022). Based on the line connecting Nd <10, it is inferred that the surface soil layer corresponds to the embankment slope. It is assumed that the surface collapse of the railway embankment occurs frequently at G.L. from -1.0 to -1.5 m (Nunokawa et al. 2009), and we measure up to G.L. of -1.0 m and measured at two points, ID1 and ID2 in the figure. At the ID1 point, soil moisture meters (SM-150T: manufactured by Delta-T) are installed at G.L. of -0.2 m, -0.8 m, and -1.0 m. At ID2, spring water from the excavation hole is confirmed near G.L. of -0.8 m. Therefore, it is installed at G.L. of -0.2 m, -0.6 m, and -0.75 m.

Figure 9 shows the cross-sectional shape of observation site B, stratum boundary connecting Nd <10, stratum boundary connecting Nd <20, and installation status of soil moisture meters. Furthermore, typical physical characteristics and particle size addition curves of field-collected samples are shown in **Tables 3** and **Figure 8**. The surface soil is coarse-grained soil with a wide grain size and low permeability, and the compaction degree, Dc, at the site is 70% or less, which is slightly lower than that at observation site A (Ishikawa, et al. 2022). The depths of Nd <10 and Nd <20, obtained via sounding, are almost the same, and there is a clear difference in the softness and hardness of the ground. Therefore, it is judged that it corresponds to the boundary between the topsoil layer and basement layer. The area above this boundary is targeted for measurement, and measurements are performed at two locations, ID3 and ID4, in the figure. At ID3 , soil moisture meters are installed at G.L. of -0.2 m, -0.4 m, and -0.6 m. At ID4, the meters are installed at G.L. of -0.2 m, -0.8 m, and -1.0 m.

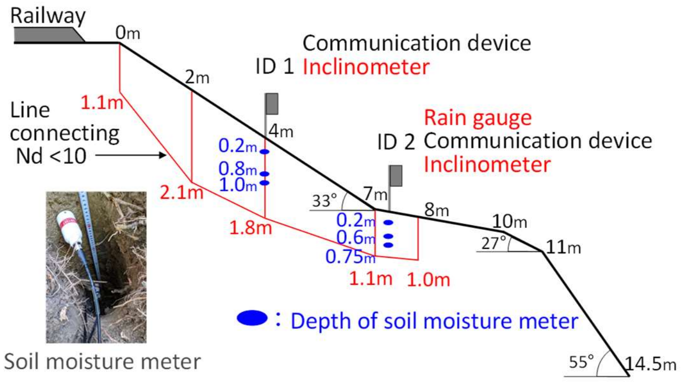

Figure 7: Cross-sectional shape and equipment status (Observation site A)

Table 3: Physical characteristics (Ishikawa et al. 2022)

	Observation site A Near ID1, G.L.-0.8m		Observation site B Near ID3, G.L.-0.6m	
Dry density : ρd	1.42	(Mg/m^3)	1.13	(Mg/m^3)
Soil particle density : ρs	2.6	(Mg/m^3)	2.68	(Mg/m^3)
Degree of compaction : Dc	79.6	(%)	67.7	(%)
Hydraulic conductivity: k (Estimated value)	2.82×10^{-7}	(m/s)	4.50×10^{-8}	(m/s)

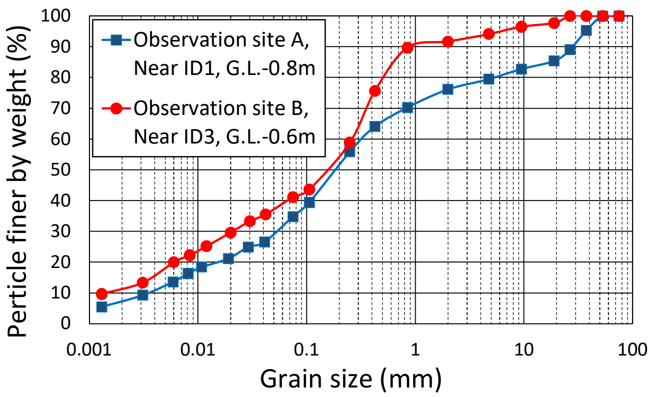

Figure 8: Grain size accumulation curve (Based on Ishikawa et al.) 2022)

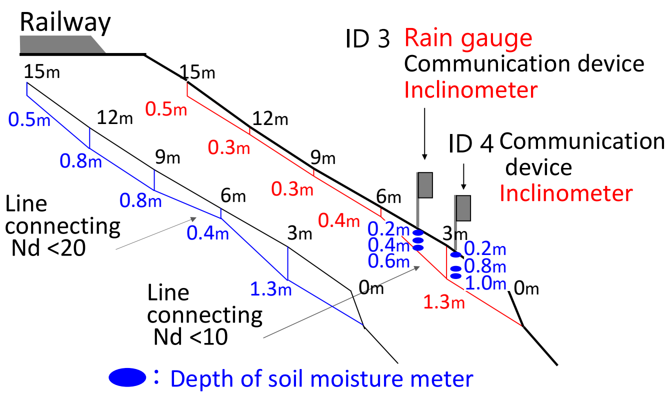

Figure 9: Cross-sectional shape and equipment status (Observation site B)

3. Rainfall and volumetric water content behaviour

3.1 Observation site A

From October 3, 2020 to February 28, 2022, there were six events when the volumetric water content of ID1 at G.L. of -1.0 m exceeded IQS and a saturation zone was formed. The values of the rain gauges at the observation sites are almost the same as the peak rainfall and time reported on the rain gauges in the neighbourhood owned by the railway operator. Two out of six times, the behaviour of the volumetric water content, which reached the IQS shown in the schematic diagram of **Figure 1,** is observed. However, four out of six times, the behaviour of volumetric water content, which is considered to be in equilibrium by IQS, is not observed. The volumetric water content of ID2 always exhibits a value of approximately 45% at G.L. of -0.6 m and approximately 50% at G.L. of -0.75 m. Furthermore, the volumetric water content does not significantly increase due to rainfall, and it is inferred that the situation is always close to saturation.

Figure 10 shows the observation results of the ID1 on April 29, 2021, when the equilibrium state is observed in IQS. Due to rainfall, the volumetric water content at G.L. of -0.2 m gradually increases. Then, the volumetric water content at G.L. of -0.8 m and G.L. of -1.0 m increases and realizes an equilibrium state, and it is presumed that IQS is realized. Subsequently, a slight difference in the degree of compaction between the embankment body and embankment slope forms a saturation zone in the upper layer above the more permeable stratum boundary, and it is inferred that volumetric water content increases again from IQS. According to the inclinometer records observed for the target slope, less deformation due to all rainfall was observed.

Figure 11 shows the observation results of the ID1 on July 1, 2021, when the equilibrium state is not observed in IQS. Specifically, the volumetric water content at G.L. of -0.2 m rises due to rainfall, and then the volumetric water content at G.L. of -0.8 m and G.L. of -1.0 m increase rapidly at the same time to reach an equilibrium state. At this time, the volumetric water content at G.L. of -0.8 m is 53%, and it is inferred that a saturation zone is formed. However, no

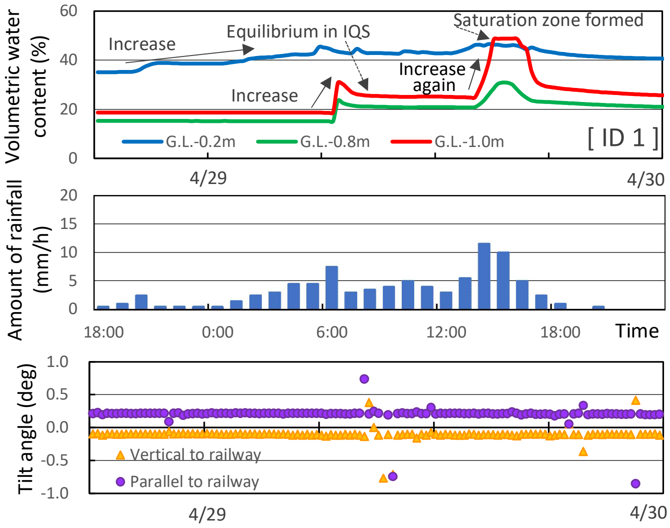

Figure 10: Temporal changes in rainfall, volumetric water content and deformation by inclinometer (Observation site A, 2021/4/29, ID1)

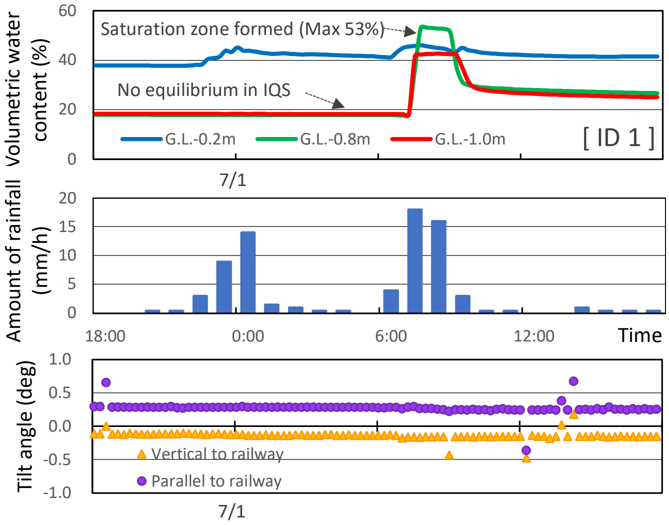

Figure 11: Temporal changes in rainfall, volumetric water content and deformation by inclinometer (Observation site A, 2021/7/1, ID1)

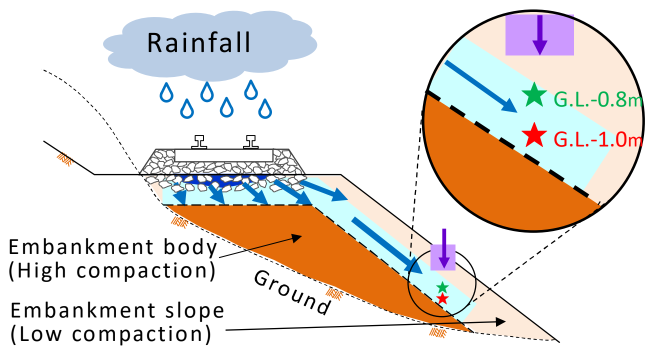

Figure 12: Estimated rainfall infiltration characteristics at the bottom of the railroad track (Observation site A)

clear IQS is observed at G.L. of -0.8 m and G.L. of -1.0 m. Furthermore, the behaviour differs from the schematic diagram in **Figure 1** wherein the infiltration process is assumed in the vertical direction.

With respect to this difference in behaviour, Nakayama et al. (Nakayama et al. 2022) showed that the difference in the amount of water retained in the embankment due to the preceding rainfall can affect the behaviour of volumetric water content, including the presence or absence of equilibrium in IQS. This implies that in the situation where the entire embankment is retaining water due to the preceding rainfall, there is a possibility that the rain that falls on the upper part of the slope, including the railroad track, Infiltrates the embankment slope and flows into ID1 at G.L. of -0.8 m and G.L. of -1.0 m from the side, which is superior to the infiltration in the vertical direction. Hence, the equilibrium state in IQS is not observed. Based on this, **Figure 12** shows the estimated rainfall infiltration characteristics at the bottom of the railroad track.

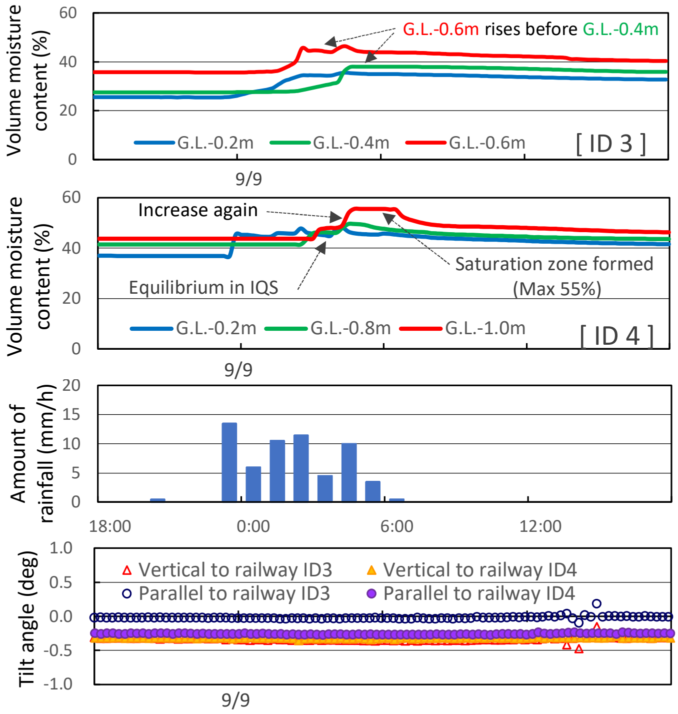

Figure 13: Temporal changes in rainfall, volumetric water content and deformation by inclinometer (Observation site B, 2021/9/9, ID3 ID4)

3.2 Observation site B

Observations from October 1, 2020 to February 28, 2022 show that there are 13 events, in which the volumetric water content at G.L. of -1.0 m of ID4 increases, and 22 events, in which the volumetric water content at G.L. of -0.6 m of ID3 increases. The values of the rain gauge at the observation site are almost the same as the peak rainfall and time of the rain gauge in the neighbourhood owned by the railway company as well as the observation site A. Among them, the behaviour of volumetric water content, which is considered to form a saturation zone after reaching the equilibrium state by IQS (as observed in the model experiment results), is confirmed by ID4. Conversely, for ID3, the behaviour of volumetric water content, which differs from the model experiment result, is observed. This is explained by the observation results on September 9, 2021 shown in **Figure 13**.

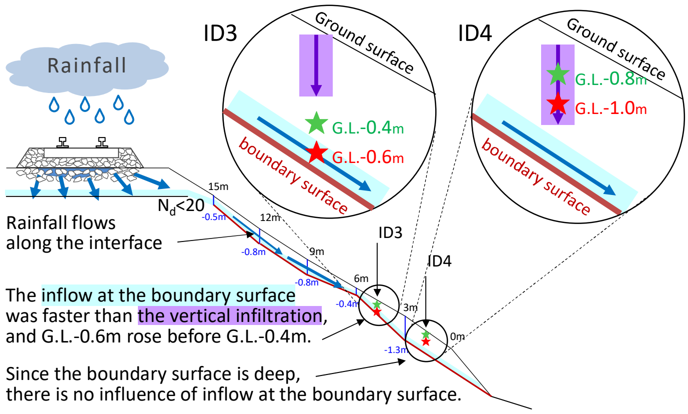

Figure 14: Estimated rainfall infiltration characteristics (Observation site B)

For ID4, the volumetric water content at G.L. of -0.2 m increases due to rainfall. Then, the volumetric water content at G.L. of -0.8 m and G.L. of -1.0 m increases and realizes an equilibrium state, and it is presumed that IQS is realized. Subsequently, the volumetric water content at G.L. of -0.8 m and G.L. of -1.0 m increases again almost simultaneously, and it is inferred that a saturation zone is formed.

For ID3, the volumetric water content at G.L. of -0.2 m increases slowly due to rainfall, and then, the volumetric water content at G.L. of -0.6 m at a high depth increases sharply. Subsequently, the volumetric water content at G.L. of -0.4 m increases, and the behaviour of the volumetric water content differs from the model experiment results wherein observation of vertical infiltration is assumed. Similar behaviour is observed seven times out of 22 events. According to the inclinometer records for the target slope, there was almost less deformation due to all rainfall, as at observation site A.

In this case, as shown in **Figure 14**, it is considered that rainfall, which infiltrates the upper part of the slope, including the railroad tracks, flows in from the side along the vicinity of the surface layer with a small overburden on the upper part of the boundary surface. Furthermore, the volumetric water content at G.L. -0.6 m increases before that at G.L. -0.4 m. At this time, with ID1, the boundary surface is assumed to be near G.L. of -1.3 m. Therefore, it is presumed that the infiltration in the vertical direction is predominant without being affected by the inflow from the side. The conditions for the inflow from the side are assumed as cumulative rainfall, rainfall intensity, and water retention on the slope due to preceding rainfall.

Based on a series of results, behaviour that appears to inflow from the upper part of the slope, including the track to the surface layer of the embankment, is observed at observation sites A and B. However, at the observation site A in the embankment slope, a high-water content zone is infiltrated from the embankment shoulder to the embankment slope. Furthermore, at observation site B, which is close to the ground, it is presumed that rainwater has infiltrates the part that appears to be the boundary surface of the ground. Therefore, it is suggested that it is potentially possible to visualize the difference in rainfall infiltration characteristics due to the difference in ground characteristics.

4. Conclusions

We conducted field monitoring of rainfall and volumetric water content at two sites, where spring water was generated during rainfall and there was a concern about surface collapse. At both sites, a behaviour similar to the infiltration process from the equilibrium state at IQS to the rise of the saturation zone obtained in the results of the model slope experiment was observed. Additionally, in the model slope experiment, inflow from the upper part of the slope (including the track), which was not assumed as an experimental condition, to the surface layer of the embankment was observed. The conclusions were limited, but based on the observation results and ground survey, cases were observed where the difference in permeability due to the compaction of the upper soil structure, including the railroad track, compaction of the embankment, and different stratum composition, affects the time and direction of rainfall infiltration, and it was suggested that the rainfall infiltration characteristics can be visualized. In future studies, we will continue to collect observation data and conduct reproducibility experiments using indoor model experiments, construct a new method to visualize the rainfall infiltration characteristics and quantitatively evaluate the process of destabilization of the surface layer of the railway embankment, and use it for train operation regulation.

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References

Ishikawa,K., Hara,T., Nakayama,T., Koizumi,K.(2022). Behavior of rainfall and moisture content by volume of railway embankments (Part 1 Soil test), *Proceedings of the Japan National Conference on Geotechnical Engineering*, (In printing).

Koizumi,K., Komatsu,M.,Oda,K.,Ito,S.and Tsutsumi,H.(2021). A consideration for evaluating of slope health monitoring during rainfall focusing on volumetric water content, *Journal of Japan Society of Civil Engineers*, Ser. C (Geosphere Engineering), 2021 Volume 77 Issue 2, 129-139.

Kojima,K.(2014). Design and Maintenance of Railway Soil Structures, *Geotechnical engineering magazine*, 62-7(678).

Nakayama,T., Hara,T., Ishikawa,K., Koizumi,K.(2022). Behavior of rainfall and moisture content by volume of railway embankments (Part 2 Field observation), *Proceedings of the Japan National Conference on Geotechnical Engineering*, (In printing).

Nunokawa,O., Sugiyama,T., Mori,T.,Ota,N., Okada,K.(2009). A method of predicting the scale of rainfall-related embankment and cut slope collapse by statistical analysis, *Journal of Japan Society of Civil Engineers*, Ser. C (Geosphere Engineering), Vol.65, No.3, 728-744.