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Economical Measures against Soft Ground at High Embankment on Peaty Ground

Hijiri Hashimoto[1,*], Hirochika Hayashi[1], Atsushi Hirose[2] and Keita Matsuda[3]
[1]Civil Engineering Research Institute for Cold Region, PWRI, Sapporo, Japan, 062-8602; qiaoben@ceri.go.jp
[2]Hokkaido Development Bureau, MLIT, Kushiro, Japan, 085-0816; hirose-a22aa@mlit.go.jp
[3]Hokkaido University of Science, Sapporo, Japan, 006-8585; matsuda-k@hus.ac.jp
*Correspondence: qiaoben@ceri.go.jp

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ABSTRACT Peat, which is considered a special soil, is widely distributed over approximately 2,000 km^2 in Hokkaido, Japan. In terms of engineering properties, peat is extremely high in water content, ignition loss, and void ratio and extremely in low shear strength. Ground improvement methods using cement are effective for the rapid construction of embankments on peaty ground. However, to avoid differential settlement and lateral flow, most of such construction is carried out with an improvement ratio of ap=50%. In this case, the improvement can certainly be expected to be effective. However, it is less economical than other soft ground improvement methods. The challenge is to reduce the cost of improving the ground. Our institution (the Civil Engineering Research Institute for Cold Region, PWRI) has developed an economical measure against soft ground that uses cement with a reduced improvement ratio in combination with a crushed-stone mat (gravel foundation reinforcement), and we conducted the test construction of a 16-meter-high embankment to verify effectiveness of the method. The crushed-stone mat consists of a 50-cm layer of crushed stone covered with a geo-synthetic material. The test construction achieved the following results. (1) Settlement of the embankment was significantly reduced. (2) Slip failure did not occur. (3) Displacement to the surrounding ground did not occur. (4) The geotextile in the crushed-stone mat exhibited less strain than that which would cause the geo-synthetic to exceed its design strength. These results show that this economical measure against soft ground was effective at stabilizing the high embankment constructed on peaty ground.

KEYWORDS Peat; High Embankment; Soft Ground Measures; Crushed Stone Mat; Geo-synthetics

1 INTRODUCTION

Peat is widely distributed in Hokkaido, Japan (Figure 1 and Photo 1). Because peaty ground has high compressibility and very low shear strength, the road surface at a road embankment built on such ground is prone to uneven or differential settlement from sliding failure or consolidation settlement in the foundation ground. Thus, solidification methods utilizing cement or other solidifiers are often used because they enable the road to promptly enter service (Hayashi & Nishikawa, 1999; Hayashi et al, 2018).

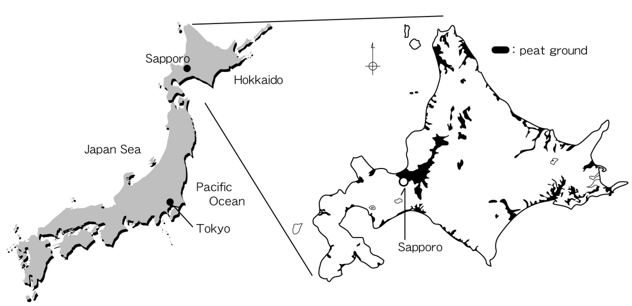


Figure 1. Peat distribution in Hokkaido

Photo 1. Fibrous peat in Hokkaido

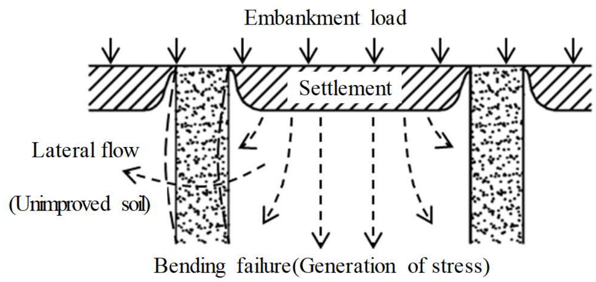


Figure 2. Problems associated with soil improvement with a low improved ratio

In the case of cylindrical cement improvements by the solidification, the design typically calls for the average strength of improved soil (i.e. the soil of solidified columns) and of the soil to be the strength of entire soil, i.e., the composite ground. Noto (1994) and Noto (1991) reported that when the improved ratio (i.e., the improvement area as a percentage of the total area) is lowered, the horizontal force resulting from the settlement of unimproved soil and the minor non-uniform load can lead to the failure of the improved soil columns (Figure 2). Based on that report and on experience, the minimum standard improved ratio for peaty ground has been set as 50 % ($a_p \geqq 50$ %). At or above this improved ratio, the entire area to be improved can be regarded as composite ground.

However, increases in the scale of soil improvement work lead to greater construction costs. To address this cost issue, the Civil Engineering Research Institute for Cold Region developed an economical soil improvement method that uses a lower improved ratio than the conventional standard in combination with a crushed stone mat (hereinafter: 'the new method') (Hashimoto et al, 2015; Hashimoto et al, 2018). It helps control construction costs while addressing the issue of failure of improved soil columns. This paper reports on field observations of the new method, which was applied as a remedial measure for soft ground at a high embankment (16 m) built on peaty ground.

2 OUTLINE OF THE NEW METHOD

Figure 3 is a schematic of the new method. In this method, a crushed stone mat is placed on ground that has been improved by the improved soil columns at an improved ratio of lower than 50 %. The crushed stone mat is a layer of crushed stone that is 0.5m thick as a standard (t = 0.5 m) and is wrapped in geo-synthetics. When an embankment is built on such a crushed stone mat, settlement of the embankment restrained with the crushed stone enclosed in the geo-synthetics. Additionally, the shear rigidity at the bottom of the embankment increases due to the tension of the geo-synthetics. Consequently, sliding failure of the embankment and differential settlement of the road surface can be prevented. Furthermore, the lateral flow of un-improved soil, which is a problem with soil improvement that uses a low improved ratio, is expected to be controlled.

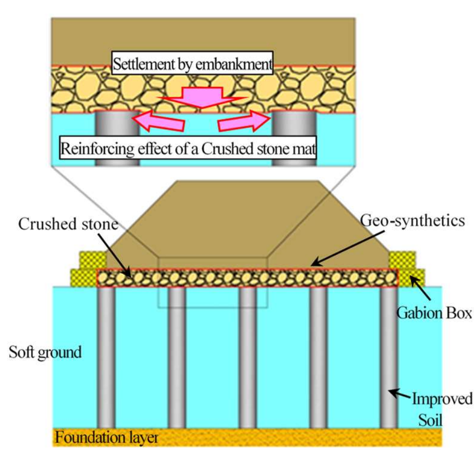


Figure 3. A soil improvement method that uses a low improved ratio in combination with a crushed stone mat

3 OUTLINE OF EXECUTION

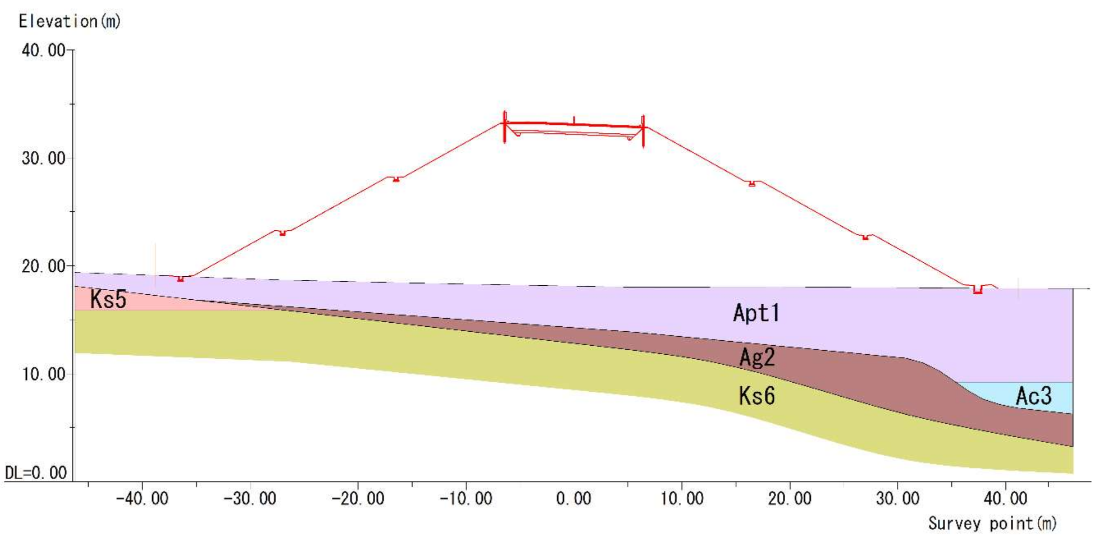
3.1 Ground and Execution Conditions

Figure 4 shows the ground conditions of the construction site. On the diluvia sand layer that slopes down toward the right-hand side of the embankment, an alluvial sand layer and a peat layer are distributed. The peat layer is 2 m thick at the slope toe on the left-hand side, and this layer thickens toward the right to reach 9 m at the right-hand slope toe. The natural water content (wn) of the peat layer is high, at 460 %, and the soil distributed from the surface layer to the depth of 3 m is very soft, with a cohesion (c) of 5 kN/m^2.

3.2 Design Conditions of the New Method

In designing the new method, the following points were examined: the stability of the embankment in light of the potential for sliding failure of the foundation ground, and the compressive failure of the improved soil from the embankment load. Regarding the stability of the embankment, based on a manual of remedial measures for soft peaty ground, the tensile strength of geo-synthetics was determined such as to ensure a safety factor against sliding (Fs) of at least 1.2 at embankment completion. Specifically, the design tensile strength (T_A) was set at 537 kN/m.

Usually, the design strength of soil in a solidification method is determined on the assumption that the embankment load will be concentrated at the heads of the improved soil columns. But this assumption is valid only when an embankment is built directly on improved soil columns. Thus, the authors consider that when a crushed stone mat is installed on top of improved soil columns, embankment load imposes on the improved soil columns should be smaller than when no crushed stone mat is installed. Therefore, we adapted q_{uck} = 570 kN/m^2 for the improved strength and a_p = 35 % for the improved ratio. These values have been obtained through analytical evaluation.



Groundwater level GL- (m)	Soil layer	Symbol	Depth z (m)	Thickness H (m)	N-Value N (回)	Natural water content Wn (%)	Unit weight γt (kN/m^3)	Cohesion C (kN/m^2)	Angle of shear φ (°)	Shear strength rate m
0.00	Peat	Apt	3.00	3.00	0	460	10.5	5.0	–	0.40
			8.80	5.80				2.5z	–	
	Cohesive soil	Ac3	11.20	2.40	4	80	15.0	2.5z	–	0.35
	Sandy soil	Ag2	–	–	7～24	–	19.0	–	36	–
	Sandy soil	Ks5	–	–	–	–	18.0	–	38	–
	Sandy soil	Ks6	–	–	15～48	–	18.0	–	38	–

Figure 4. Cross-section of the soil layers at the construction site

3.3 Measurement Device Installation

The installation locations for the measurement devices are shown in Figure 5. Settlement plates are needed in order to control settlement caused by embankment construction. Seven settlement plates were installed at the center and the top/face/toe of the slope on the embankment whose soil had not been improved; three settlement plates were installed on the center and the top of the slope on the embankment, immediately above improved soil columns, and one piezometer was installed. To check the soil displacement at the slope toe, the settlement of the gabion boxes at the right and left ends of the embankment was measured. Twelve strain gauges were installed to determine the distribution of strain in the geo-synthetics on the upper and lower surfaces of the crushed stone mat. To clarify how the embankment load acts on the improved soil columns and the unimproved soil, two earth pressure gauges were placed on the unimproved soil and four earth pressure gauges were placed directly on the improved soil columns.

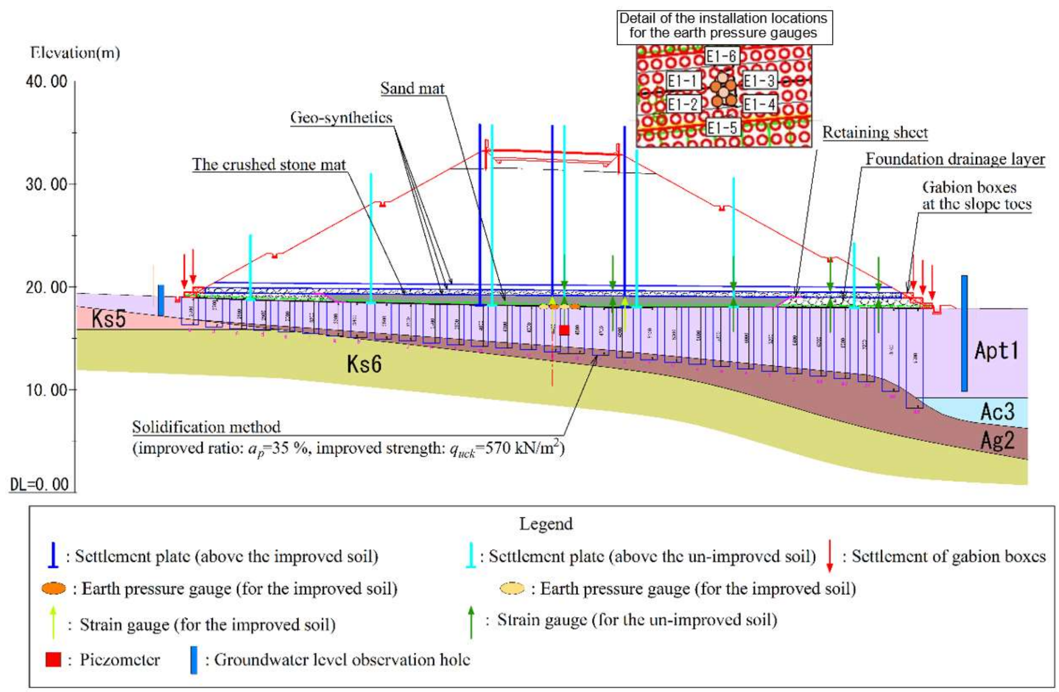


Figure 5. Schematic of remedial work for soft ground utilizing the new method and installation of measurement devices

Additionally, one hole was bored at the right toe and another at the left toe to record the groundwater level, in order to clarify the effects of the embankment on the surface water and groundwater.

4 FIELD OBSERVATION RESULTS

4.1 Settlement and Displacement in the Surrounding Ground

Figure 6 shows temporal changes in the settlement of the improved soil columns, unimproved soil, and gabion boxes. The settlement of the improved soil and unimproved soil progressed during embankment construction, but it stopped immediately once construction was discontinued.

Figure 7 shows a cross-section of settlement. Settlement is greatest in the central area and at the top of the slope, decreasing toward the slope toes. On December 10, 2022, the final day of measurement, the settlement of the improved soil columns under the crest of embankment measured 51.1~55.5 cm, similar to or slightly greater than the 44.9~52.5 cm settlement of the unimproved soil. The N-value on the upper side of the Ag2 layer was 7, indicating soft ground, so it was presumed that the Ag2 layer experienced compressive settlement due to the embankment load imposed via the improved soil. During embankment construction, no settlement of gabion boxes installed at the slope toes was confirmed. Thus, the new method is fully expected to be effective in controlling the deformation of the surrounding ground that results from embankment construction.

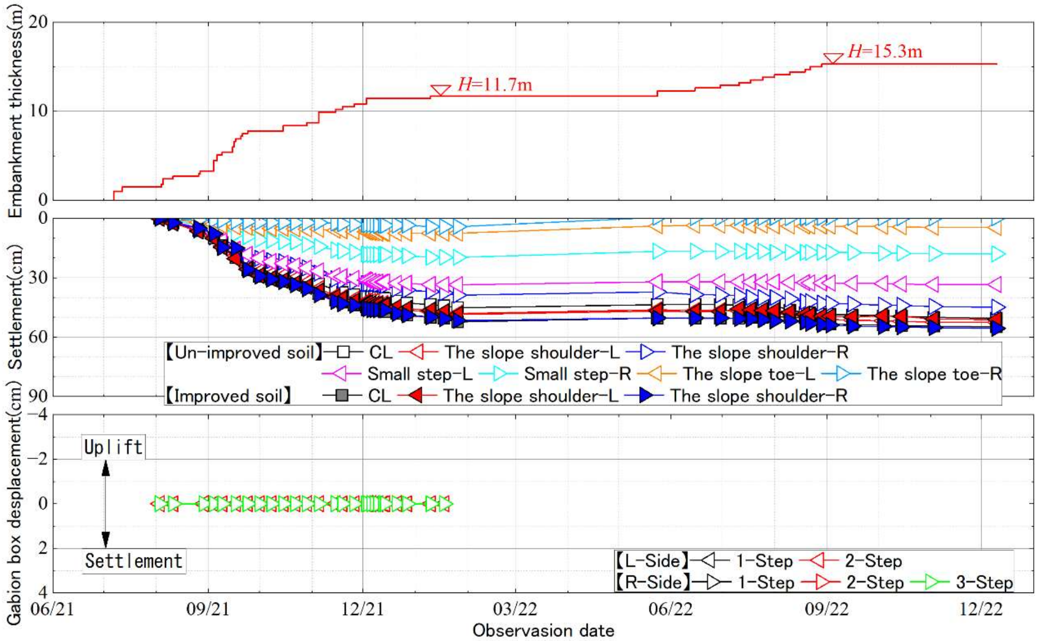


Figure 6. Temporal changes in the settlement of the improved soil, the un-improved soil and the gabion boxes

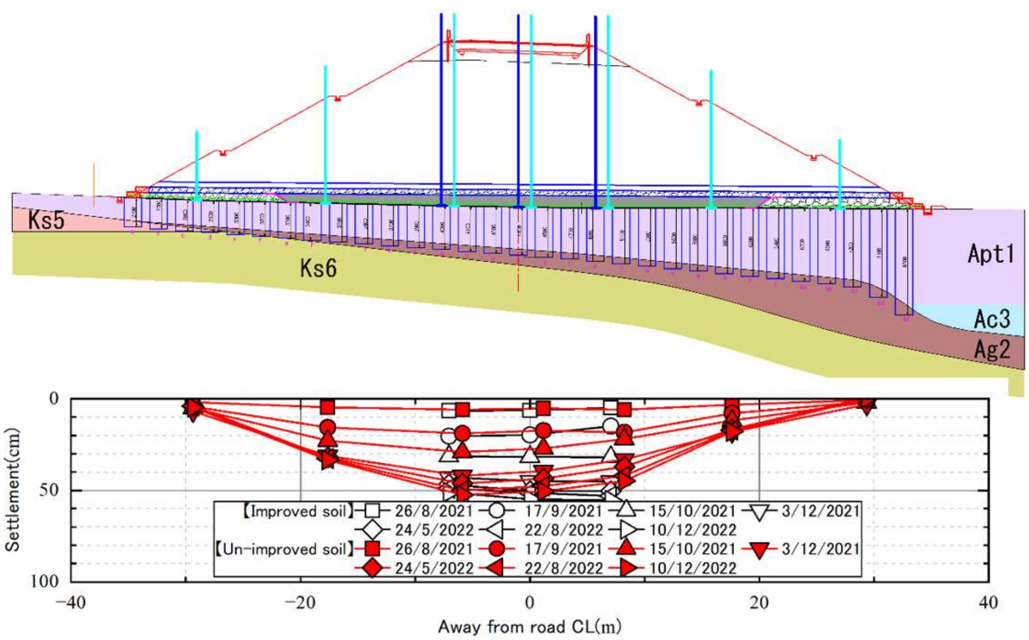


Figure 7. Cross section of the settlement of the improved soil and the un-improved soil

4.2 Pore Water Pressure

Figure 8 shows temporal changes in the pore water pressure at a depth of 1.5 m in the peat layer under the central part of the embankment. The water pressure in that area increased slightly, but it decreased immediately after the embankment was completed. It is probable that the peat layer did not experience significant stress because the crushed stone mat, which served as a simple beam supported by improved soil columns, bore the embankment load.

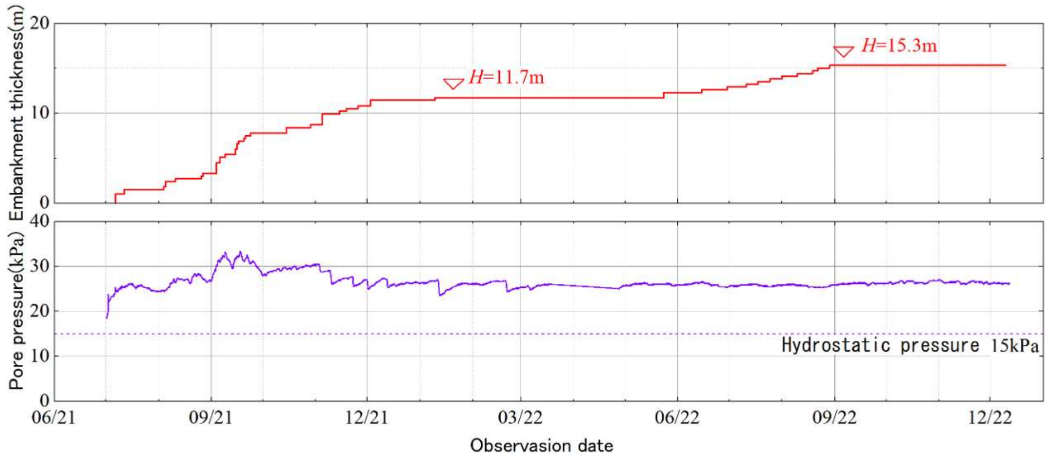


Figure 8. Temporal changes in the pore water pressures in the peat layer

4.3 Strain the Geo-Synthethics

Figure 9 shows the temporal changes in strain at the upper and lower surfaces of the geo-synthetics. In the initial phase of construction, the strain hardly increases with increase in embankment load. Once the embankment exceeds 10 m in height, strain begins to develop on the upper and lower surfaces of the geo-synthetics. When the embankment construction height exceeds 13 m, significant increases in strain are observed on the lower surface of the geo-synthetics, just below the crest of embankment.

Under the embankment crest, the improved soil columns settled. At the beginning of embankment construction, the improved soil columns and the crushed stone mat settled together; thus, the geo-synthetics did not exhibit strain. However, once the embankment exceeded 13 m in height, the bottom of the columns reached the Ag2 layer (the load-bearing layer). Thorough the crushed stone mat, the embankment load acted on the tops of the improved soil columns and on the top of the unimproved soil areas. Because the columns were supported by the Ag2 layer, they did not settle, but the unimproved soil did settle. This caused strain in the lower surface of the crushed stone mat. Thus, the geo-synthetics that were set on the lower surface of crushed stone mat exhibited strain.

4.4 Vertical Earth Pressure on the Soil Improved Soil and the Un-improved Soil

The bottommost chart in Figure 9 shows temporal changes in the vertical earth pressure on the improved soil columns and the unimproved soil. The vertical earth pressure on the unimproved soil remains largely unchanged with increases in embankment load. A slight increase is observed for the earth pressure gauges E1-2 and E1-4 installed on the improved soil columns. Measurements from E1-3 show that the vertical earth pressure gradually increases after the start of embankment construction and begins to rapidly increase once the embankment height exceeds 13 m.

Because the improved soil columns on which E1-1 and E1-3 were installed did not settle, the embankment load was not imposed on these improved soil columns. However, the improved soil columns beneath E1-2 and E1-4 subsided; thus, it is likely that these gauges failed to accurately measure the earth pressure. The values measured by E1-1 and E1-3 are taken as true values and are used for the analysis of the embankment load that was imposed on the improved soil columns.

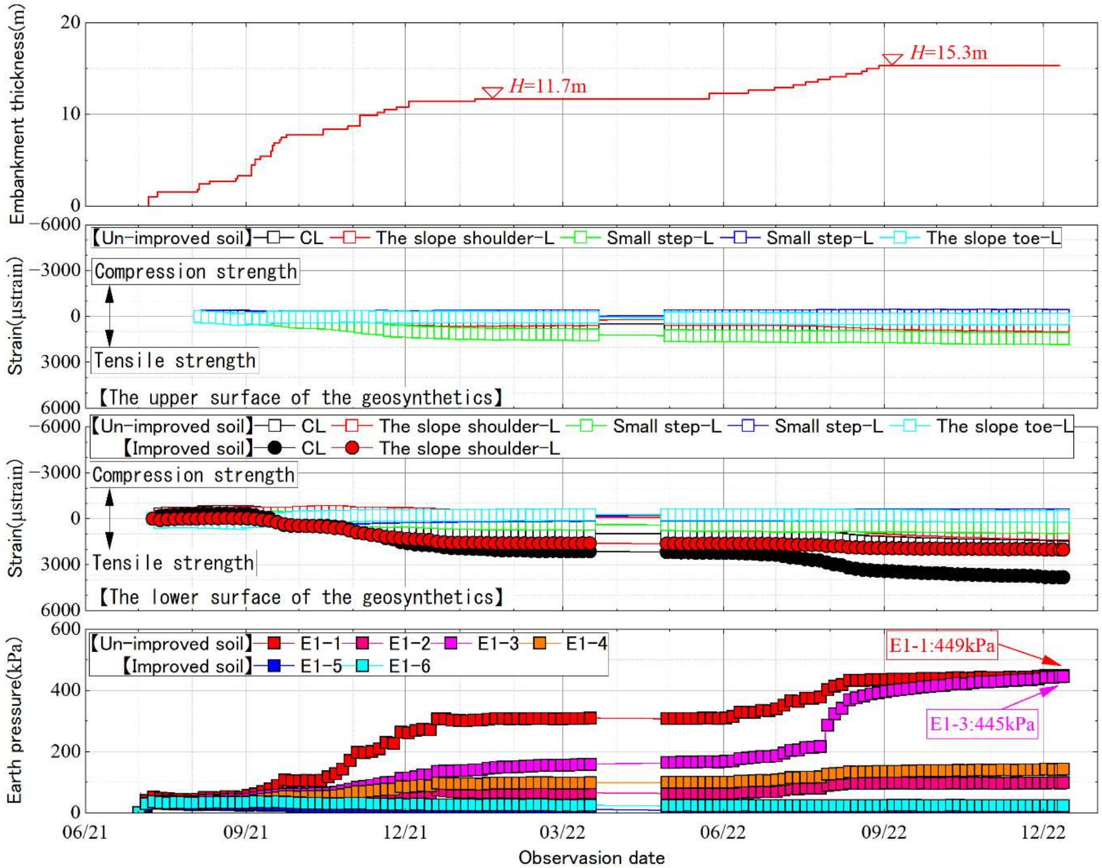


Figure 9. Temporal changes in the strain of the upper and lower surfaces of the geo-synthetics and in the vertical earth pressure on the improved soil and the un-improved soil

The design strength of the improved soil columns was determined on the assumption that these improved soil columns and the unimproved soil would be subjected to embankment load. However, it is presumed that the embankment load did not act on the unimproved soil, because the pore water pressure increased only slightly in the peat layer after the embankment was completed. Thus, on the assumption that the embankment load was acting only on the improved soil columns, the improved strength was calculated by using Equation (1).

$$q_{uck} = F_s \cdot \frac{\gamma_t \cdot H}{a_p} \quad (1)$$

In Equation (1), q_{uck} is the improved strength (kN/m^2), F_s is the safety factor (=1.0), γ_t is the unit weight of embankment material (kN/m^3), H is the embankment height (m), and a_p is the improved ratio.

The improved strength calculated by Equation (1) is 762 kN/m^2 (q_{uck}=762 kN/m^2). This means that 762 kN/m^2 of load was imposed on the improved soil columns. However, the vertical earth pressure imposed on the improved soil columns was 445~449 kPa, less than the embankment load of 762 kN/m^2. The embankment height with a strength corresponding to the improved strength of 445~449 kPa is 9.1 m, as calculated by using Equation (1).

This result was obtained probably because the embankment load was dispersed due to the rigid crushed stone mat that was placed beneath the bottom of the embankment, thus reducing the vertical earth pressure on the improved soil columns. In considering the maximum earth pressure imposed on the improved soil columns, the load acting on those columns should be addressed under the assumption of a uniformly distributed load that is equivalent to the load imposed by an embankment with height of 9.1 m exerted on the crushed stone mat (Figure10).

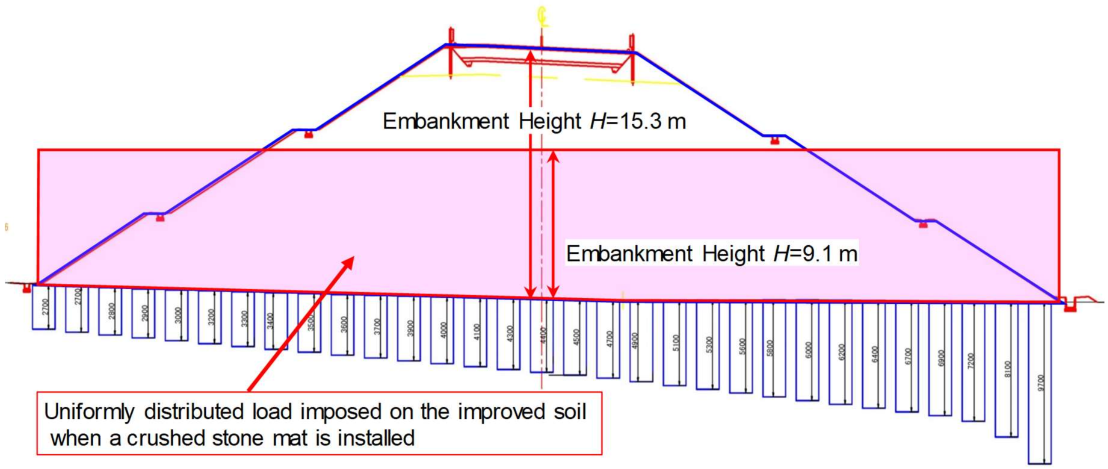


Figure 10. Load imposed on the improved soil when a crushed stone mat is installed

However, the settlement at the slope toes and the cross-sectional distribution of vertical earth pressure have not been clarified. These will be examined in the future.

4.5 Groundwater Level

Figure 11 shows the temporal changes in groundwater level at the slope toe on the left-hand side and the right-hand side. Hourly rainfall recorded by meteorological equipment installed near the construction site is also shown. At the left-hand slope toe, the groundwater level remains largely unchanged during and after the embankment construction. At the right-hand slope toe, the groundwater level increases by only 10 cm.

Thus, it was confirmed that the new method did not affect the flow of surface water or groundwater transverse to the embankment.

5 CONCLUSION

An economical remedial measure for soft ground was adopted for the construction of a 16 m-high embankment on peaty ground. The findings of field observations regarding this measure are stated below.

a) Because no settlement was observed for either of the gabion boxes installed on the slope toes, the new method is fully expected to control the deformation of the ground surrounding the embankment.
b) Excess pore water pressure in the unimproved soil increased only slightly during embankment construction. It is probable that the embankment load was imposed on the improved soil columns through the crushed stone mat.
c) In the initial phase of construction, the increase in embankment load did not lead to the development of strain in the geo-synthetics, but when the embankment construction exceeded the height of 13 m, a significant increase in strain at some locations was observed on the lower surface of the geo-synthetics. It is likely that because the improved soil columns did not settle as they were supported by the Ag2 layer, or the bearing layer, the crushed stone mat mainly supported the increased load of the embankment that exceeded 13 m height.
d) It was confirmed that the vertical earth pressure imposed on the improved soil columns was lower than the design value. The vertical earth pressure was significantly lower than the improved strength determined on the assumption that the embankment load would be fully imposed on the improved soil. This result can probably be attributed to the dispersal of the

embankment load just below the embankment crest due to the rigid crushed stone mat that was installed beneath the bottom of the embankment, thus reducing the vertical earth pressure on the improved soil columns.

e) The groundwater level at the slope toes of the embankment remained unchanged during and after embankment construction. It was confirmed that the new method would not affect the flow of surface water and groundwater.

The new method is a very effective remedial measure for soft ground, because it helps stabilize an embankment built on peaty ground, controls deformation of the surrounding ground, and has a low impact on groundwater.

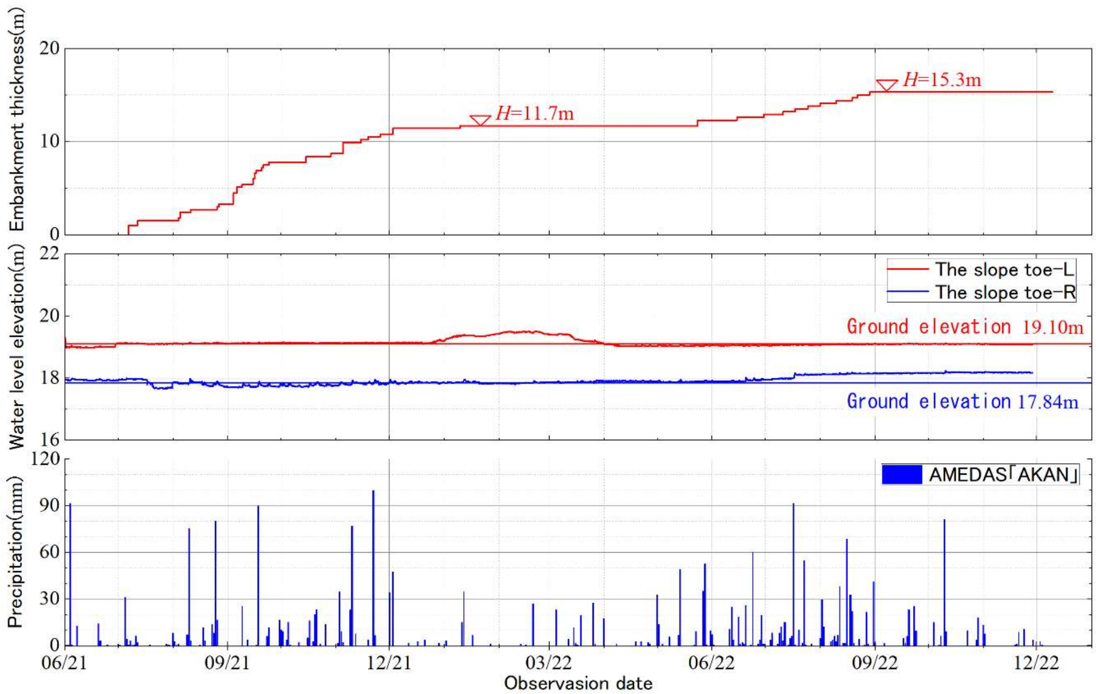


Figure 11. Temporal changes in groundwater level in un-improved soil around the embankment

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