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Study on condition assessment of embankments settled in peaty ground by using geophysical exploration

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Abstract. In Hokkaido, peaty ground is widely distributed, and it's estimated that there's a considerable amount of road embankment constructed and used on such ground. Peaty ground have extremely low undrained shear strength and high compressibility. When embankments are constructed on peaty ground that have been improved by surcharge method, accelerated consolidation method, the embankments are settled in the peaty ground over time, and a part of the embankment that's settled below the groundwater level becomes saturated. When road embankments made of liquefiable embankment materials such as sandy soil are subjected to seismic motion, the embankment itself liquefies, leading to major collapse. Therefore, it's important to determine the distribution and thickness of saturated embankments continuously and extensively from the viewpoint of maintenance and management of road embankments. Therefore, in this study, we conducted geophysical surveys with the aim of obtaining distribution of ground conditions simply and continuously. The results of the comparison and verification between geophysical surveys and conventional ground investigation methods are described, as it was found that the boundary between the bottom of the clay embankment and the top of the peat layer could be evaluated by supplementing the point information.

1 Introduction

Soft peaty ground is widely distributed in Hokkaido, and numerous road embankments are in use on such ground there. Peaty soils exhibit much lower undrained shear strength and higher compressibility than other soils. When embankments are constructed on peaty ground, they sink deep into the peat layer. The portions of the embankment that sink below the groundwater level become saturated. It is known that when seismic motion acts on road embankments that have been constructed with liquefaction-prone materials (e.g., sandy soil), the embankment itself can undergo liquefaction, leading to major collapse [1, 2].

It is estimated that a considerable length of road embankments in Hokkaido have sunk into peat soil. From the perspective of road embankment maintenance and management, it is considered important to comprehensively and continuously identify the saturated embankment sections that have sunk in peat soil and to evaluate these sections for liquefaction risk.

This study used geophysical surveys to determine the following: (1) the water level within the embankment, and (2) the boundary between the embankment base and the underlying peat layer.

2 Survey sites

The surveys were conducted at two locations. Site 1 features a cohesive soil embankment constructed on soft peaty ground; Site 2 has a sandy embankment constructed on soft peaty ground. Since the embankments at the study sites were constructed for the purpose of establishing snow-break forests, no measures were taken to address the soft ground conditions. Site 1 consists of an embankment constructed at a rate of 3.0 cm/day to a required thickness of Ht = 2.5 m, while Site 2 consists of an embankment constructed at a rate of 5.0 cm/day to a required thickness of Ht = 2.8 m. Field surveys and sampling were conducted approximately one year after the completion of embankment construction at Site 1 and approximately two years after completion at Site 2.

3 Survey method

Fig. 1 shows the plan views of the survey Site 1 and Site 2. This study employed geophysical surveys to compare and evaluate information on the embankment and the peat ground obtained through conventional soil investigation methods. The conventional ground investigation methods included boring, testing by standard penetration test (SPT), and electrical logging. Groundwater levels were measured using manual water level gauges.

Electrical logging was conducted in a borehole at the center of the embankment in accordance with the Japan Geotechnical Society Standard (JGS1121) [3]. (Fig. 1), and the depth-dependent resistivity ρ_T was measured. The purpose of the electrical logging was to compare the

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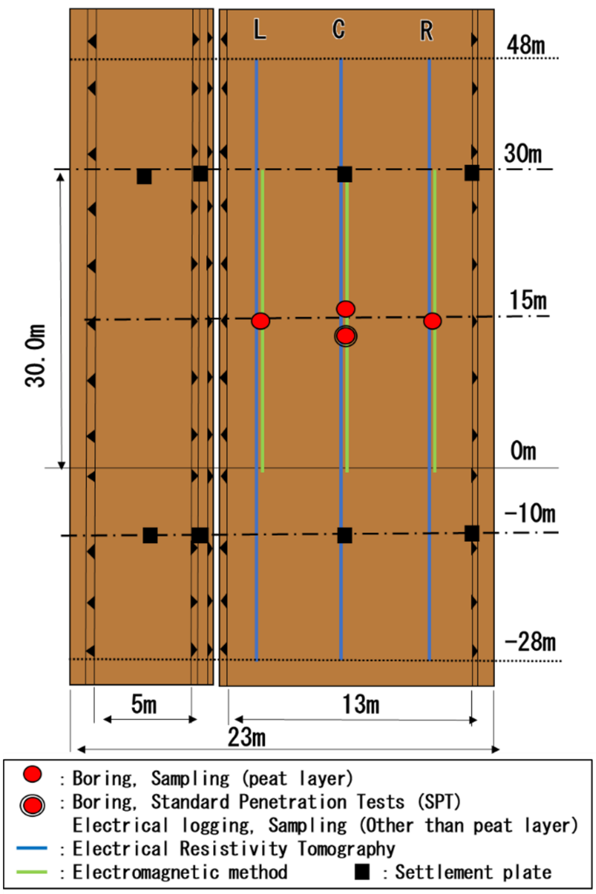


Fig. 1. Plan view of Sites 1 and 2.

penetration resistance and physical properties of the fill and peat layers obtained from boring and SPT with the results of the geophysical surveys (electrical resistivity tomographic survey, electromagnetic (EM) surveys) described later.

The electrical logging was performed using micro-logging, in which electrodes were pressed against the borehole wall; measurements with an electrode spacing of a = 5.0 cm were evaluated. Since electrical logging involves passing a current through the borehole water and measuring the potential, its general scope of application is considered to be below the groundwater table) [3]. However, in this study, the boreholes were filled with borehole water even in the unsaturated fill section (fill below the groundwater table); therefore, the ground level of the borehole in the center of the fill was set to G.L. = 0 m, and the area was included in the evaluation regardless of the presence or absence of groundwater.

The geophysical surveys included an electrical resistivity tomographic survey and the electromagnetic (EM) surveys. These were conducted along three survey lines (Line L, Line C, Line R) in the longitudinal direction of the embankment. Boring was conducted at the midpoint of a 30-m section on each survey line. The apparent resistivity obtained from electrical logging is denoted as ρ_T, while the resistivities obtained from the electrical and EM surveys are denoted as ρ_a and ρ_e, respectively. This study treats apparent resistivity and resistivity as synonymous.

EM surveys were conducted using the loop-loop method. For depths of 5 m or less, a single-loop system was used, while for depths greater than 5 m, a dual-loop system was employed. For measurements using the single-loop system, the GENICS EM31 (frequency 9.8 kHz) was used. For measurements using the split-loop system, a GENICS EM34 was used, with loop spacings of 10 m (frequency 6.4 kHz) and 20 m (frequency 1.6 kHz). Data was acquired at 1.25-meter intervals.

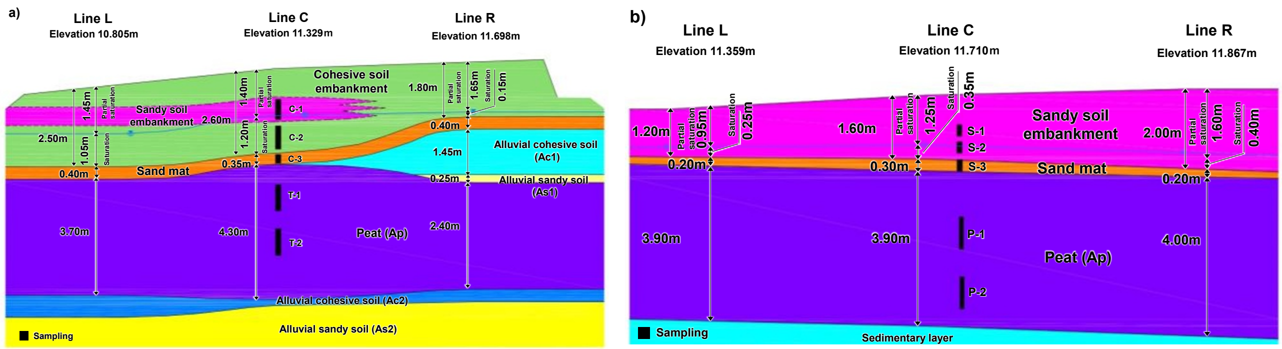
4 Results

4.1 Stratigraphic composition and soil properties of the embankment and the peat layers

4.1.1 Site 1 (cohesive soil)

Fig. 2(a) shows the soil stratigraphic composition at Site 1 (cohesive soil). Fig. 3(a) presents the results of the soil investigation at Site 1 (cohesive soil). Table 1 lists the physical properties of the embankment and the peat layers at Sites 1 and 2.

The resistivity ρ_T at Site 1 (cohesive soil) shows no significant difference between the saturated versus unsaturated conditions. The resistivity ρ_T of the sand mat is approximately ρ_T = 30 Ω·m. No significant differences in resistivity ρ_T are observed between the sand mat and the layers immediately above and below it. The resistivity ρ_T is higher for each peat layer than for the embankment.



(a) Site 1 (cohesive soil)

(b) Site 2 (sandy soil)

Fig. 2. Embankment layer and peat layer composition at each site during the investigation (based on the boring results).

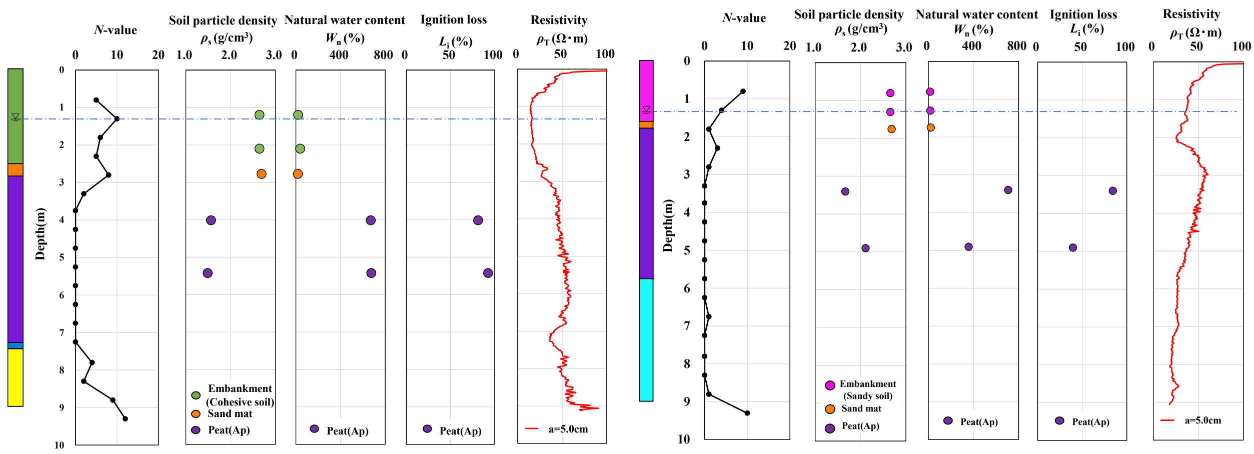


Fig. 3. Results of soil investigation for each embankment.

Table 1. The physical properties of the embankment and peat layers at each site.

				Site1					Site2				
				Embankment			Peat		Embankment			Peat	
Soil layer symbol				C-1	C-2	C-3	T-1	T-2	S-1	S-2	S-3	P-1	P-2
Depth of sampling(m)				0.80～1.60	1.60～2.60	2.60～2.95	3.60～4.43	5.00～5.85	0.65～0.95	1.15～1.45	1.60～1.90	3.00～3.80	4.50～5.30
General	Soil particle density	ρ_s	(g/cm³)	2.643	2.641	2.689	1.561	1.489	2.657	2.656	2.685	1.662	2.111
	Natural water content	w_n	(%)	20.7	39.4	18.8	671.1	676.2	15.6	17.1	21	706.9	356.7
	Void ratio	e		0.704	1.362	0.609	-	-	-	-	-	-	-
	Porosity	n	(%)	41.31	57.66	37.85	-	-	-	-	-	-	-
	Degree of saturation	S_r	(%)	82.6	99.5	73.7	-	-	-	-	-	-	-
Gradation	Gravel fraction		(%)	2.6	0.1	0	-	-	9.9	9.9	1.1	-	-
	Sand fraction		(%)	70.7	23.4	97.7	-	-	77.3	74.9	96.1	-	-
	Silt fraction		(%)	16.9	46.8	1.3	-	-	8.6	9.1	1.9	-	-
	Clay fraction		(%)	9.8	29.7	1.0	-	-	4.3	6.1	0.9	-	-
	Fine fraction content	F_c	(%)	26.7	76.5	2.3	-	-	12.8	15.2	2.8	-	-
	Uniformity coefficient	Uc		36.6	-	2.2	-	-	8.6	16	1.9	-	-
Consistency	Liquid limit	w_L	(%)	37.8	61.0	NP	-	-	NP	NP	NP	-	-
	Plastic limit	w_p	(%)	21.7	26.5	NP	-	-	NP	NP	NP	-	-
	Plasticity index	I_p		16.1	34.5	-	-	-	-	-	-	-	-
	Ignition loss	L_i	(%)	-	-	-	81.3	92.6	-	-	-	84.2	39.6
Classification	Geomaterials Classification Name			Clayey sands (SCs)	Sandy clay (CHS)	Poorly graded Sand (SP)	Peat (Pt)	Peat (Pt)	Sand with clayey gravel (S-CsG)	Clayey sands with gravel (SCs-G)	Poorly graded Sand (SP)	Peat (Pt)	Peat (Pt)

4.1.2 Site 2 (sandy soil)

Fig. 2(b) shows the soil layer composition for Site 2 (sandy soil). Fig. 3(b) presents the results of the soil investigation at Site 2 (sandy soil).

The ρ_T values obtained from electrical logging show no clear boundaries between the unsaturated embankment section, saturated embankment section, and sand mat layer. The ρ_T of the peat layer tends to decrease with increases in depth.

4.2 Resistivity distribution captured by electrical resistivity tomography

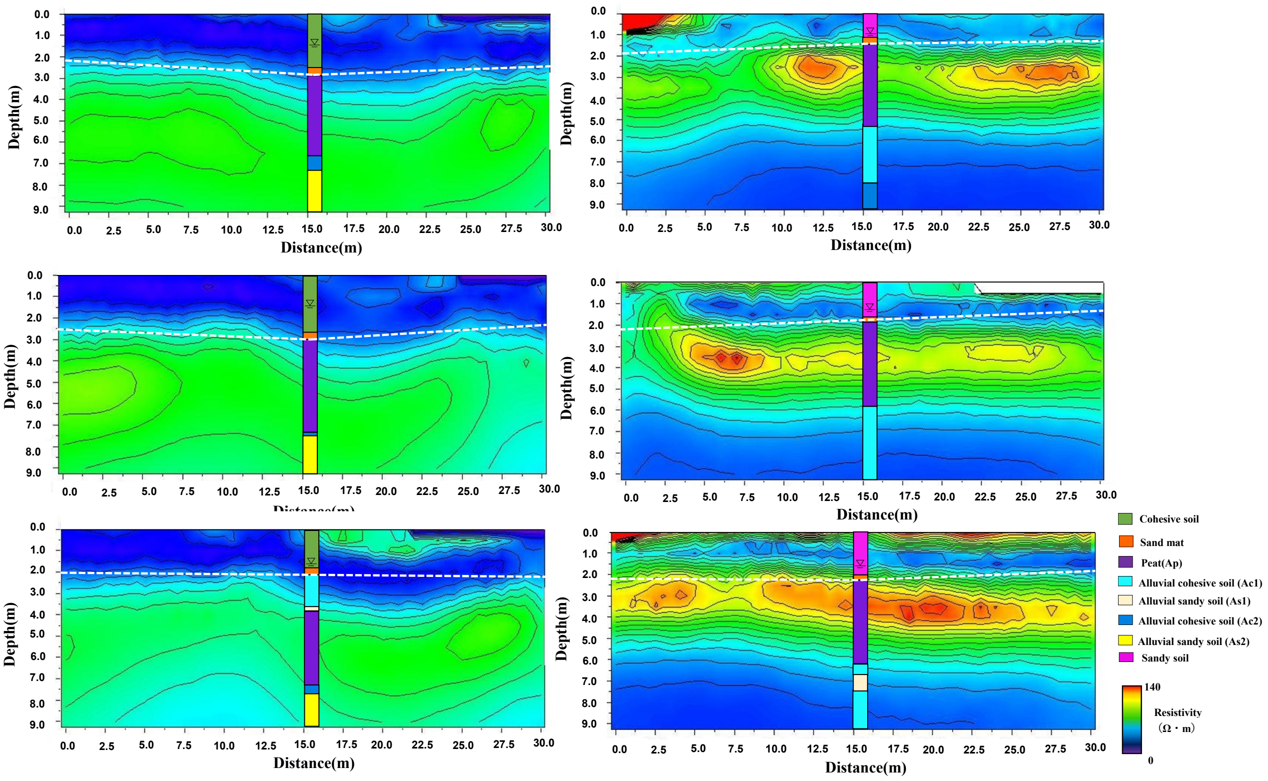
Fig. 4(a) shows the results of electrical resistivity tomographic surveys conducted at Site 1 (cohesive soil) to obtain ρ_a, while Fig. 4(b) shows the results for Site 2 (sandy soil). Fig.s 4 and 5 show the locations of settlement plates installed at measurement points (directly below the sand mat = top surface of the peat layer) and the estimated top surface of the peat layer based on the results of the boring survey, indicated by dashed white lines.

4.2.1 Resistivity distribution at Site 1 (cohesive soil)

In Fig. 4(a), the ρ_a within the embankment at Site 1 (cohesive soil) is ≤ 30 Ω·m regardless of whether the condition is saturated or unsaturated. The ρ_a of the sand mat does not significantly differ from that of the embankment base immediately above the mat nor from that of the top surface of the peat layer below the mat. The ρ_a of the peat layer ranges from 40 to 100 Ω·m on all survey lines, confirming generally higher resistivity zones than that of the embankment (cohesive soil).

4.2.2 Resistivity distribution at Site 2 (sandy soil)

In Fig. 4(b), the ρ_a of the embankment within Site 2 (sandy soil) shows different trends across the three survey lines. Line L shows a high resistivity zone with ρ_a ≥ 160 Ω·m in some areas, but its overall ρ_a ranges from 30 to 50 Ω·m. Line C exhibits a two-layer structure: ρ_a = 70 to 130 Ω·m at depths around 0.0 to 1.0 m and 30 to 60 Ω·m at depths around 1.0 to 2.0 m. A two-layer structure similar to that observed on Line C is also observed on Line R, however, along Line R, ρ a is 80-160 Ω·m at depths of approximately 0.0-1.0 m,



(a) Site 1 (cohesive soil) (b) Site 2 (sandy soil)

Fig. 4. Distribution of resistivity ρ_a from electrical resistivity tomography (from top: the embankment's left shoulder survey line (Line L), center survey line (Line C), and right shoulder survey line (Line R)).

indicating that the specific resistance is higher in the shallow layer. The ρ_a of the sand mat is ≤ 60 Ω·m for Lines L and C, and ≤ 80 Ω·m for Line R. The resistivity of the peat layer ranges from ρ_a = 70 to 160 Ω·m, confirming a relatively higher resistivity zone than that of the embankment.

4.3 Resistivity distribution captured by EM survey

Fig. 5(a) shows the resistivity results from the EM survey conducted at Site 1 (cohesive soil), and Fig. 5(b) shows the results for Site 2 (sandy soil).

4.3.1 Resistivity distribution at Site 1 (cohesive soil)

In Fig. 5(a), the resistivity within the embankment at Site 1 (cohesive soil) is ρ_e ≤ 30 Ω·m regardless of saturation status. The resistivity ρ_e of the sand mat shows no significant difference compared to those of the lower part of the embankment above the mat or the upper part of the peat layer below the mat. The resistivity of the peat layer is ρ_e = 30 to 70 Ω·m. It is confirmed that the resistivities ρ_e of the peat layer fall in a higher range of resistivities than those of the embankment (cohesive soil).

4.3.2 Resistivity distribution at Site 2 (sandy soil)

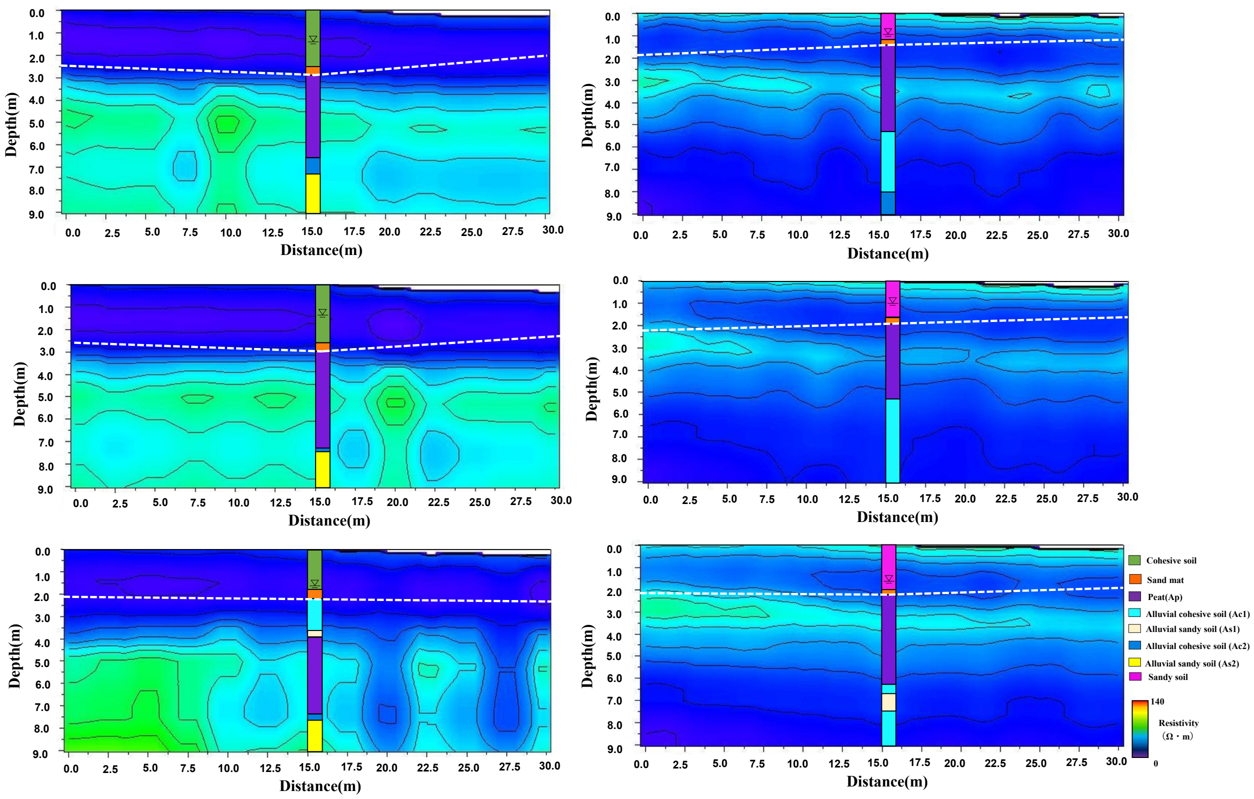
In Fig. 5(b), the resistivity within the embankment at Site 2 (sandy soil) shows no significant differences between survey lines. The resistivity of the peat layer is ρ_e = 10 to 30 Ω·m across all survey lines. The resistivity of the peat layer is ρ_e = 10 to 50Ω·m, and no significant difference is observed between the embankment and the peat layer.

5 Discussion

Based on the results in Chapter 4, we will examine whether the first objective of this study—(1) [determining] the water level within embankments buried in peat layers—and the second objective (2)—[determining] the boundary between the embankment base and the upper peat layer—can be achieved using geophysical surveys.

5.1 The water level within embankments buried in peat layers

Regarding the results of the electrical survey (Fig. 4), when examining the saturated and unsaturated sections of the fill using the measured water levels at the borehole locations (Fig. 3) as a boundary, no difference in ρa was observed regardless of the fill material. Similarly, the results of the EM survey showed no difference in electrical conductivity between the



(a) Site 1 (cohesive soil) (b) Site 2 (sandy soil)

Fig. 5. Conductivity distribution captured by EM survey (from top: the embankment's left shoulder profile, center profile, and right shoulder profile).

saturated and unsaturated sections of the embankment, regardless of the embankment material (Fig. 5).

One possible reason for this is that the thickness of the saturated embankment section was relatively thin. The thickness of the saturated fill section at Site 1 (cohesive soil) was 1.05 m at the left shoulder survey line, 1.20 m at the center survey line, and 0.15 m at the right shoulder survey line; At Site 2 (sandy soil), the thickness of the saturated fill section was 0.25 m at the left shoulder survey line, 0.35 m at the center survey line, and 0.40 m at the right shoulder survey line. In contrast, the resolution of electrical surveys is generally about 1 m, and the effective depth of EM surveys is said to be approximately 9 ft (about 3 m) [4]. Therefore, it is clear that the geophysical survey methods adopted in this study do not possess the resolution necessary to identify thin saturated fill sections such as those at the survey site.

According to Keller and Frischknecht [5], the relationship between the resistivity R of unsaturated rock and the saturation degree S_w is summarized as follows:

$$R = S_w^{-n} \cdot R_{100} \quad (1)$$

R_{100} refers to the resistivity of rock at 100% saturation (S_w=100%), and n is a test constant. This equation indicates that, since resistivity is inversely proportional to the nth power of saturation, the higher the saturation, the smaller the difference in resistivity becomes.

Furthermore, Park et al. [6] conducted experiments on the factors affecting the specific resistance of soil and

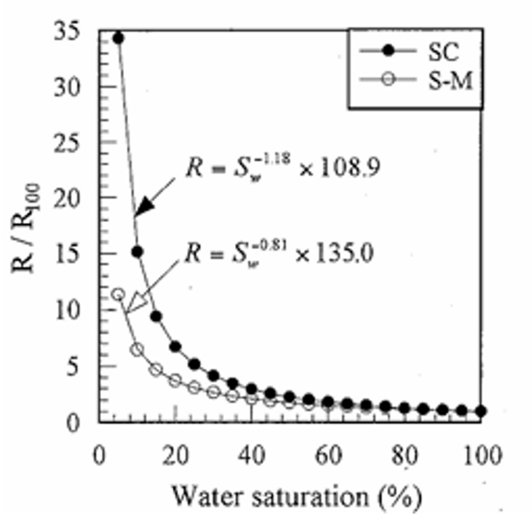


Fig. 6. Relationship between saturation (S_r) and resistivity ratio (R/R_{100}) in clayey sand (SC) and silt-sandy sand (S-M) [6].

reported that, in unsaturated soil, saturation has a significant effect on specific resistance, but the range of variation in specific resistance decreases as saturation increases. Fig. 6 shows the relationship between saturation S_w and the specific resistance ratio (R/R_{100}) for clayey sand (SC) and silt-mixed sand (S-M), based on the experimental results of this prior study. The horizontal axis represents the saturation ratio S_r, and the vertical axis represents the ratio of the specific resistance R of the unsaturated soil to the specific resistance R_{100} at a saturation ratio of 100% (R/R_{100}). These results indicate that as the saturation ratio increases, the specific resistance ratio R/R_{100} tends to converge to a constant value regardless of the sample.

Checking the saturation Sr for Site 1 (cohesive soil) in Table 2, the unsaturated fill section (C-1) had a saturation of S_r = 82.6%, while the saturated fill section (C-2) had a saturation of S_r = 99.5%, showing no significant difference. Based on Equation (1) and Fig. 8, it is considered that there is no difference in the specific resistivity between the unsaturated fill (C-1) and the saturated fill (C-2) at Site 1.

Although there are no measured values for the saturation ratio S_r at Site 2 (sandy soil), both the unsaturated fill section (S-1) and the saturated fill section (C-1) at Site 2 (sandy soil) are coarse-grained soils with a predominant sand content. Furthermore, there is no difference in the fine-grain content ratio Fc between the unsaturated fill section (S-1) and the saturated fill section (S-2) at Site 2 (sandy soil). Therefore, it is inferred that there is no difference in the saturation ratio Sr between the unsaturated fill section (S-1) and the saturated fill section (S-2) at Site 2 (sandy soil) significant enough to cause a difference in the resistivity ratio R/R_{100}. Consequently, based on Fig. 8, it is inferred that the resistivity ratio R/R_{100} for the unsaturated fill (S-1) and saturated fill (S-2) at Site 2 is also approximately the same.

Based on the above, it is considered that the differences between the unsaturated and saturated fill sections at Sites 1 and 2—namely, the water table within the fill—could not be determined due to the influence of the electrical survey's resolution and the degree of saturation Sr.

5.2 The boundary between the bottom of the embankment and the top of the peat layer

5.2.1 Site 1 (cohesive soil)

Fig. 4(a) (electrical survey results) and Fig. 5(a) (EM survey results) show a difference in resistivity between the embankment (cohesive soil) and the peat layer. These results are consistent with the resistivity trends observed for the embankment and peat layer in the electrical logging data (Fig. 3(a)).

Mohamad et al. [7] reported that electrical surveys tend to give higher resistivity values for peat than for clay. The results of the current investigation are consistent with those of Mohamad et al.[3)] in showing relatively high resistivity values ρ_a and ρ_e for the peat layer. Furthermore, cohesive soils with a high fine-grained fraction (Fc) generally conduct electricity well. Therefore, ground structures where cohesive soil with low resistivity is located at the top tend to be easily detected by electrical and EM surveys [8, 9].

Based on the above, at Site 1, the low resistivity of the embankment (cohesive soil) and the high resistivity of the peat layer were easily detected by both the electrical and the EM surveys. This allowed the boundary between the embankment base (cohesive soil) and the upper peat layer to be identified.

5.2.2 Site 2 (sandy soil)

Fig.s 4(b) (electrical survey) and 5(b) (EM survey) for Site 2 (sandy soil) showed results consistent with the electrical logging data (Fig. 3(b)). However, the correlation was less distinct than that observed at Site 1 (cohesive soil). Therefore, it is difficult to conclude that the boundary between the embankment base and the upper peat layer was clearly identified.

According to V. N. Dakhn [10], the resistivity of peat is ρ_a = 10 to 300 Ω·m, while that of sandy soil is ρ_a = 0.5 to 1000 Ω·m. Thus, it is inferred that the resistivity of sandy soil can be higher or lower than that of the peat layer.

Therefore, the resistivity values obtained at Site 2 (sandy soil) showed variation within the embankment, and it is considered that the boundary between the embankment base and the upper peat layer could not be captured as clearly as at Site 1 (clay soil). Consequently, it is inferred that using electrical and EM surveys to capture the boundary between the embankment base (sandy soil) and the upper peat layer is extremely difficult.

6 Summary

Using geophysical surveys (electrical and EM surveys) on cohesive soil (Site 1) and sandy soil (Site 2) embedded in peaty ground, the primary objective was to determine the water level within the embankment and the boundary between the embankment base and the upper peat layer. The findings were compared with the results of conventional ground evaluation methods (boring, SPT, electrical logging), which yielded the following insights.

1) Electrical and EM surveys successfully identified the boundary between the embankment base and the upper peat layer in the cohesive soil (Site 1). This is likely because cohesive soil has low electrical resistivity due to its high fine-grained content, whereas the peat layer has high resistivity. This combination corresponds to a soil structure whose boundary is easily detected by electrical and EM surveys.
2) It was difficult for the electrical and EM surveys to identify the boundary between the embankment base and the upper peat layer in sandy soil (Site 2). This difficulty is likely due to the overlapping ranges of resistivity values possible for both sandy soil and peaty soil.

This investigation has demonstrated that electrical and EM surveys can potentially provide continuous evaluation of the boundary between the embankment base of cohesive soil and the underlying peat layer, serving to complement point data obtained from boreholes and settlement plates.

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