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Study on a method for predicting deformation of surrounding ground suitable for embankment on peaty ground

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Abstract. When strip loads such as road embankments act on peat ground, settlement directly below the embankment and uplift of the surrounding ground due to expansion and lateral displacement occur concurrently, affecting surrounding structures. Deformation of the surrounding ground caused by the embankment is estimated using a simplified method based on measured data. However, many uncertainties remain regarding the applicability of this simplified method to highly compressible peat ground. To evaluate the applicability of simplified methods to peat ground, we compared the influence zones estimated by simplified methods with measured values for embankments constructed on peaty ground. The results showed that when constructing low-load embankments on peaty ground, the influence zone affecting the surrounding ground was smaller than the estimated value from the simplified method, regardless of the peat's natural water content. Therefore, based on the measured results, a parametric study was conducted using the physical properties of peat and clay as parameters. This study proposes a prediction method for the appropriate influence zone and displacement amount on the surrounding ground when constructing embankments on peaty ground.

1 Introduction

Peat ground is widely distributed throughout Hokkaido, which is the northernmost of Japan's four main islands. Although peat ground also exists in other regions, its distribution is extremely localized. Peat ground is distributed over an area of approximately 2,000 km^2 in Hokkaido (Fig. 1 [1]). This is equivalent to approximately 6% of the flat area on this island. Peat ground is distributed widely in the northeastern part of Sapporo, the largest city in Hokkaido. Peat ground in Japan is, in many cases, lacustrine peat, which is formed when lakes and marshes become filled with dead plants growing around them and then turn into land. This type of peat is characterized by the spongy formation of plant fiber (Fig. 2).

In the peat ground of Hokkaido, peat usually accumulates a thickness of 3 to 5 meters on the ground surface and the soft clay layer underlying it is often over 20 meters thick. In some areas, a sand layer exists between the peat and clay layers. Together with the unique features of peat, the existence of the thick soft clay layer makes the ground behavior even some complex.

The engineering properties of peat at a typical Hokkaido peat ground site in the suburbs of Sapporo are shown in Table 1. Some peat ground in Hokkaido has a natural water content of over 1,000% and ignition loss of more than 90%. Its void ratio and compression index are extremely high, while its set density of soil particles are considerably low. Peat is characterized by the great increase of shear strength in consolidation, although its

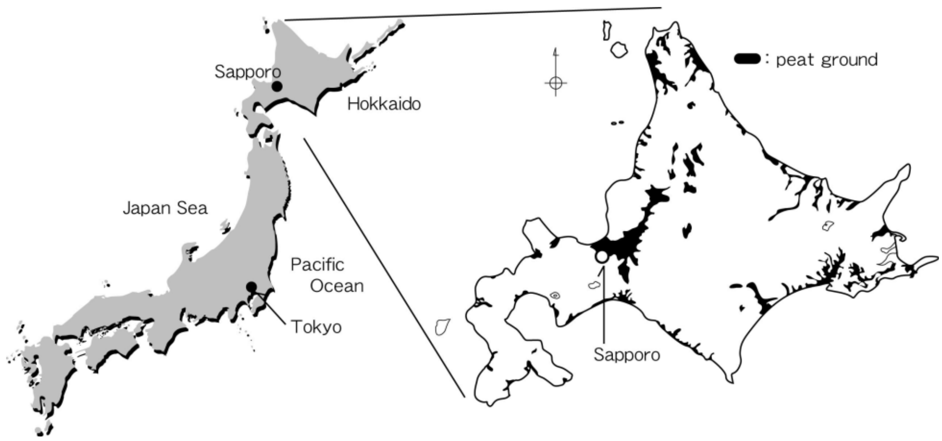

Fig. 1. Distribution of peaty ground in Hokkaido, Japan.

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original shear strength is lower than that of soft clay [1].

When a truncated pyramidal load such as that exerted by a road embankment is applied to soft peaty ground, settlement occurs immediately below the embankment; at the same time, entrained settlement occurs in the area abutting the base of the embankment, and lateral ground deformation causes uplifting. Therefore, an embankment constructed on peaty ground may affect surrounding structures.

Fig. 2. Fibrous peat in Hokkaido.

To clarify the applicability of the Simplified Method for Assessing Ground Deformation (hereinafter: the Simplified Method) to embankments constructed on soft peaty ground, this report evaluates how the degree of influence on the surrounding ground differs according to differences in construction speed, embankment height, and peat layer thickness, based on data from existing embankments constructed on soft peaty ground.

Table. 1. Parametric study analysis patterns.

Case	First layer	Second layer	Total thickness (m)
	Peat (t=6m) Water content (%)	Cohesive soil (m)	
1	500		
2	800	5	11
3	1000		
4	500		
5	800	10	16
6	1000		
7	500		
8	800	15	21
9	1000		
10	500		
11	800	20	26
12	1000		

2 Deformation of ground embankments and related issues

The deformation (settlement, uplift, and horizontal displacement) of the ground surrounding embankments has been estimated using the Simplified Method, which was developed based on observation data (Fig. 3 [2]). The method, which is based on the (1), (2), (3) equations below, it is possible to estimate the settlement the width of the embankment base, as well as the horizontal and vertical displacements of the surrounding ground. The equations were formulated based on values recorded at expressways and national highways in Japan. The range of influence of road embankments built on peaty ground on the ground around the embankments in Japan is examined using Fig. 3. Settlement is defined as:

$$S_t = C_1 \cdot S \tag{1}$$

uplift of the ground at a given distance from the embankment:

$$\delta_y = C_1 \cdot S \tag{2}$$

horizontal displacement of ground abutting the embankment base:

$$\delta_x = C_2 \cdot S \tag{3}$$

where: S is the settlement at the central part of the embankment, H the thickness of the soft layer, x the horizontal distance from the embankment, δv uplift (settlement) of the ground at a given distance from the embankment, δx horizontal displacement of the ground abutting the embankment base and C1, C2 are coefficients.

In Fig. 3, C1 values above 0 indicate the coefficient of uplift of the surrounding ground, C1 values below 0 indicate the coefficient of settlement of the surrounding ground, and C2 is the coefficient of horizontal displacement of the surrounding ground.

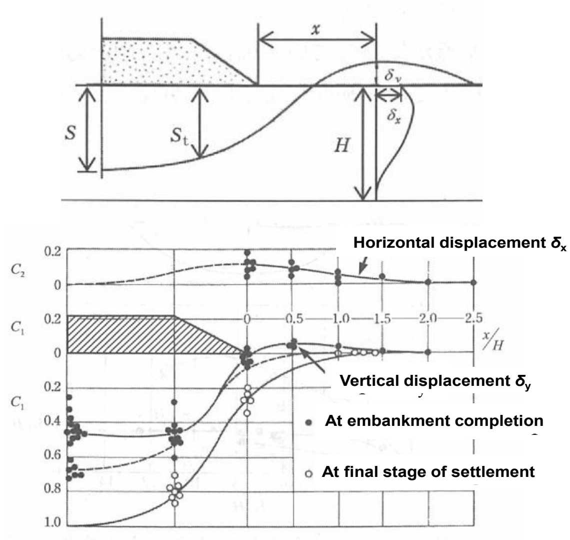

Fig. 3. Settlement behavior of embankments and their impact on surrounding ground (simplified method).

The embankment in Fig. 2 is an example of a road embankment with a base width of 30 to 60 m that was constructed within a specified time (50 to 200 days as in [3]). It is understood that the deformation is very small at distances of two or more times the thickness of the soft layer H from the toe of the embankment slope [4].

However, this figure does not account for the physical properties of the peaty ground, the shape of the embankment, the gradient of the slope, nor the speed at which the embankment is constructed. For this reason, embankment designers in Hokkaido have stated that Fig. 2 does not adequately represent the condition of embankment on soft peaty ground with a highly compressible peat layer and a thick underlying layer of clay.

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3 Extent of deformation induced by embankments constructed on peaty ground

The authors conducted a field survey to estimate the extent to which constructing an embankment on peaty soft ground affects the surrounding ground.

The target of the survey was a low embankment (approximately 3 m in height) built on peaty soft ground. Fig. 4 shows the site for field observation.

Fig. 4. Embankment construction status.

A total of 25 cross-sections were examined. The embankment construction rate was 3 cm/day, with a required total thickness (H_t) ranging from 2.9 to 5.3 m. The thickness of the peaty soft ground (z) ranged from 3.5 to 12.7 m, of which the peat layer itself accounted for 1.6 to 6.5 m. For analysis, the natural water content $\mathbf{w}_n$ of the peat layer was classified into three categories (Fig.5). The symbols in Fig.5 represent values obtained by multiplying the final settlement at the embankment center by coefficients (C_1, C_2). The final settlement was calculated using the Noto equation for peat layers and the $e - \log p$ equation for cohesive soil layers.

The dashed lines in Fig. 5 represent the coefficients (C_1, C_2) used in the Simplified Method to estimate the vertical and horizontal deformation of the surrounding ground upon embankment completion.

As shown in Fig. 5, while some values of C_1 and C_2 obtained from the 25 cross-sections exceed the dashed lines, the majority remain below them.

Regarding C_2 (the coefficient of horizontal displacement), values tend to decrease with increases in the distance from the embankment toe. However, no significant correlation is observed between C_2 and the water content of the peat layer.

Regarding C_1, approximately 70% of the datapoints within the range of $x/H = 0$ to 1.5 are below $C_1 = 0$. This phenomenon is attributed to the high compressibility and low undrained shear strength that characterize peat layers.

These results suggest that entrained settlement consistently occurs within this range when the embankment reaches its target height. Similar to C_2, the moisture content of the peat layer does not appear to have a clear effect on C_1.

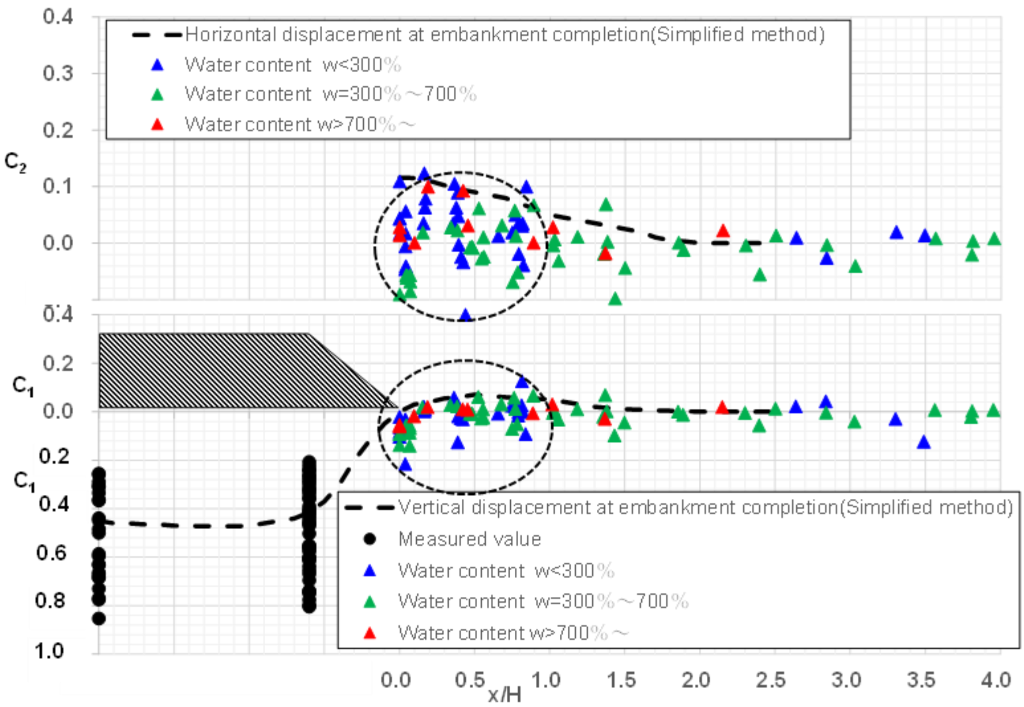


Fig. 5. Distribution of surrounding ground in field observation results of embankments constructed on peaty ground.

4 Development of a simplified method for estimating the displacement of peaty ground

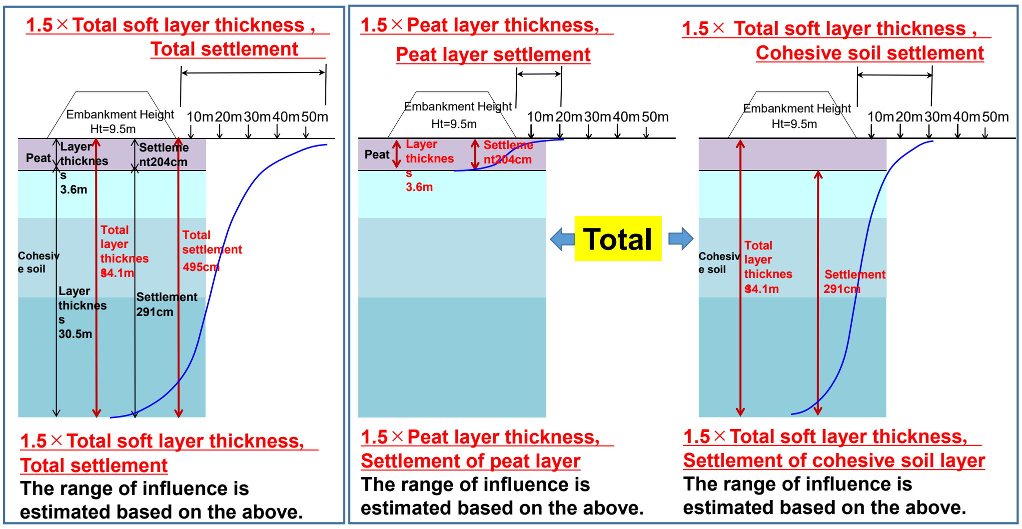
The Simplified Method estimates the displacement (δ_x, δ_y) of the surrounding ground based on the final total settlement S at the center of the embankment and on coefficients C_1 and C_2. These coefficients represent the extent of the embankment's influence on the surrounding ground as a function of x/H (where x is the horizontal distance from the embankment toe and H is the thickness of the soft layer).

Consequently, the displacement within the range of x/H is uniquely $A = \pi r^2$ determined by x, H, and S, regardless of the consolidation characteristics of the target soft layer.

Fig. 6a illustrates an example calculation of the influence range for peaty soft ground consisting of a 3.6 m peat layer and an underlying 30.5 m clay layer, totalling 34.1 m. According to the conventional Simplified Method, the zone of influence on the surrounding ground extends approximately 51 m from the embankment toe ($x = 1.5H$). In this survey, S was calculated to be approximately 5 m, suggesting that displacement will be confined to this 51 m range.

However, two key factors must be considered: (1) the layer thickness and final settlement differ significantly between highly compressible peat and less compressible clay, and (2) the surrounding ground displacement is closely related to x/H and S.

Taking these into account, we developed the "Combined Method" for determining displacement. This approach divides the peaty soft ground into an upper layer (peat) and a lower layer (cohesive soil) and integrates the range of influence and displacement results obtained for each layer (Fig. 6b).



(a) (b)

Fig. 6. Conceptual diagrams for the Simplified Method (a) and the Combined Method (b) for estimating deformation in peaty soft ground.

5 Verification of the applicability of the combined method for Peaty soft ground

Fig. 7 shows the construction process during embankment construction at the field observation point (SP=4,880), the settlement process of the central embankment crown, and the final settlement estimated using the hyperbolic method. The final settlement was calculated by extrapolating the results of the one-dimensional consolidation analysis performed during using the Noto method for the peat layer and the $e - \log p$ method for the clay layer.

Comparing results calculated using the simplified method and the combined method, the simplified method showed deviation from measured values in terms of influence zone and displacement.

However, the combined method showed higher compatibility regarding the influence zone of ground deformation. As stated in Section 4, when evaluating only the peat layer using the simplified method, the nature of the simplified method's equation limits the influence zone due to the thin peat layer thickness.

Nevertheless, due to the large total settlement, the displacement of the surrounding ground concentrates near the embankment toe. On the other hand, when evaluating only the clay layer using the simplified method, although the layer depth is thick, the total settlement is small, resulting in a wider influence range. Nevertheless, the settlement values tend to be smaller. Therefore, calculating separately for the peat layer and the cohesive soil layer, then combining these results, is considered suitable for estimating the influence range of peaty soft ground and the displacement of the surrounding ground (Fig. 8).

6 Numerical study

Using the Combined Method, which estimates the peat and cohesive soil layers separately, to determine the zone of influence and displacement of peaty soft ground yields results that agree closely with field observations. Therefore, a parametric study was conducted using the Combined Method, with peat layer thickness and peat water content as parameters. Fig. 9 diagrams the cross-section examined in the parametric study.

Table 1 summarizes the parameters and conditions of the parametric study. A general-purpose consolidation settlement calculation system was used in the player thickness, and the values obtained using the Combined Method (Fig. 6) are shown on the horizontal axis.

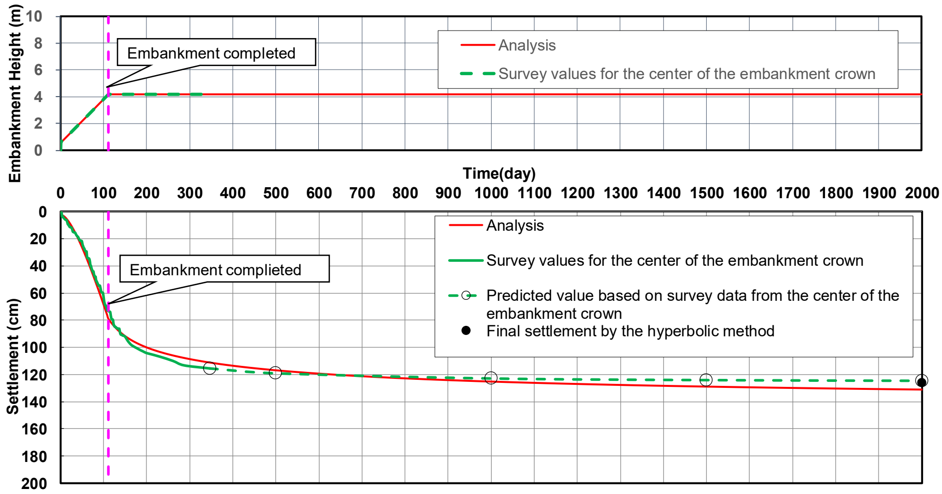


Fig. 7. Settlement process at the center of crown embankment on peaty soft ground.

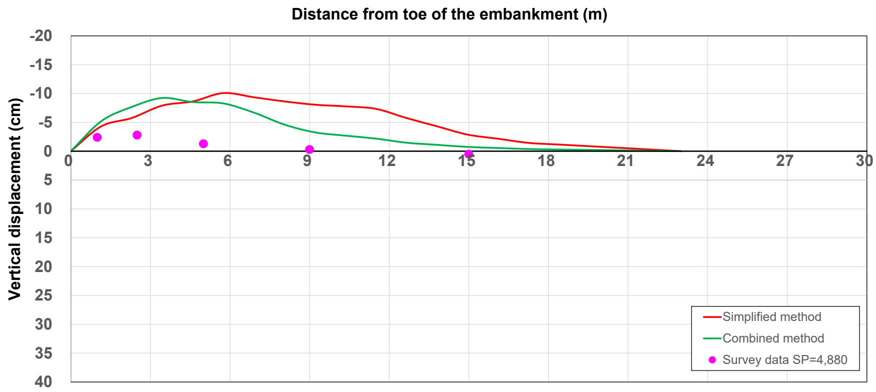


Fig. 8. Comparison of the influence degree of surrounding ground on embankments using the simplified method and the combined method.

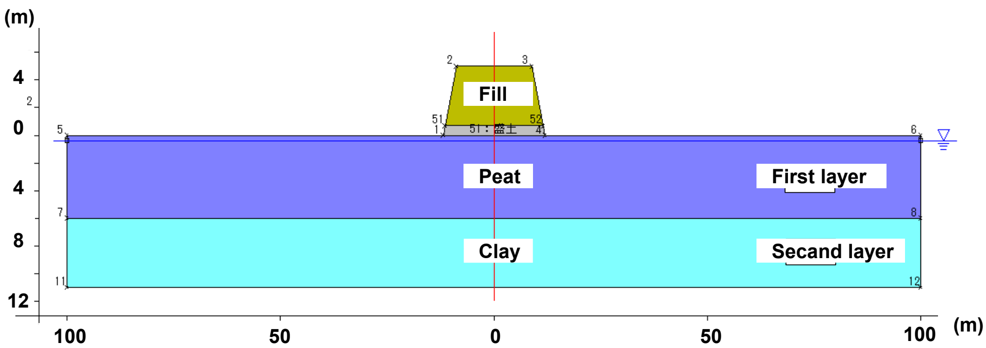


Fig. 9. Parametric study cross-sections.

The range of influence in the surrounding ground and the maximum values of deformation (Max) are also shown in the figures.

When we observe the vertical and horizontal displacements at embankment completion and the vertical displacement at final settlement, we see that displacement values are large near the embankment toe (x/H = 0 to 0.5) and tend to converge rapidly as x/H increases. By separately examining the thin, highly compressible peat layer and the thick, moderately compressible clay layer, the physical properties of each layer are reflected in the results.

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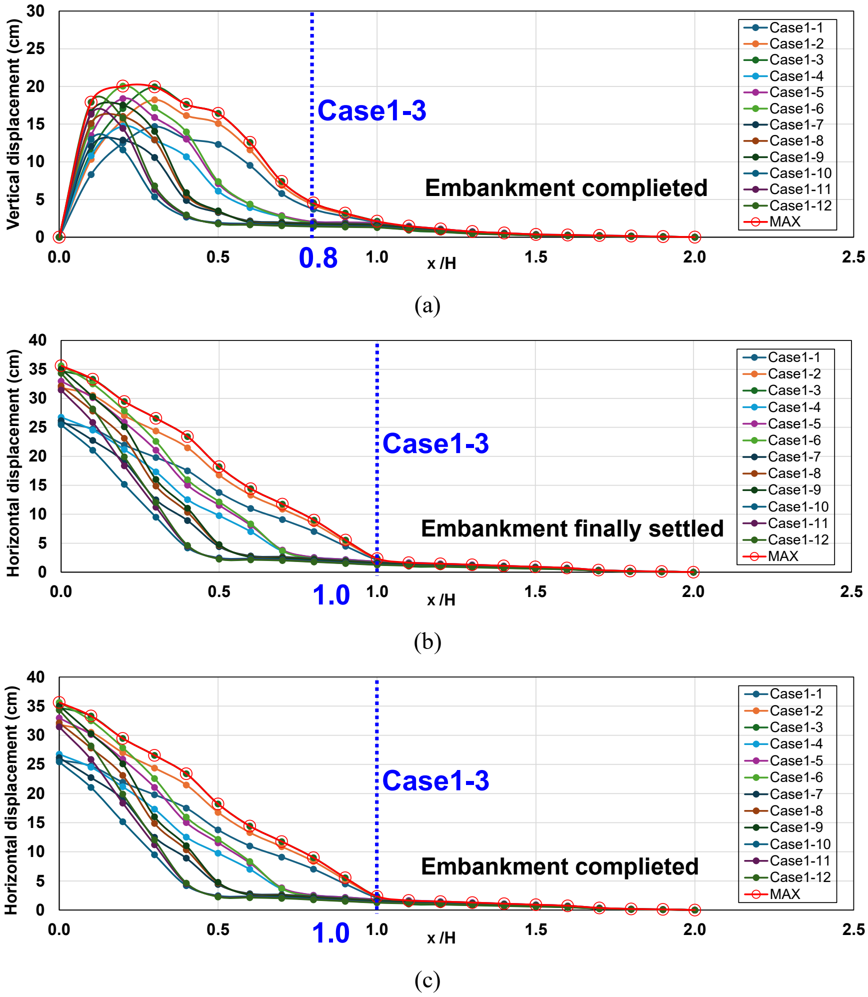

Fig. 10. Results of the parametric study: (a) upon the completion of embankment (vertical displacement); (b) at the final stage of settlement (horizontal displacement) and (c) upon the completion of embankment (horizontal displacement).

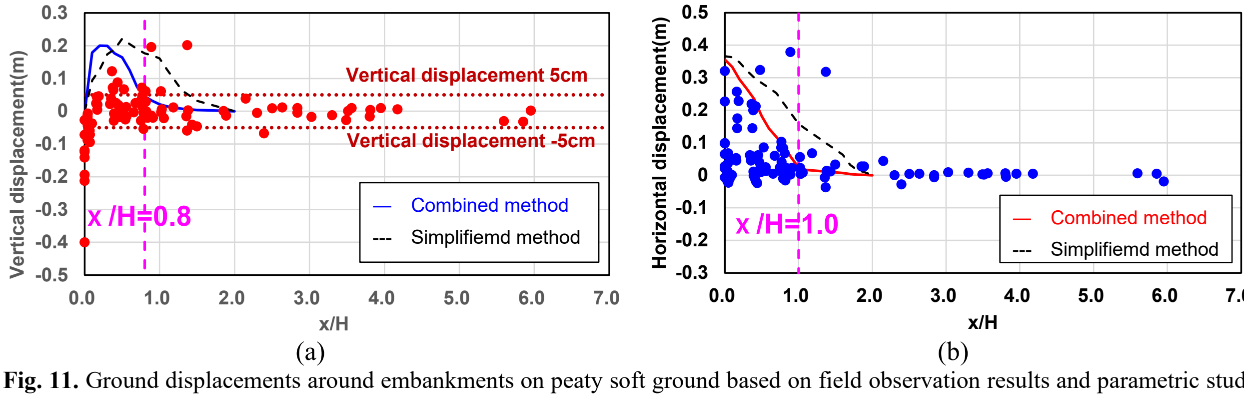

Fig. 11. Ground displacements around embankments on peaty soft ground based on field observation results and parametric study results: (a) the relationship between x/H and vertical displacement and (b) the relationship between x/H and horizontal displacement.

As the allowable displacement for the ground surrounding the embankment, we used the elevation difference specification value (±50 mm) for foundation preparation (topsoil grading) for field preparation. The parametric study results shows that regardless of the presence of sand layers, the x/H ratio at embankment completion and final settlement is within the specification (<50 mm) when $x/H\ \leq 0.8$ (Fig. 10 a and Fig. 10b). While no evaluation criteria exist for the horizontal displacement of the surrounding ground, if we assume ±50 mm as the standard value similar to vertical displacement, then $x/H \leq 1.0$ is within the standard value (Fig. 10c).

Fig. 11 superimposes the results from Fig. 10a to Fig. 10c onto the field observation results. Fig. 11a and Fig. 11b plot vertical displacement and horizontal displacement versus x/H.

Vertical displacement generally converges within ±50 mm at $x/H \geq 0.8$, and horizontal displacement at $x/H \geq 1.0$. Vertical and horizontal displacements in the surrounding ground that result from the peaty soft ground tend to concentrate near the embankment toe, even when determined by absolute magnitude.

Fig. 12 displays coefficients C_1 and C_2 overlaid on Fig. 5. These coefficients are derived by normalizing the vertical displacements from Fig. 10a and Fig. 10c by the settlement of each layer and then combining them.

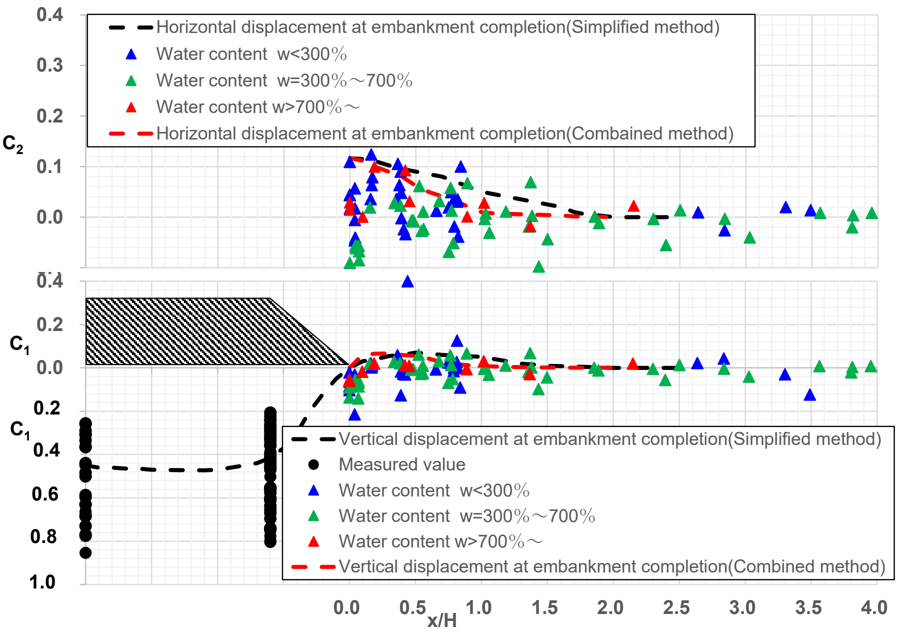

Fig. 12. Distribution of surrounding ground in field observation results of embankments constructed on peaty ground (Simplified method, Combined method).

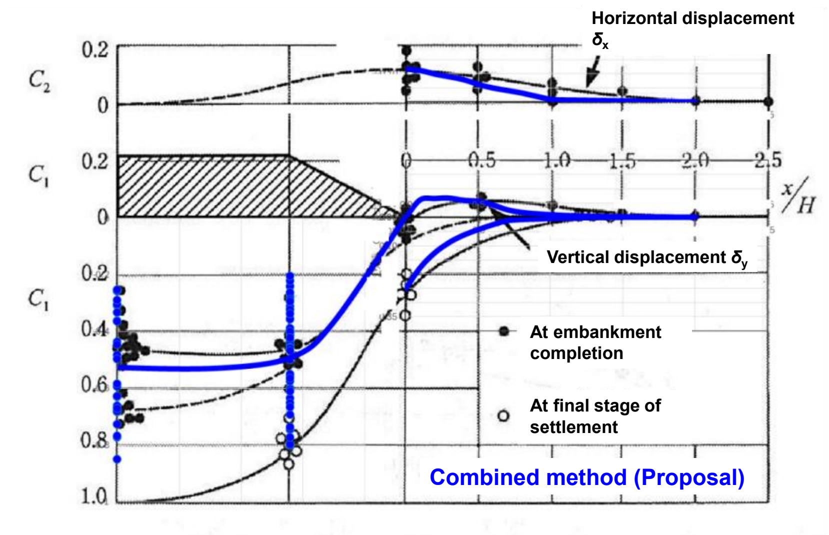

Fig. 13. Settlement behavior of embankments and their impact on surrounding ground (Combined method).

Fig. 12 indicates that C_2 at $x/H \leq 1.0$ in the field observation results exceeds the threshold for C_2 in the Combined Method.

The coefficients (C_1, C_2) are values normalized by $\boldsymbol{S}$ for each displacement (δ_x, δ_y) of the surrounding ground, per the equation in Figure 2. Therefore, depending on the site conditions (the cross-section under consideration), the estimated final settlement value may be smaller than the measured displacement, potentially leading to an overestimation of the coefficients (C_1, C_2).

However, as shown in Fig. 11a, Fig. 11b the displacements of the surrounding ground observed through field monitoring and parametric studies are limited to the vicinity of the embankment. Therefore, the Combined Method is considered a reasonable technique for predicting deformation of the ground surrounding an embankment built on peaty soft ground (Fig. 13).

7 Summary

This paper has proposed a combined method for estimating the influence zone and displacement of surrounding ground suitable for local ground conditions, based on field observation results of the influence zone and displacement obtained from embankments on peaty soft ground. Furthermore, a parametric study was conducted using the field observation results as a basis, with the physical properties and layer thickness of the peat layer and cohesive soil layer as parameters. The results are as follows.

- Field observations indicated that the zone of influence in the ground surrounding an embankment on peaty soft ground extends to approximately x/H=1.5. Vertical and horizontal displacements tend to concentrate at x/H ≤ 1.0.

- To estimate the range of influence and the displacement specifically for peaty soft ground, we developed a method that separately calculates and then combines the values for the peat layer and the underlying cohesive soil layer.
- A parametric study was conducted to support the planning of slow-loading embankments on peaty soft ground. This study accounted for maximum embankment height, soil properties sensitive to deformation during construction, and layer thickness.
- The results show the threshold for maintaining vertical and horizontal displacements within ±50 mm to be $x/H \leq 0.8$ to 1.0. The field observations yielded similar findings.

During the design phase, while the condition of predicting surrounding ground deformation amounts is applied, this method indicated the possibility of narrowing the influence range of the surrounding ground due to embankments on peaty soft ground. As a result, the setting of an influence range on the surrounding ground, which was previously assessed too widely using conventional simplified methods, can be eliminated, avoiding the need for land borrowing or countermeasures. Therefore, it contributes to reducing project costs.

References

1. S.,Noto(1991): Peat Ground Engineering, Gihoudo Shuppan publication, Tokyo, Japan (in Japanese).
2. Japan Road Association (2012): Road Earthworks: Guidelines on Remedial Measures for Soft Ground (in Japanese).
3. East, Central and West Nippon Expressway Companies (2012): Design Guidelines Vol. 1 Earthwork (in Japanese).
4. Public Works Research Institute, Ministry of Construction (1982): Materials of the Public Works Research Institute, “Investigation of the Effect on Adjacent Area by Earth Structures on the Soft Ground (1st) —Field Observation of the Embankment on the Soft Ground—,” Material of the Public Works Research Institute No. 1806 (in Japanese)