Prediction of and countermeasures for embankment-related settlement in ultra-soft ground containing peat

Prédiction et contre-mesure sur les tassements de remblais dans les sols ultra-meubles contenant de la tourbe

Tashiro M.
Nagoya University, Japan

Inagaki M.
Central Nippon Expressway Company Limited, Japan

Asaoka A.
Association for the Development of Earthquake Prediction, Japan

ABSTRACT: In the Mukasa area of the Maizuru-Wakasa expressway in Japan, delayed settlement as large as 11 m has occurred by test embankment loading on a ground that includes approximately 50 m of ultra-soft sediment layers containing peat and clay. In this paper, based on deductions of the initial in-situ soil conditions, simulations were carried out on the settlement and pore water pressure observed until now at the site, and predictions were made of the settlement that could occur in the future. In addition, the effects of countermeasures such as ground improvement by sand drain, replacement of the existing embankment with lightweight materials, and reduction of the loading rate, were also investigated using numerical analysis. These analyses were performed using the soil-water coupled finite deformation analysis program *GEOASIA*, in which the SYS Cam-clay model was mounted as the constitutive equation for the soil skeleton. The results showed that improvement of the mass permeability and the slow or lightweight banking are effective means of improving the stability during loading and reducing the residual settlement after entry into service. The results analyzed in this paper were applied to the actual construction design of a culvert and the lightweight embankment surrounded it.

RÉSUMÉ : Sur l'autoroute Maizuru-Wakasa au Japon, un tassement différé de près de 11m s'est produit suite à des essais de chargement de remblai sur un terrain incluant près de 50 m de couches de sédiments ultra-meubles contenant de la tourbe et de l'argile. Dans cet article, des simulations de tassement et de pression de l'eau interstitielle observées jusqu'à maintenant sur le site ainsi que des prédictions de tassement pouvant survenir dans le futur ont été réalisées en déduisant les conditions initiales de sols in situ. En outre, les effets des contre-mesures, comme l'amélioration du sol par drain de sable, le remplacement des remblais existants avec des matériaux légers, et la réduction de la vitesse de chargement, ont également été étudiés par analyse numérique. Ces analyses ont été employées en utilisant le programme d'analyse de déformations finies sol-eau couplées *GEOASIA*. Les résultats ont montré que l'amélioration de la perméabilité de masse, un tassement lent et léger sont des méthodes efficaces pour atteindre la stabilité pendant le chargement et la diminution du tassement résiduel après l'entrée en service. Les résultats analysés dans ce document ont été appliqués à la conception de la construction réelle d'un ponceau et du léger remblai qui l'entourait.

KEYWORDS: peat, prediction of settlement, soil-water coupled analysis

1 INTRODUCTION

In the Mukasa area of the Maizuru-Wakasa expressway, the ground consists of ultra-soft sediment layers comprising peat and clay with N-values on the order of 0 to 1 and a maximum depth of 50 m. Delayed settlement in excess of 11 m has occurred due to test embankment loading for approximately four years. While the construction of the embankment did not induce catastrophic sliding failure, it did dramatically impact the surrounding ground, causing substantial lateral displacement of up to 2 m and ground upheaval of up to 1 m (Inagaki et al 2010b).

In this paper, we simulated the large-scale ground settlement behavior observed in the region based on soil-water coupled finite deformation analysis, and in addition to predicting future settlement, we demonstrated that ground improvement by drain, and reduction in loading rate and weight are effective means of improving stability during embankment loading and reducing residual settlement of ultra-soft sediments containing peat. Numerical analyses were conducted using the SYS CAM-clay model (Asaoka et al. 2002) as an elasto-plastic constitutive equation mounted on the *GEOASIA* analysis program (All Soils All States All Round Geo-Analysis Integration: Asaoka and Noda 2007, Noda et al. 2008). The simulation results were applied to the actual construction design of a culvert and the lightweight embankment surrounding it.

2 SUMMARY OF THE TEST EMBANKMENT

Figure 1 presents a longitudinal cross-section of the soil strata underlying the test embankment that is the subject of this study. Three types of test embankments were established utilizing the

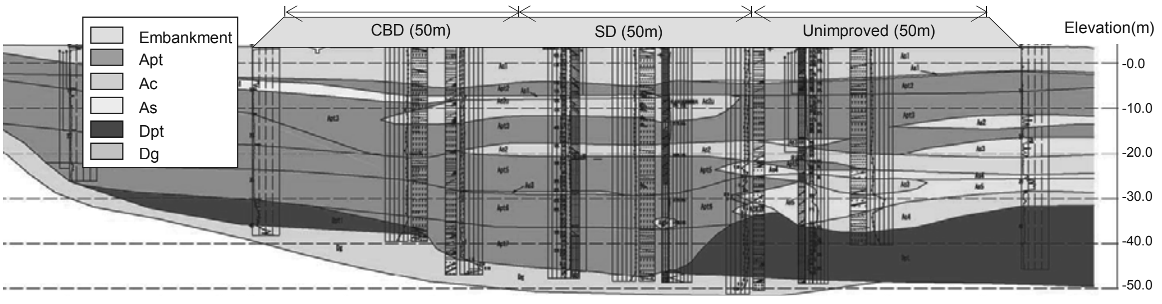


Figure 1. Schematic of test embankment and underlying soil strata (longitudinal cross section).

card-board drain (CBD) method, the sand drain (SD) method, or no improvement, with the aim to select a countermeasure for soft ground. Among these, the soft ground layer was thickest directly under the test embankment established using the SD method. When taking into consideration the settlement of all layers up to the deep peat layers, the total settlement, estimated prior to embankment construction, was 8.6 m. In practical terms, however, as presented in Figure 5, this meant that in order to achieve the planned embankment height of 7 m, the embankment had to be 15 m (embankment height + settlement) thick.

The large-scale settlement has been accompanied by substantial changes in an extensive area surrounding the embankment. Ground upheaval of up to 1 m and lateral displacement of up to 2 m have been observed in the vicinity of the toe of the slope. The surrounding ground has also experienced an inclination of waterways and cracking of the soil surface. At this point, 4 years after the establishment of the test embankment, settlement has reached 11 m, representing a settlement rate of 3.0 cm/month with little sign of convergence.

1 PREVIOUS RESEARCH

The long-term settlement that accompanies embankment loading is referred to as “delayed compression” or “secondary consolidation” and is a problem frequently encountered in sensitive naturally-deposited clay. For example, according to the construction records of the former Japan Highways Public Corporation, approximately 20% of embankments on soft ground in Japan have experienced 1 m or more of residual settlement after entry into service, which has necessitated substantial sums of money and labor for maintenance and repair including the expansion of road shoulders and rectification of level differences. However, we know from experience that settlement predictions based on Terzaghi’s Theory of Consolidations (Terzaghi 1943) and observational methods such as the Asaoka method (Asaoka 1978) tend to underestimate the magnitude and time span of settlement in such sites. Meanwhile, because settlement estimates based on visco-plastic theory (e.g. Šuklje 1957) assume perpetual delayed compression, it is difficult to explain why and under what conditions delayed compression occurs and the efficacy of particular countermeasures.

Mounting the SYS Cam-clay model as an elasto-plastic constitutive equation for the soil skeleton structure into the soil-water coupled finite deformation analysis program *GEOASIA*, we have explained the mechanism of delayed compression as a consolidation phenomenon accompanied by plastic compression due to progressive failure of the soil skeleton structure (Noda et al. 2005). While, we have also proposed a simple method for assessing the risk of delayed compression based on a laboratory mechanical test and a novel method for predicting long-term settlement accompanied by delayed compression (Inagaki et al. 2010a). In addition, we have applied these methods to the analysis of embankment loading sites built on soft clay ground that has actually experienced long-term settlement (Tashiro et al. 2011).

The elasto-plastic constitutive SYS Cam-clay model that serves as the basis for the above simulations enables the wide range of soil components, from sand to clay, to be treated within the same theoretical framework. Furthermore, the *GEOASIA* analysis program into which the model is integrated, enables all manner of mechanical conditions, including ground consolidation, deformation, stability and failure to be analyzed in series. In this paper, we apply the various insights gained from soft clay ground to peat ground and attempt to describe, predict, and evaluate countermeasures related to large-scale settlement behavior.

2 DEDUCTION OF INITIAL GROUND CONDITIONS

Prior to conducting the simulation, in order to estimate the initial ground conditions, we examined historical data related to ground formation as well as various survey data, including pore water pressure. The area is located between faults, and it is believed that the soil was deposited through the repeated upheaval, settlement, and deep sediment of organic components in a valley that experienced continuous artesian conditions. In this paper, the initial distribution of pore water pressure and effective overburden pressure of the ground prior to embankment loading is estimated in Figure 2. For reference, the distribution when artesian pressure is not taken into consideration is included as a dotted line. This represents an unusual case in which the initial effective overburden pressure p_0 becomes greater than the consolidation yield stress p_c ($p_0 > p_c$). In this region, it is expected that the increase in artesian pressure accompanying the increase in soft ground thickness resulted in a continuous low effective pressure in the deep ground.

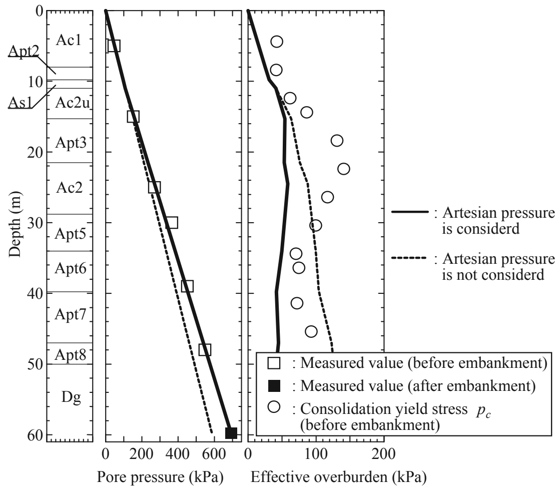


Figure 2. Estimated distribution of initial pore water pressure and effective overburden pressure

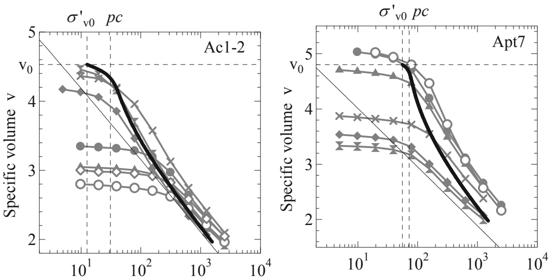


Figure 3. Examples of compression curves for undisturbed samples (gray lines) and estimated compression curves for in-situ soil (thick black lines).

Next, through laboratory tests, we attempted to determine the material constants and initial conditions. As presented in Figure 3, based on previous research on naturally deposited clay (Inagaki et al. 2010), we estimated compression curves for in-situ soil from the compression curves for undisturbed samples, taking into consideration the various “disturbances” that might occur during sampling, removal from the sampling tube, specimen preparation and setting-up on the testing machine. However, we observed considerable heterogeneity among samples from the deep peat layers with regard to factors such as mixing of plant fibers. In addition, it was expected that these samples were substantially impacted by “disturbances,” given their poor strength resulting from their high water content. For this reason, we conducted simulations based on a range of assumed initial conditions and determined the initial conditions that best reproduced the measured settlement. With regard to the permeability coefficient *k*, given the high compressibility of the peat layers, we assumed that the void ratio e was related to *k* by the expression $e=C\ln k/k_0+e_0$ and, for the other layers, we assumed a constant permeability coefficient. In addition, in order to represent the improvement by SD, we assigned a 100-fold greater permeability to finite elements corresponding to the SD area.

3 PREDICTION OF FUTURE SETTLEMENT BEHAVIOR

The finite element mesh and boundary conditions are presented in Figure 4. For simplicity, in this analysis, the SD section of Figure 1 was modeled assuming ground stratification.

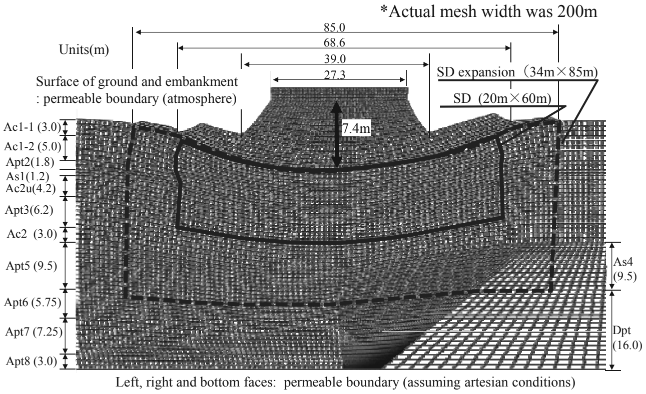
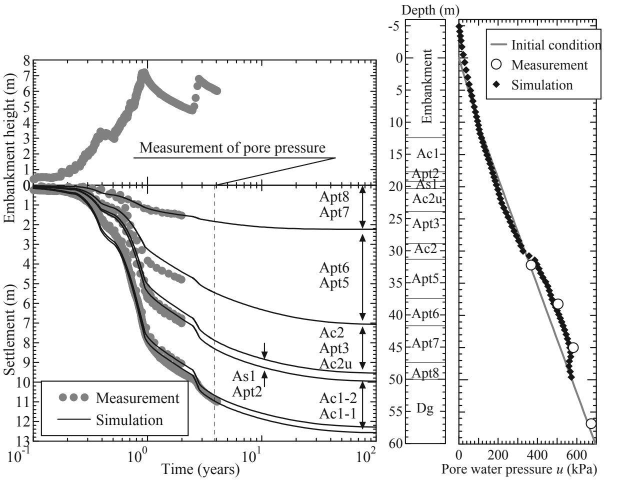


Figure 4. Finite element mesh (after embankment construction).



(a)Prediction of future settlement (b)Distribution of pore pressure

Figure 5. Simulation results (directly below the embankment center).

Figure 5(a) shows the predicted settlements at ground surface and for all layers directly below the center of the embankment. After adjusting the initial conditions and permeability coefficients to reproduce the observed settlement values, the simulation was allowed to continue to predict future settlement behavior. According to this analysis, additional residual settlement on the order of 1.5 m is expected to occur over the next 70 years. Figure 5(b) shows a comparison of the measured and simulated pore water pressure approximately 1,400 days after the entry of embankment loading (dotted line in Figure 5(a)). It can be seen that the simulation closely reproduces the distribution of excess pore pressure. Although the initial high void ratio for the deep peat layers experiences an rapid compression as a result of embankment loading, after a certain degree of volume compression has occurred, the layers then exhibit extremely poor permeability and have trouble dissipating excess pore pressure. Consequently, large settlement continues over a long term in these layers.

4 COUNTERMEASURES FOR SOFT PEAT GROUND

4.1 *Effect of ground improvement using SD method*

We evaluated the effect of SD on the test embankment ground by simulating the following three cases:

Case 1: Simulating the actual SD-improved area of the test embankment (20 × 60m (L ×W))
Case 2: No SD-improvement
Case 3: Expanding the SD-improved area in accordance with specific site conditions. (34 × 85 m (L × W), i.e., the entire area directly under the embankment down to the Apt5 layer)

In each case, based on actual records at the construction site, the simplest construction history was used (constant increasing the embankment thickness at a rate of 2.35 cm/day).

Although the magnitude of the settlement during initial embankment construction is lowest in Case 2, it was shown that because the poor permeability induces shear deformation under undrained condition, large-scale circular slip extends to the deep ground layers below the embankment center (Figure 6). From this result, it appears that ground improvement using SD in this area was effective in preventing catastrophic slip failure.

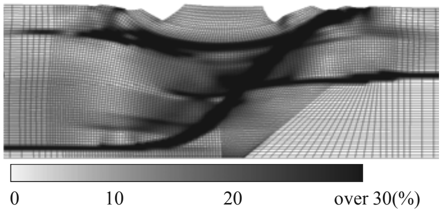


Figure 6 Circular slip during loading (Case 2: No SD-improvement)

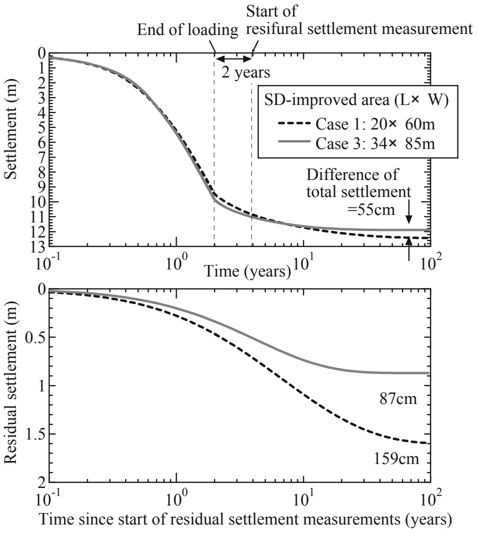


Figure 7 Comparison of SD-improvement area.

Case 3 resulted in stability, particularly of the deep peat layers, and early settlement convergence. Figure 7 shows the settlement for Cases 1 and 3. The residual settlement starting at a point 2 years (assuming the entry into service) after embankment construction is also illustrated in the lower panel. Expansion of the SD-improved area, particularly in the deep peat layers, reduces lateral displacement due to undrained shear deformation and settlement associated therewith. The total settlement is reduced by 55 cm across the entire area of ground under the embankment. Furthermore, residual settlement was reduced by approximately half due to the fact that the settlement approached convergence earlier. However, because consolidation of the deep peat layers also occurred earlier, deformation was concentrated in the upper peat layers, and upheaval of areas near the toe of the slope increased (Figure omitted). Potential countermeasures for this problem associated with expansion of SD-improved area, include expanding the area and load of the counterweight embankment and reducing the rate of embankment loading, particularly in the initial stages.

4.2 *Effect of slow banking method*

Table 1 shows the results of simulations performed under the same conditions as Case 3 above, but with lower (1.5 cm/day) or higher (3.0 cm /day) rates of embankment loading. Reducing the rate of loading allowed for greater drainage during loading, which resulted not only in earlier convergence of settlement and reduction in residual settlement but also a slight but significant reduction in total settlement. Although the data is not presented here due to space constraints, the lower loading rate was effective in reducing lateral displacement of the shallow ground layers and upheaval of the soil surface, and resulted in an earlier shift from outward deformation to inward deformation in the embankment loading process.

Table 1. Effect of rate of embankment loading.

Loading rate (increase in embankment thickness/day)	Total settlement (m)	Residual settlement (cm)
1.5cm/day	11.7	74
2.35cm/day	11.9	87
3.0cm/day	12.0	94

Although construction of the test embankment shown in Figure 5 (a) was managed so that the embankment “height” generally increased at a rate of 3.0 cm/day, because obvious settlement occurred during embankment construction, the actual rate of loading per unit time (increase in embankment “thickness”) was higher than that specified in any of the above simulations. Although no catastrophic slip failure occurred, this rapid construction resulted in increased lateral displacement and upheaval. Slow embankment loading is effective not only for increasing stability during construction but also for reducing residual settlement and impacts on the adjacent ground. When it is not possible to secure adequate time for embankment construction, combinations with other countermeasures such as vacuum consolidation should be considered.

4.3 *Effect of lightweight banking method*

Figure 8 shows the effect of weight reduction of the existing embankment with lightweight materials. For simplicity, in the simulation, the reduced loading was represented by removal of the embankment. Greater reduction in loading was accompanied by less residual settlement and earlier occurrence of settlement convergence. Furthermore, although not shown here, it was demonstrated that greater reduction in loading resulted in reduced inward deformation of the ground surrounding the embankment.

Based on these simulations, the culvert in actual construction site has been designed with a 1.2-m freeboard, and in order to reduce differential settlement, the material of the embankment in the vicinity of the culvert is planned to be replaced with lightweight material.

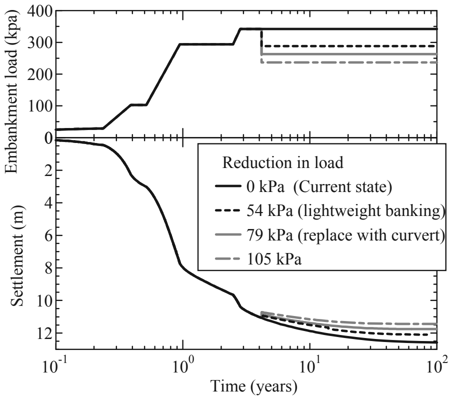


Figure 8 Effect of weight reduction of the existing embankment.

5 CONCLUSION

In this paper, we attempted to simulate the large-scale settlement in excess of 11 m and predict future settlement of ultra-soft ground containing peat due to loading by a test embankment. When the stress state of peat exceeds the consolidation yield stress under heavy loading, the undrained shear deformation resulting from poor permeability causes large lateral displacement to occur, which can lead in severe cases to slip failure. Furthermore, because rapid compression occurs even under drained conditions in peat layes, permeability improvement using SD, reduction of the loading rate, and the more drastic countermeasure of reducing the load itself are effective in increasing stability during loading, reducing the deformation of the ground surrounding the embankment, and reducing residual settlement after the enter into service.

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