Hybrid Application of Deep Mixing Columns Combined with Walls as a Soft Ground Improvement Method Under Embankments

Application hybride de la méthode de « Deep Mixing » sur des colonnes combinées à des murs en tant que méthode d'amélioration des sols mous sous remblais

Matsui H., Ishii H., Horikoshi K.
Technology Center, Taisei Corporation, Yokohama, JAPAN

ABSTRACT: In this paper, we introduce theconcepts and general functions of a hybrid application of deep mixing columns combined with walls. This newmethod for improving the soft ground under embankments helps control ground deformation. We brieflydescribe a case in which the method was applied under an embankment 7m in height. The method effectively restricted the induced deformation of the ground surface to a target level, not only under the embankment but also adjacent to the embankment toes. Two-dimensional finite element analysis was adopted to the case and foundeffective for simulating the performance. Also proposed is a design flow for the new methodto efficiently determine the best arrangement of deep mixing columns and walls. Numerical parametric studies were carried out to compare the new method with conventional methods.

RÉSUMÉ : Dans cet article, nous présentons les concepts et les fonctions générales de l'application hybride de méthode de « Deep Mixing » sur des colonnes combinées à des murs. Cette nouvelle méthode d'amélioration de sols mous sous remblais aide à contrôler la déformation du terrain. Nous décrivons brièvement un cas dans lequel la méthode a été appliquée sous un remblai d'une hauteur de 7 m. La méthode a permis de limiter efficacement la déformation induite de la surface du sol à un niveau cible, non seulement sous le remblai, mais aussi dans les zones adjacentes aux pieds de talus. Une analyse par éléments finis en deux dimensions a été appliquée à ce cas et s'est avérée efficace pour simuler les performances. Une méthode d'optimisation est également proposée en vue de déterminer de manière efficiente la meilleure disposition des colonnes et des murs. Des études paramétriques numériques ont été menées pour comparer la nouvelle méthode avec les méthodes classiques.

KEYWORDS:soft ground improvement method, finite element analysis, deep mixing method

1 INTRODUCTION

Deep mixing methods have been widely used in Japan for the foundation systems of embankments constructed on soft clayey ground, and various low improvement ratio arrangements have been proposed (Miki and Nozu 2004, Ishikura et al. 2009, Miki et al. 2011). Typical of recent applications is to achieve limited soil improvement— around 10-20%—through an arrangement of soil improvement columns. This reduces the volume of soil that must be improved and limits the ground settlement under the embankments. Moreover, embankment construction in urban areas requires strict control of ground deformation, especially in the areas adjacent to the embankment toes.

The authors propose a new hybrid application of deep mixing columns combined with walls (Tsutsumi et al. 2009) as a method of improving the soft ground under embankments to control ground deformation. In this paper, the concepts and general functions of the method are introduced. The paper then describes a case in which the method was applied under a tall embankment 7 m in height. Two-dimensional finite element analysis was adopted to simulate the performance. Also proposed is a design flow for the new method that efficiently determines the best arrangement of deep mixing columns and walls. Finally, numerical parametric studies were carried out to compare the new method with conventional methods.

2 CONCEPTS AND GENERAL FUNCTIONS OF A HYBRID APPLICATION OF DEEP MIXING COLUMNS COMBINED WITH WALLS

The basic concept of this method is to place deep mixing walls in the ground directly under the embankment slopes, which

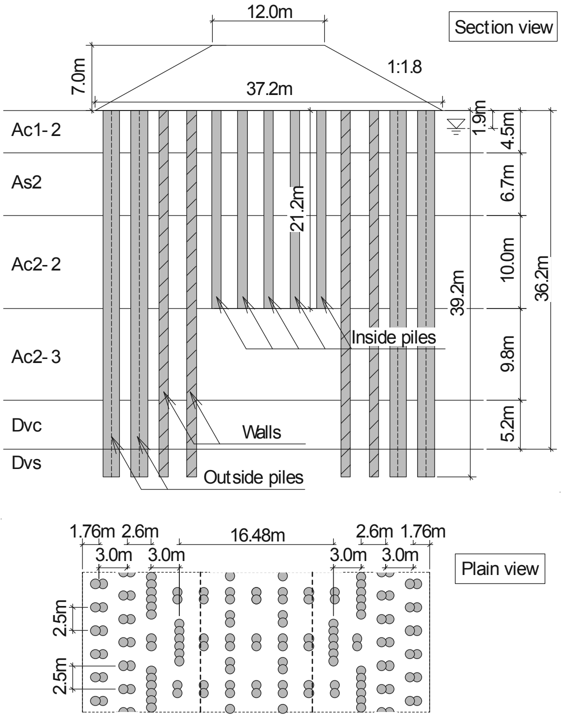

Figure 1.Geological profile and arrangement of the deep mixing columns and walls at theconstruction site where the method was applied.

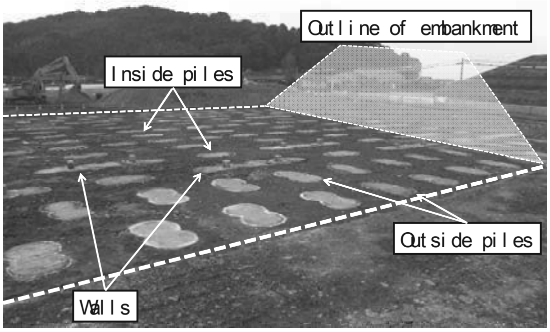

Figure 2.Ground surface after soil improvement.

bear the embankment loads as well as the lateral movement of the soft ground. Deep mixing piles are placed inside and outside the walls to restrict vertical and horizontal deformation caused by the embankment.

Figure 1 shows an example of the arrangement of deep mixing columns and walls at a site. The function and placement of each pile and wall are explained below.

Inside piles: Columns placed in the ground directly under the crown of the embankment. This part transfers the load from the center part of the embankment to the deep layer.

Walls: Walls are placed in the ground under the edges of the embankment crown. This part bears a large part of the embankment load and prevents the soil from moving.

Outside piles: Columns placed in the ground directly under the embankment slopes. This part transfers the load of the embankment slopes.

This method is designed to economically satisfy the limit value of settlement by optimizing and minimizing these parts in the design.

3 TRIAL EMBANKMENT

3.1 *Work outline*

The effectiveness of this method was demonstrated in a road construction project along the Ariake Sea in Kumamoto Prefecture. The soft clay at the construction site was about 40 m thick, so a large volume of settlement could be expected after constructingan embankment 7m in height. Some parts of the proposed road were close to residential buildings. Therefore, a limit value for deformation was set not only for the embankment but also for the area adjacent to the embankment, as described below.

Embankment: Settlement sincethe start of service is equal to or lower than 300 mm.

Adjacent area: Lateral and horizontal displacement since the start of construction is equal to or lower than 20 mm.

During the design stage, many of the arrangements were compared using two- and three-dimensional effective stress analysis. After considering all of the above, the arrangement shown in Fig. 1 was determinedto be optimal. Each column had a design strength of 1.0MN/m^2, and the arrangement hadan improvement ratio of 18.5%.

Before the embankment was constructed, settlement plates and pressure gauges were installedfor the purpose of taking measurements. The ground surface after soil improvement is shown in Fig. 2.

3.2 *Result of construction*

Figure 3 shows the settlement history of the ground surface at the center of the embankment. The same figure also shows a similar settlement history, observed at a trial embankment nearby with no subsoil treatment. In the improvement case, 200mm of settlement occurred one year after embankment construction. Subsequently, settlement converged in both cases.

Table 1.Material properties used for numerical model

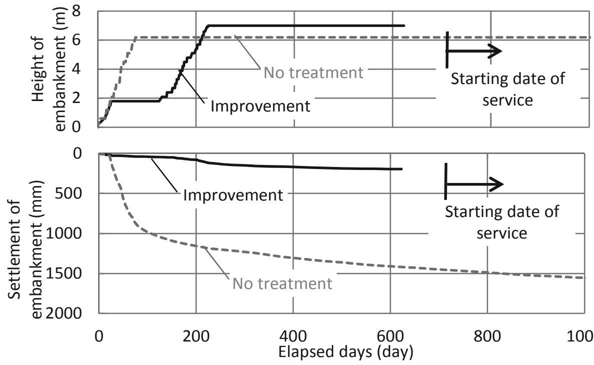

Figure 3.History of ground surface settlement in at the center of the embankment.

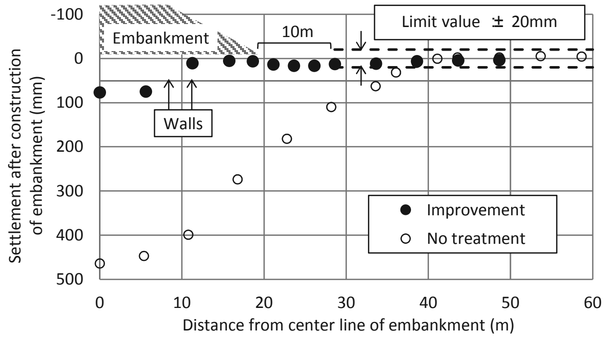

Figure 4.Distribution of ground surface settlement after construction of the embankment.

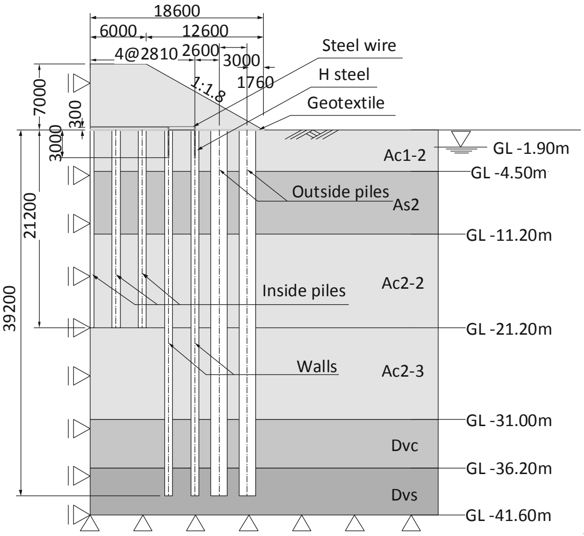

Figure 5.Section view of the numerical model.

Figure 4 shows the settlement history fora one-year period after the construction road was removed.In the improvement case, large the walls prevented deformation under the embankment, keeping the settlement around the embankment below the limit value. The vertical strain measured in the walls is shown in Fig. 7; this, too, was kept below the fracture strain value.

3.3 *Back-analysis*

To investigate the applicability of two-dimensional effective stress analysisunder actual construction conditions, the geological profile and mechanical properties of the deep mixing columns were analyzed using Plaxis 2D Ver.9.02.

The numerical model is shown in Fig. 5. Due to the symmetry of the embankment, only half of the geometry was considered for the model. The distance from the embankment

	Unit weight γ_t (kN/m^3)	Effective cohesion c' (kN/m^2)	Effective angle of friction φ' (deg.)	Deformation modulus E (kN/m^2)	Initial void ratio e_0	Consolidation yield stress p_c (kN/m^2)	Compression index λ	Expansion index κ	Critical state parameter M	Poisson's ratio ν	Coefficient of permeability k (cm/sec)
Embankment	19.0	10.0	35.0	28,000	-	-	-	-	-	0.25	1.00×10^{-3}
Ac1-2	14.6	10.0	36.4	1,720	2.13	36.8	0.289	0.029	1.48	0.35	1.30×10^{-6}
As2	18.7	-	-	28,000	-	-	-	-	-	0.25	1.00×10^{-3}
Ac2-2	14.3	10.0	36.2	6,380	2.53	146.1	0.665	0.067	1.47	0.35	3.00×10^{-7}
Ac2-3	15.1	10.0	33.0	7,130	2.00	178.5	0.408	0.041	1.33	0.35	2.30×10^{-7}
Dvc	15.8	10.0	33.0	6,510	1.21	215.7	0.149	0.015	1.33	0.35	1.40×10^{-9}
Dvs	19.0	-	-	70,000	-	-	-	-	-	0.35	1.00×10^{-3}
Columns	19.0	-	-	367,000 – 718,000*1	-	-	-	-	-	0.20	1.40×10^{-9} - 1.00×10^{-3}*2

*1 The deformation modulus of thedeep mixing columns was derived from quality verification tests, which reduced dependence on the improvement ratio.

*2 The coefficients of permeability of the deep mixing columns are same as those for each layer.

toe to the lateral boundary is 80m. As a boundary condition of deformation, the bottom surface was fixed. The side surface was free verticallyand fixed horizontally.As a drainage condition, excess pore water pressures at the ground surface and bottom surface were set to zero.

The soil layer is modeled as an elasto-plastic material using the Sekiguchi-Ohta model (Sekiguchi and Ohta 1977). The sand layers and deep mixing columns are modeled as a linear elastic material. The embankment is modeled as an elasto-plastic material using the Mohr-Coulomb model. Table 1 lists the model parameters used for the analysis.

The history of the embankment construction was modeled bybuilding up the elements. In converting from actual three-dimensional ground to the two-dimensional numerical model, the deformation modulus of the deep mixing columns was reduced according tothe improvement ratio and the coefficient on permeability for deep mixing columns was set to thevalue for each layer of ground.

The following figures are for the sake of comparison and analysis: Figure 6 shows the history of ground-surface settlement at the center of the embankment; Fig.7 shows the distribution of ground-surface settlement after construction of the embankment; Fig. 8 shows the horizontal displacement and vertical strain of the walls. The settlement history and displacement of the ground surface and walls are quantitatively evaluated using two-dimensional analysis. However, a clear difference in the vertical strain exists at greater depths. In the numerical models, the deformation modulus of wallsless than 21 m in height is lower than that of walls greater than 21m in heightas perthe arrangement of the deep mixing columns. This is thought to be the cause of the difference in vertical strain. Individual material propertiesare effective for evaluating the strain distribution of walls.

4 DETERMINING THE OPTIMUM ARRANGEMENT OF DEEP MIXING COLUMNS

In this method, the piles and walls are effectively arranged according to the limit values of deformation in the embankment and the adjacent area. Due to the countless combinations of planar arrangements and improvement depths, arbitrary parametric studies require considerable time to identify optimum arrangement. Therefore,the following3-step method is proposed fordetermining the optimum arrangement.

1) Determine the planar arrangement: First, walls are placed in the ground under the edges of the embankment crown. Next, inside and outside piles are arrangedequidistantly by an amount not less than the necessary improvement ratio α, defined as

$$\alpha=\gamma\cdot H/q_{uck} \quad (1)$$

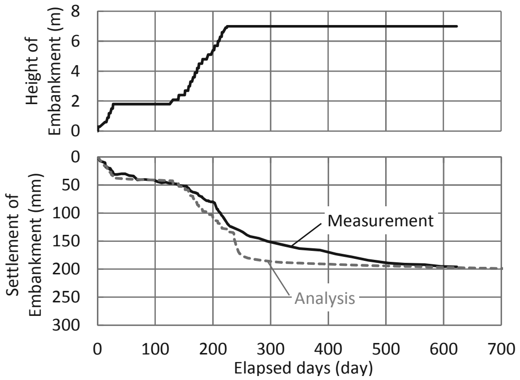

Figure 6.Settlement history of ground surface in center of the embankment

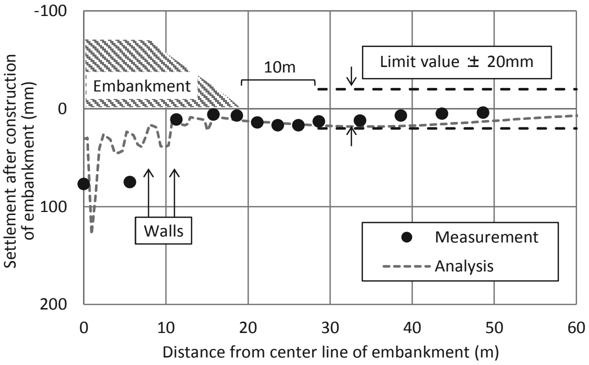

Figure 7.Distribution of ground surface settlement after construction of the embankment

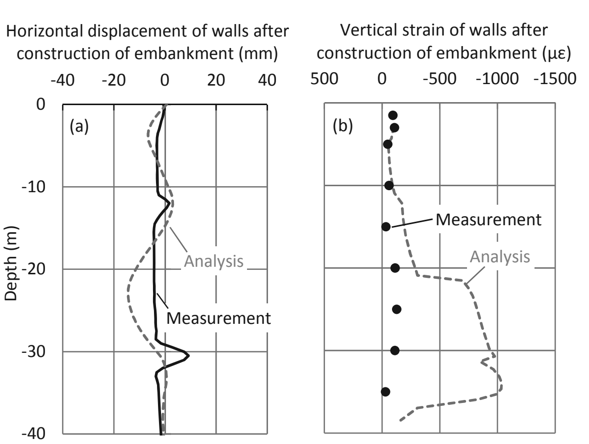

Figure 8.(a) Horizontal displacement of walls (b) Vertical strain in walls

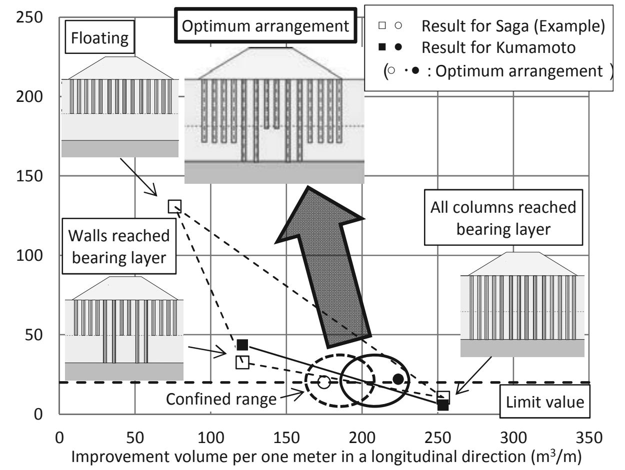

Figure 9.Example of confining the range of consideration and the result of the consideration for in-situ construction in Kumamoto

in which γ is the unit weight of the embankment, H is the height of the embankment and q_{uck} is the design strength of the deep mixing columns.

2) Confine the range of consideration: For the planar arrangement noted above, the deformation of three arrangements with different improvement depths(as shown in Fig.9) is calculated. The relation between the improvement volume and the deformation of the three arrangements is illustrated in Fig. 9. The range of consideration is narrowed by comparing with the limit value of deformation in the adjacent area.

3) Identify the optimum arrangement: The optimum arrangement in the range noted above is the arrangement with the lowest improvement volume that satisfies the limit value.

Figure 9 shows the results of a search for the optimum arrangement in areas along the Ariake Sea in Saga Prefecture. Figure 9 also showsthe results of a search in Kumamoto as an example of an arbitrary parametric study. The positional relation between both cases is fitted and the results indicate the effectiveness of the search method.

5 COMPARISON WITH CONVENTIONAL METHODS

To confirm the effect of displacement suppression, a hybrid arrangement is compared with conventional columns arrangements as well asan arrangement in which the columns are equidistant and narrowly spaced.

Under the same geological conditions and embankment height as in the Kumamoto case, the settlement of the embankment and at a point 10 m from the embankment toes of each arrangement were calculated using two-dimensional analysis.

Figure 10 shows the relation between individual settlement values and improvement volumes per meter in the longitudinal direction. Regarding settlement of the embankment, the settlement of the hybrid arrangement and the equidistant arrangement are lower than the arrangement under the slopes, confirming the effect of displacement suppression. For the settlement ata point 10m from the embankment toes, the hybrid arrangement is the lowest among same improvement volumes. When the limit value of settlement in the adjacent area is 20mm, the hybrid arrangement is more effective than conventional methods in reducing the improvement volume.

6 CONCLUSIONS

On-site measurements confirmed the method’s effectiveness in suppressing displacement. The validity of deformational estimation using two-dimensional effective stress analysis also

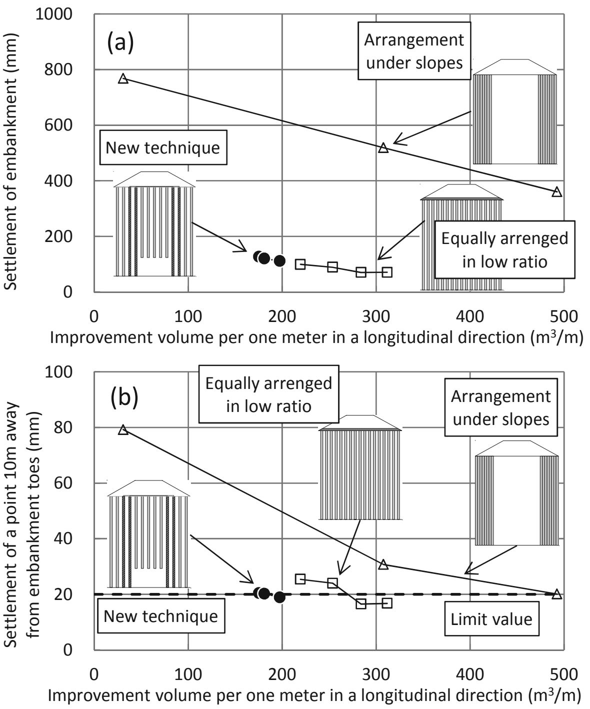

Figure 10.(a) Settlement of embankment (b) Settlement at a point 10 meters from the embankment toes.

was confirmed. However, little difference was seen in the estimation of stress and strain distribution in the walls.Using individual material properties for the walls, however, is effective.The two examples of searching for the optimum arrangement using the method proposed in this paper confirmed the method’s effectiveness. Analytical comparison ofthe new method with conventional methods also confirmed the economic efficiency of the new method.

7 ACKNOWLEDGEMENTS

The development of this column link method is the result of collaborative research involvingthe Public Works Research Institute, Japan, and thirteen private corporations in Japan. The authors are particularly gratefulfor the kind assistance of ShouichiTsutsumi (PWRI), Hirotaka Kawasaki (Shimizu Corp.), ShouichiTsukuni (Takenaka Civil Eng. & Const. Co., Ltd.), and NaotoshiShinkawa (Fudo Corp.).

8 REFERENCES

Miki, H. and Nozu, M. 2004. Design and numerical analysis of road embankment with low improvement ratio Deep Mixing method,*Geotechnical Engineering for Transportation Projects*, Vol. 2,1935-1402.

Ishikura, R. Ochiai, H. and Matsui, H. 2009. Estimation of settlement of in-situ improved ground using shallow stabilization and floating-type columns, *Proceedings of 17th International Conference on Soil Mechanics and Geotechnical Engineering*, 2394-2398.

Miki, H. Okochi, Y. and Makino, M. 2011. Evaluation of constraint effect of DMM with varied shape and arrangement of stabilized bodies using centrifuge model test, *Proceedings of Indian Geotechnical Conference*, 501-504.

Tsutsumi, S. Sawamatsu, T. Iso, Y. and Oshita, T. 2009. Centrifuge model experiment of new improvement type in deep mixing method with steel tied by cable for lateral flow, *Deep mixing 2009 Okinawa symposium*.

Sekiguchi, H. and Ohta, H. 1977. Induced anisotropy and time dependency in clays, Constitutive equations of soils, *Proceedings of, 9th International Conference on Soil Mechanics and Foundation Engineering*, 229-238.