Visualization of Settlement Behavior for Friction Pile Group during Consolidation

Visualisation du tassement pour un groupe de pieux frottant lors d'une consolidation

Ishikura R.
Kyushu University, Fukuoka, Japan

Matsuda H., Igawa N.
Yamaguchi University, Ube, Japan

ABSTRACT: Combined technology by using surface stabilization and floating type deep mixing soil stabilization has been developed as a method with acceptable settlement for maintaining the proper functioning of superstructures on deep soft soil layers. In this study, in order to apply for the practice of this ground improvement technique, settlement properties and skin friction were investigated by using two types of model tests and full scale FEM analysis in the consolidation process. For applying the image analysis to the model test, it was clarified that vertical strain of soft clay in the upper part of the improved portion was restrained by transferring the load to the deep soft soil layer. Further, from the analytic results, it was also found that full mobilization length of skin friction increased with elapsed time and converged to the constant value under the consolidation condition.

RÉSUMÉ : Une technologie combinée comprenant une stabilisation de surface et des fondations de type pieux sur sol renforcé a été développée pour limiter le tassement et assurer la stabilité des super structures dans les sols mous. Dans cette étude, afin d'analyser cette technique d'amélioration du sol, le tassement et le frottement ont été étudiés à l'aide de deux types de modèle numérique à grande échelle (MEF) pendant la phase de consolidation. Les essais sur modèles réduits ont montrés un transfert de la charge verticale de la partie supérieure du massif renforcé vers la partie profonde sur sol mou. En outre, à partir des résultats, il a également été constaté que la longueur de mobilisation du frottement augmente avec le temps et tend vers une valeur constante au cours de la consolidation.

KEYWORDS: ground improvement, skin friction, consolidation, floating soil pile

1 INTRODUCTION

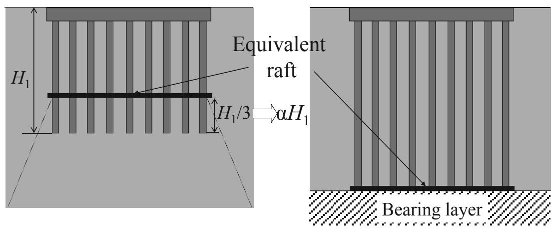
Economy and environmental safety have recently become very important factors in the construction of soil structures. So it is essential to develop the rational construction technique to correspond with the diversity of performance. In this demand of society, it is beginning to recognize the importance of the technique that combines different individual methods.

Piled raft foundation has recently been considered as a rational foundation type in Japan. This technology can reduce raft settlement by combining piles with maintaining the safety of the foundation on deep soft soil layers.

In the ground improvement field, combined technology by using surface stabilization and floating type deep mixing soil stabilization has also been developed. This technology has the advantage to reduce the construction cost of soil structures on deep soft soil layers. The structural form of the floating deep mixing soil piles with shallow stabilization is similar to that of the piled-raft foundation. In order to apply for the practice, it is important to clarify the mechanical behavior of this improved ground in relation to the combined effect between pile and raft.

In previous studies, several model tests for simulating this type of improved ground were conducted to investigate the influence of the improvement parameters such as improvement ratio and improvement depth on the settlement (Bergado et al., 1994; Miki et al., 2004; Ishikura et al., 2006). A method for predicting the total settlement of this improved ground has been previously proposed (Ishikura et al., 2006). On the other hand, from the model tests of piled raft foundation conducted on soft ground, it has been clarified that the failure of piled raft foundations was caused by the block consisted of the pile and soft clay enclosed within the pile group by Whitaker (1957).

Figure1 shows the concept of the equivalent raft method. In this figure, H_1 is defined as the improvement depth. As shown in this figure, Tomlinson et al. (2008) suggested that the pile



Floating type   End bearing type

Figure 1. Equivalent raft method

group transfers the load to the bearing layer at the elevation of the pile tips by an end-bearing-type mechanism. He also suggested that the pile group transfers the load to the soft soil layer at an elevation corresponding to 2/3 the pile length below the top of the piles. However, this method is still experimental and has not been sufficiently validated.

In this study, in order to investigate the group effect of this improved ground in the consolidating ground, consolidation settlement behavior was observed by using two types of model tests. From the test results, the influence of improvement conditions on the consolidation settlement and skin friction was discussed. Secondly, ground behavior was observed through the rubber membrane of transparent plate. By using image analysis, several strain distributions of the model ground were clarified. Based on the model tests, group effects during consolidation were discussed. In particular, skin friction under different improvement conditions were formulated.

Finally, in order to consider the equivalent raft elevation in relation to the improvement conditions, full scale FEM analysis were performed in the consolidating ground using the different pile skin friction resistance. From the results, equivalent raft elevations were discussed in the consolidation process.

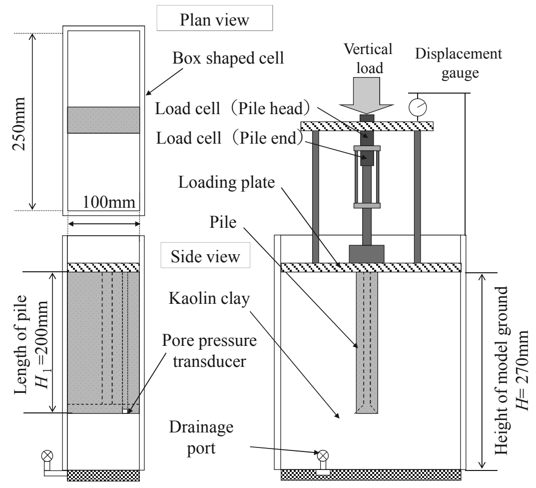


Figure 2. Loading model test under the plane strain condition

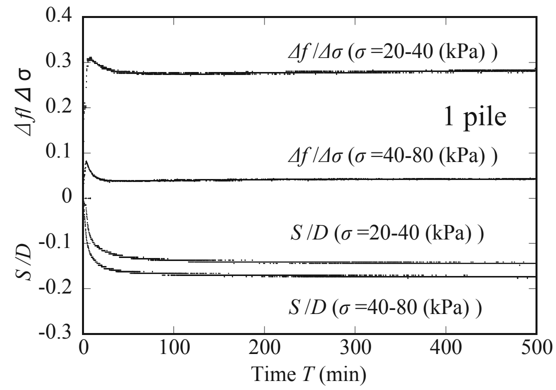


Figure 3. Relationships between skin friction and settlement

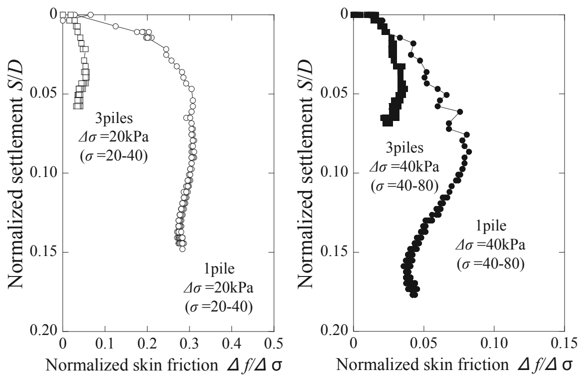


Figure4. Relationships between normalized settlement and skin friction

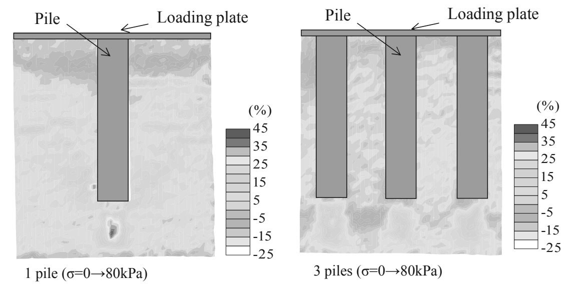


Figure5. Vertical strain distribution after consolidation

2 VISUALIZATION OF GROUND BEHAVIOR UNDER PLANE STRAIN CONDITION

2.1 *Outline of model test*

Figure 2 shows the apparatus used in the model test under the plane strain condition. The model tests were carried out with drainage at the upper and lower surfaces. Wall friction was reduced by a rubber membrane between the specimen and acrylic plate. The tests for the model ground were conducted under stress controlled conditions. The vertical load and consolidation settlement were also measured. This apparatus can also measure the pile head and end resistance individually at the center of model pile (Ishikura et al., 2012).

The model ground was prepared by using Kaolin clay and model pile. Kaolin clay was remolded in a slurry condition with a water content of about 80%. This slurry was then poured into the consolidation cell up to a depth of about 350mm. The specimen was consolidated under a pre-consolidation pressure of 20kPa using a bellofram cylinder until the end of primary consolidation. After pre-consolidation, a model ground with a height H of about 270mm was obtained.

The model piles are composed of aluminum and have 30mm in width D, 100mm in depth and 200mm in length H_1. Pore pressure transducer was placed at the bottom of model pile. After the model ground was prepared, consolidation pressure was applied and increased stepwise from σ =20kPa to 40kPa, 40kPa to 80kPa using bellofram cylinder. The loads are applied to unimproved ground and improved grounds with 1 or 3 piles.

2.2 *Test results and discussions*

Figure 3 shows the relationships between normalized settlement S/D, normalized incremental averaged skin friction $\Delta f/\Delta\sigma$ and elapsed time in the consolidation process with 1 pile. Incremental averaged skin friction Δf is the value that divides the load difference between the pile head and pile end by the surface area of the model pile. As shown in this figure, normalized settlement S/D increased with elapsed time and converged to the constant value. On the other hand, incremental averaged skin friction Δf initially increased just applying on the vertical pressure, however, after reaching the peak incremental skin friction Δf, these began to decrease with elapsed time and later converged to the constant values.

Figure 4 shows the corresponding relationships between the normalized settlement S/D and normalized averaged incremental skin friction $\Delta f/\Delta\sigma$ under several test conditions. It is considered that averaged incremental skin friction Δf is mobilized by acting relative displacement between the model pile and soft clay around the pile end surface during consolidation. As shown in this figure, normalized skin friction and normalized settlement curves with 1 pile are different from that with 3 piles under several consolidation pressures. However, normalized averaged incremental skin friction $\Delta f/\Delta\sigma$ increased initially with an increase of the normalized settlement and later converged to the constant value under all the test conditions.

Figure 5 shows the vertical strain distributions with 1 pile and 3 piles. These strains can be obtained from the deformation vectors during loading model tests. Deformation vectors are obtained by observing the ground behaviors through the rubber membrane. As shown in this figures, vertical strain of soft clay just below the pile end increased significantly with 1 pile. It is considered that the applied load is transferred from the model pile to the soft clay. It is also observed that vertical strain of soft clay just below the pile end with 3 piles is smaller than that with 1 pile. On the other hand, soft clay just below the loading plate has little vertical strain in comparison with that of just below the pile end in both test conditions.

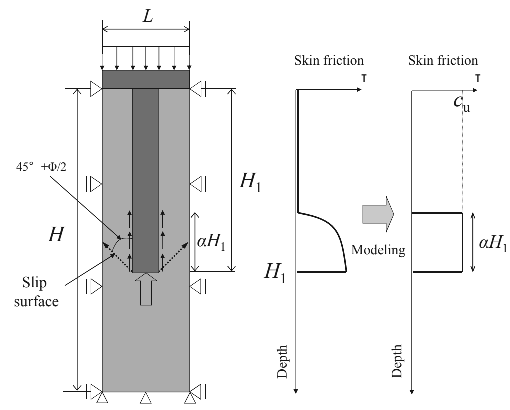


Figure6. Hypothesis of skin friction around the surface

2.3 *Prediction model for skin friction of floating-type column*

In this study, in order to evaluate the skin friction applied around the surface of floating-type columns, FEM analysis with the Cam-clay model as the constitutive equation was performed using axi-symmetric and plane strain models (Ishikura et al., 2006). H, H_1 and L denote the ground depth, the improvement depth and the distance between the improved columns or walls, respectively. The ground surface was deformed equally by the rigid plate on the assumption of shallow stabilized ground.
From the results of FEM analysis, the upward skin friction applied around the surface of the improved column is determined using the approximate formula given in Eq. (1).

$$\frac{\bar{\tau}}{p_0} = \frac{c_u}{p_0} \bullet \frac{1}{H_1/L} \ (\bar{\tau} \Box c_u) \qquad (1)$$

p_0 denotes the pre-consolidation pressure of the soft clay. $\bar{\tau}$ denotes the averaged skin friction applied around the surface of the column. This value is obtained from the difference between the stress applied on and immediately below the improved column. Each value of $\bar{\tau}$ is normalized by the p_0. H_1 is normalized by the value of L. The normalized average friction $\bar{\tau}/p_0$ decreases with an increase in H_1/L. Furthermore, the maximum value of $\bar{\tau}/p_0$ is almost equal to the shear strength ratio c_u/p_0. It is clarified that $\bar{\tau}$ changes under several conditions with different values of H, H_1, and L.

Here, c_u is the undrained shear strength. The approximate curve almost corresponds to the relationship between the upward averaged skin friction and the improvement parameters. It is considered that skin friction is mobilized around surface acting relative displacement between the column and soft clay. The combined foundation transfers the load to the pile group via the raft; hence soft clay between the friction piles in the upper part of the combined foundation is enclosed.
Figure 6 shows the hypothesis of skin friction around the surface of columns. As shown in this figure, if the slip surface that has inclination of 45 degrees from the pile end to the upper part has occurred, the intersection adjacent the column has been existed. When the length from this intersection to the column end is supposed the length that the skin friction is mobilized, the equivalent conversion ratio α which is defined as the ratio between the column length and the length that the skin friction is mobilized is introduced in Eq.(2).

$$\alpha = L/H_1 \qquad (2)$$

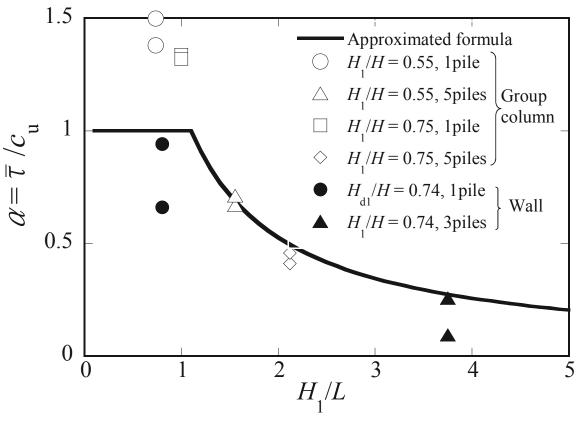


Figure7. Formulation of equivalent conversion ratio α

When c_u is defined as the undrained shear strength near the surface acting relative displacement between the column and soft clay, α is also given in Eq.(3) by using Eq.(1).

$$\alpha = \frac{\bar{\tau}}{c_u} = \frac{1}{H_1/L} \ (H_1/L \Box 1) \qquad (3)$$

Figure7 shows the formulation of the equivalent conversion ratio α. Experimental values of two types of loading model tests were also plotted (group column type and wall type). As shown in this figure, equivalent conversion ratio α nearly corresponds with the calculated value from Eq.(2) or Eq. (3).

3 TENDENCY OF SKIN FRICTION MOBILIZATION IN THE CONSOLIDATION PROCESS

3.1 *Numerical modeling*

In this section, in order to evaluate skin friction mobilization of this type of improved ground during consolidation, time dependent behaviors of skin friction were investigated by using FEM analysis. Numerical analysis has already been performed to investigate the neutral plane of pile in the consolidating ground (Yan, W. M. et al., 2012). Figure 8 shows the Axi-symmetric model for evaluating skin friction in this study.

Elastic model was applied to the shallow stabilized ground (raft) and column (pile). Modified Cam-clay model was also used in the soft clay as the constitutive equation. In this figure, h means the thickness of shallow stabilized ground, H_1 and L means the column length and distance between columns. H and d also means the thickness of soft soil layer and column diameter. In this analysis, in reference to the field measurement (Ishikura et al., 2009), h, H_1, d, L was set to 1.0m, 6.5m, 1.0m, 2.0 m , respectively. Table1 shows the material parameters. The ground water level was located at the ground surface of model ground and drainage boundaries were set to the upper and lower part of model ground. After applying to the 1 kPa on the ground surface, 150 kPa of Δp was applied to the ground surface in the assumption of fill with 7.5m. In this study, full shear resistance of soil-pile interface was modeled by Eq.(4).

$$\tau_f = Rc' + R\sigma_n \tan\phi' \qquad (4)$$

Here, c' and ϕ' means the effective cohesion and friction angle of soil, σ_n means the normal effective stress applied to the interface and R means the interface friction coefficient. These R values were used in 0.90, 0.75, 0.50, 0.30, respectively.

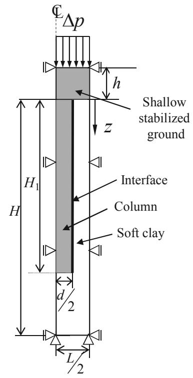
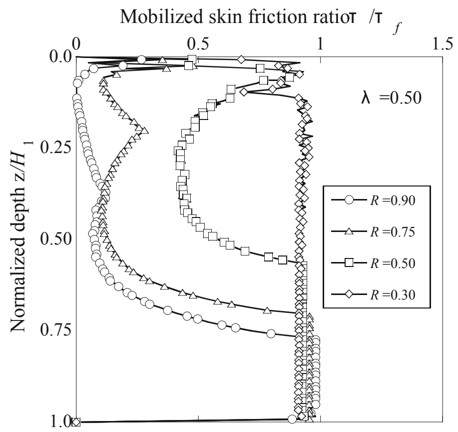


Figure8. Axi-symmetry analytic model

Table1. Material parameters for analysis

	Raft and Pile	Soil	Interface
γ_{sat}(kN/m^3)	16.8	16.8	
E(kPa)	1.0× 10^8		
ν	0.30	0.15	
λ		0.5 or 0.1	
κ		0.1 or 0.02	
c'(kN/m^2)		1.0	1.0
ϕ'(°)		30	30
OCR		1	
e_{ini} (at p'=1kPa)		1.8	
R			0.9,0.75,0.5,0.3



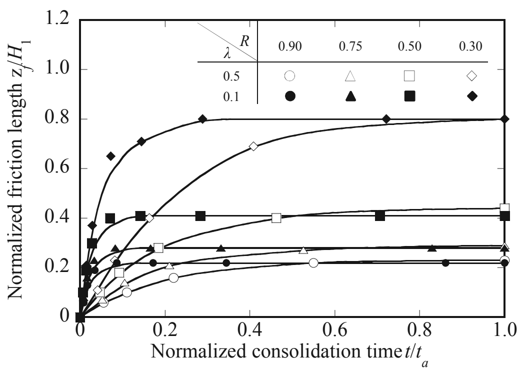


Figure9. Mobilized skin friction used in the different shear strength
Figure10. Time dependent tendency of friction mobilization

3.2 *Tendency of skin friction mobilization*

Figure 9 shows the relationships between degree of mobilized skin friction and normalized column depth after primary consolidation. Mobilized skin friction ratio was defined as the ratio of the current mobilized skin friction to the full skin friction resistance. Normalized depth was defined as the ratio between the column depth from just below the shallow stabilized ground and the column length. As shown in this figure, full mobilized skin friction length reduced with an increase of interface friction coefficient.

Figure10 shows the relationships between the normalized friction length and consolidation time by using different full shear resistance of soil-pile interface and soil properties. Normalized friction length means the ratio of full mobilized skin friction length to the column length. Normalized consolidation time was also defined as the ratio between the current time and the time that excess pore water pressure reached under 1 kPa in the soft clay. In all the conditions, full mobilized skin friction length increased with elapsed time and converged to the constant value. In this analysis, soil property λ has little influence on the full mobilized skin friction length. It is considered that skin friction is mobilized around the soil –pile interface acting relative displacement between pile and soft clay. So there is some possibility that the equivalent raft elevation can also be moved upward in the consolidation process.

4 CONCLUSION

In order to investigate the settlement behavior and skin friction of floating type improved ground with shallow stabilization during consolidation, loading model tests and full scale FEM analysis were performed. From the results, It was clarifed that vertical strain of soft clay in the upper part of the improved portion was restrained by the combined effect of pile and raft. Further, from the analytic results, it was also found that full mobilization length of skin friction increased with elapsed time and converged to the constant value in the consolidation process.

5 ACKNOWLEDGEMENTS

The authors wish to express their gratitude to many students, at graduate school of Yamaguchi University, for their supports. The first author is grateful to Prof. Y. Nakata of Yamaguchi University for his support of image analysis and is also grateful to Professor Noriyuki Yasufuku of Kyushu University and Professor Kiyoshi Omine of Nagasaki University for their advice and encouragement.

6 REFERENCES

Bergado, D.T., Chai, J.C., Alfaro, M.C. and Balasubramaniam, A.S. 1994. Improvement Techniques of Soft Ground in Subsiding and Lowland Environment, *Taylor and Francis*,pp.108 –121.

Ishikura, R., Matsuda, H., Yasufuku, N., Omine, K., Kashima, K., Igawa, N. 2012. Settlement behavior of piled raft foundation in soft ground, *Proceedings of the 9th International Conference of on Testing and Design Methods for Deep Foundation*, pp.485 -490.

Ishikura, R., Ochiai, H., 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*, pp.2394-2398.

Ishikura, R., Ochiai, H., Yasufuku, N., Omine, K., and Kobayashi,T. 2006. Estimation of the settlement of improved ground with floating-type cement-treated columns, *Proceedings of the 4th International Conference on Soft Soil Engineering*, pp. 628–635.

Miki, H.and Nozu, M. 2004. Design and numerical analysis of road embankment with low improvement ratio deep mixing method, *Geo-trans*, ASCE, 126(12), pp.1395-1402.

Tomlinson,M.J., Woodward, J. 2008. Pile design and construction practice, *5thEdition,Taylor and Francis*,pp.240-243.

Whitaker, T.1957. Experiments with model piles in groups. *Geotechnique*, l(4), pp.147-167.

Yan,W. M., Sun, T. K. and Tham, L. G. 2012.Coupled-consolidation modelling of a pile in consolidating ground, *Journal of Geotechnical and Geoenvironmental Engineering* ASCE, 138(7), 789-798.