A design verification method for pile foundations used in combination with solidified improved columns

Une méthode de vérification de la conception des pieux en combinant avec des colonnes de sol améliorés

Tomisawa K.
International member, Civil Engineering Research Institute for Cold Region
Miura S.
International member, Hokkaido University Graduate School of Engineering

ABSTRACT: In this study, research and development were conducted on a method of forming composite ground around piles mainly with solidified improved columns and reflecting the increased shear strength in pile design to support progress with a new foundation type for application in soft ground. The use of this approach, which is referred to as the composite ground pile foundation method, in line with site conditions is expected to reduce construction costs and improve the earthquake resistance of foundations. To systematize the technique, the study examined a design verification method based on the results of a large-scale model experiment.

RÉSUMÉ : Dans cette étude, une méthode de l'amélioration du sol autour des pieux à l'aide des colonnes solidifiées améliorées a été développée. L'effet de l'augmentation de la résistance au cisaillement dans la conception des pieux a été étudié pour un nouveau système de fondation dans les sols mous. L'utilisation de cette approche, appelé la méthode fondation composite, avec les conditions du site devrait permettre de réduire les coûts de construction et d'améliorer la résistance au séisme des fondations. Afin de systématiser la technique, l'étude a porté sur une méthode de vérification de la conception basée sur les résultats d'une modèle expérimentale à grande échelle.

1 INTRODUCTION

To support progress with a new foundation type for soft ground, research and development were conducted concerning a rational design method (Tomisawa *et al.* 2005, Tomisawa *et al.* 2007) in which composite ground consisting mainly of solidified improved columns is formed around piles and shear strength enhanced by such ground improvement is reflected in the form of horizontal resistance and bearing capacity. Although the use of this approach (tentatively referred to as the composite ground pile foundation method) in line with site conditions is expected to reduce construction costs, partial improvement to the support mechanism of piles alone is not enough; it is also necessary to ensure the seismic performance of foundations (Japan Road Association 2002) and to fully systematize the design and construction involved in the method.

Accordingly, this study closely investigated past research results (Tomisawa *et al.* 2005, Tomisawa *et al.* 2010) on the static and dynamic mechanical behavior of pile foundations used in combination with solidified improved columns, and examined the concept of a design verification method for composite ground pile foundations in line with existing design approaches (Japan Road Association 2002, Architectural Association of Japan 2001) based on the results of a large-scale model experiment.

2 DESIGN CONCEPTS

The concept of the composite ground pile foundation is based on reducing the foundation size to cut construction costs and improve seismic performance. Figure 1 shows a comparison of pile foundation specifications with the conventional method and composite ground foundation. For very soft ground, the number of piles is increased to ensure safety against the permissible horizontal displacement, and especially against the reaction force of the superstructure (Japan Road Association 2002). More than ten rows of cast-in-place piles measuring 1,000 mm in diameter are needed for preliminary design at an actual site, as shown in the figure.

Conversely, if a composite ground pile foundation is used for the same site, construction costs (including expenses incurred for ground improvement) can be cut by approximately 30% because only two rows of piles are required and the substructure and building frame sizes are reduced considerably.

The key points in the design of composite ground pile foundation are listed at the bottom of Fig. 1. In the new basic design method, the horizontal subgrade reaction/bearing capacity of piles is converted into the modulus of ground deformation E based on the increased shear strength, and the necessary range of ground improvement (i.e., the range of horizontal resistance of the piles) is set as a three-dimensional quadrangle that includes an inverted cone raised to the gradient of the passive slip surface $\theta = (45° + \phi/2)$ (ϕ: angle of soil shear resistance) from the depth of the characteristic length of piles $1/\beta$. In other words, the elastic subgrade reaction design method for piles is applied with the improvement strength of solidified improved columns set relatively low (equivalent to q_u = 200 kN/m^2). The validity of this method of handling solidified improved columns around piles as a reaction mass has been confirmed statically in horizontal/vertical loading and centrifuge model tests involving actual piles at several sites (Tomisawa *et al.* 2009). Centrifugal excitation testing and dynamic nonlinear finite element analysis have also verified seismic performance improvement effects, such as the reduction of pile foundation deformation by almost half compared to the conventional design method for unimproved ground, against Level 1 (acceleration: approx. 150 gal) and Level 2 (acceleration: approx. 750 gal) earthquake motion (Tomisawa *et al.* 2008).

However, for pile foundations used in combination with solidified improved columns to satisfy the performance requirements of the current design method (Japan Road Association 2002, Architectural Association of Japan 2001), it is considered necessary to develop a design verification technique to ensure the soundness of solidified improved columns, especially in relation to the dynamic behavior of piles.

Against this background, a large-scale model experiment was conducted for the purpose of establishing a new design verification method for composite ground pile foundations. The experiment focused on the manifestation of horizontal subgrade reaction (i.e., the feasibility of the elastic subgrade reaction design method for piles) in particular when the strength and depth of solidified improved columns were changed.

3 LARGE-SCALE MODEL EXPERIMENT

3.1 *Experiment overview*

The large-scale model experiment involved static horizontal cyclic loading tests on piles in composite ground with solidified improved columns using a laminar shear box (1,200 mm in width (loading direction) × 800 mm in depth × 1,000 mm in height) and a 15-tiered shear frame) (Japanese Geotechnical Society 2010). Photo 1 shows the experimental setup.

The test ground had an upper layer with solidified improved columns and a lower layer of natural soil to simulate a composite ground pile foundation. The natural soil was the sandy type with an *N* value of 10, and was formed with a compaction water content of w = 5%. The required strength of the composite ground with solidified improved columns was achieved using bentonite as the base material and adding early-strength cement (Public Works Research Center 2004). The test piles were the point-bearing steel pipe type simulating the actual scale (pile diameter D = 101.6 mm, thickness t = 4.2 mm, length L = 1,110 mm).

In the static horizontal loading experiment, peak-to-peak alternate loads were applied repeatedly with displacement controlled. Each loading step was performed three times with the maximum horizontal displacement of piles at the road

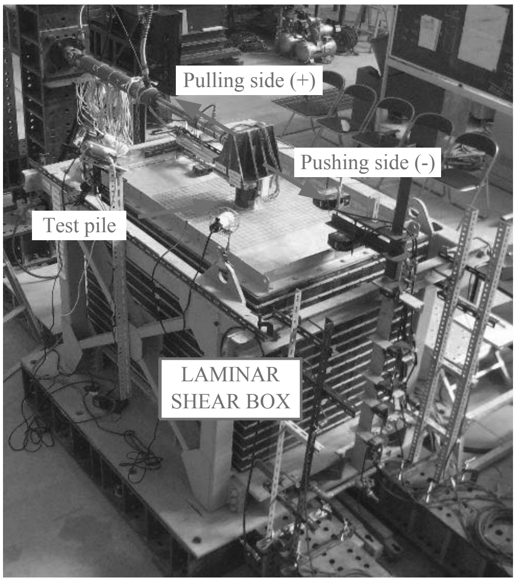


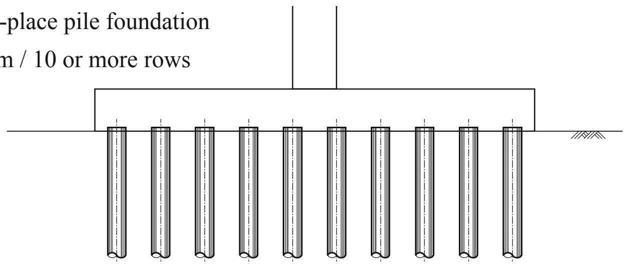
Photo 1. Setup of the large-scale model experiment

[Conventional design method]

Pile design method for soft ground: Horizontal resistance is insufficient and the foundation is large; the design method is not feasible.

(Site example) Cast-in-place pile foundation

Pile diameter 1,000 mm / 10 or more rows



Design-related problems: (1) group pile design method, (2) bearing capacity of piles depending on arrangement, (3) bending rigidity of footing

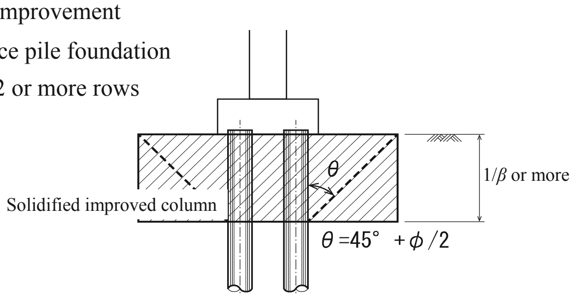
Problems with other methods: (1) lightweight embankment method: seismic performance; (2) inclined pile foundation: axial force, bending stress

[Composite ground pile foundation]

Concept: reduction of foundation size and improvement of seismic performance based on the use of piles in combination with ground improvement

(Site example) Cast-in-place pile foundation

Pile diameter 1,200 mm / 2 or more rows



Key points of design: (1) composite ground design method, (2) range of $1/\beta$ or more, $\theta = 45° + \phi/2$), (3) strength: q_u = 200 to 500 kN/m^2

Key points of the actual design method:
(1) Normal conditions: elastic subgrade reaction method (sliding/horizontal subgrade reaction verification)
(2) During Level-1 earthquake motion: seismic coefficient method (permissible horizontal displacement/cross-sectional force of piles at the boundary)
(3) During Level-2 earthquake motion: verification of horizontal load bearing capacity during earthquakes (permissible response ductility), dynamic nonlinear analysis

Figure 1. Comparison of the conventional design method for pile foundations in soft ground and composite ground pile foundations

Table 1. Experiment cases

Experiment case	Ground condition	Unconfined compressive strength q_u (kN/m^2)	Remarks
CASE-1	Entire layer: natural ground 1.00 m	-	No improved ground (natural ground)
CASE-2	Upper layer: solidified improved columns 0.50 m (= 1/β); lower layer: natural ground 0.50 m	200 (actual strength: 223)	Standard strength
CASE-3	Upper layer: solidified improved columns 0.50 m (= 1/β); lower layer: natural ground 0.50 m	1000 (actual strength: 1,440)	Varied improvement strength
CASE-4	Upper layer: solidified improved columns 0.25 m (= 1/2β); lower layer: natural ground 0.75 m	200 (actual strength: 205)	Varied improvement depth

surface *y* (1) 0.5 mm, (2) 1.0 mm, (3) 2.5 mm and (4) 5.0 mm, which was set at the time of design to simulate normal and earthquake conditions.

The large-scale part of the model experiment was conducted for the four cases listed in Table 1. Case 1 involved natural ground with no improvement and an N value of 10 for the entire layer. Case 2 involved two-layered ground where the unconfined compressive strength of the solidified improved columns in the upper layer qu was close to the standard value of q_u = 200 kN/m^2 (223 kN/m^2 in actual strength) and the improvement depth was $1/\beta$ = 50 cm in accordance with the basic design method for composite ground pile foundations. Case 3 involved two-layered ground where the improvement depth of solidified improved columns in the upper layer was $1/\beta$ = 50 cm and the unconfined compressive strength q_u was around 1,000 kN/m^2 (1,440 kN/m^2 in actual strength), which was about five times as large as that of Case 2 (ratio in actual strength: 1,440 kN/m^2 / 223 kN/m^2 ≈ 6.5 times). Case 4 involved two-layered ground where the unconfined compressive strength of solidified improved columns in the upper layer was similar to that of Case 2 (205 kN/m^2 in actual strength) and the improvement depth was half ($1/2\beta$ = 25 cm).

3.2 *Results of horizontal subgrade reaction experiment*

Tables 2 to 4 summarize the experimental results regarding the horizontal subgrade reaction in Cases 2 to 4 as obtained from the large-scale model experiment. The actual modulus of subgrade reaction *k* in the horizontal direction in the table was found via back-calculation from the basic equation of the elastic subgrade reaction method for finite piles (Eq. (1)) based on the H-y relationship at each displacement as found from the static horizontal cyclic loading experiment (Japan Road Association 2002).

$$y = (C_1 + C_2) / (2EI\beta^3) \tag{1}$$

Here, C_1 and C_2 are the integral constants of the pile head fixation condition, β is the characteristic value of piles (m^{-1}) $\beta = \sqrt[4]{(kD)/4EI}$, *D* is the pile diameter (m) and *EI* is the pile bending rigidity (kN/m^2). The measured horizontal subgrade reaction P_H was set as the product of the modulus of subgrade reaction in the horizontal direction *k* and the displacement of piles at the ground surface (maximum displacement).

The design modulus of subgrade reaction in the horizontal direction *k'* was calculated as the modulus of deformation *E* for the solidified improved columns. The design horizontal subgrade reaction P_{HU} was assumed to be the upper-limit value of the horizontal subgrade reaction, which is the passive earth pressure strength of composite ground with solidified improved columns as calculated using Eq. (2) (Japan Road Association 2002).

Table 2. Modulus of subgrade reaction in the horizontal direction *k* and horizontal subgrade reaction P_H in Case 2

Experiment case	Pile displacement at the ground surface (ratio to pile diameter)	Experiment value		Design value	
		Modulus of subgrade reaction in the horizontal direction k (kN/m^3)	Horizontal subgrade reaction P_H (kN/m^2)	Modulus of subgrade reaction in the horizontal direction k' (kN/m^3)	Horizontal subgrade reaction P_{HU} (kN/m^2)
CASE-2	0.5 [0.5%]	383,466	191.7	Composite ground with solidified improved columns 395,642	Upper-limit value for solidified improved columns 334.5
	1.0 [1.0%]	233,577	233.6		
	2.5 [2.5%]	121,290	303.2	Natural ground with an *N* value of around 10 110,165	
	5.0 [5.0%]	73,880	369.4		

Table 3. Modulus of subgrade reaction in the horizontal direction *k* and horizontal subgrade reaction P_H in Case 3

Experiment case	Pile displacement at the ground surface (ratio to pile diameter)	Experiment value		Design value	
		Modulus of subgrade reaction in the horizontal direction k (kN/m^3)	Horizontal subgrade reaction P_H (kN/m^2)	Modulus of subgrade reaction in the horizontal direction k' (kN/m^3)	Horizontal subgrade reaction P_{HU} (kN/m^2)
CASE-3	0.5 [0.5%]	2,150,363	1,075.2	Composite ground with solidified improved columns 3,098,529	Upper-limit value for solidified improved columns 2,160.0
	1.0 [1.0%]	1,056,491	1,056.5		
	2.5 [2.5%]	412,912	1,032.3	Natural ground with an *N* value of around 10 110,165	
	5.0 [5.0%]	202,867	1,014.3		

Table 4. Modulus of subgrade reaction in the horizontal direction *k* and horizontal subgrade reaction P_H in Case 4

Experiment case	Pile displacement at the ground surface (ratio to pile diameter)	Experiment value		Design value	
		Modulus of subgrade reaction in the horizontal direction k (kN/m^3)	Horizontal subgrade reaction P_H (kN/m^2)	Modulus of subgrade reaction in the horizontal direction k' (kN/m^3)	Horizontal subgrade reaction P_{HU} (kN/m^2)
CASE-3	0.5 [0.5%]	295,440	147.7	Composite ground with solidified improved columns 240,555	Upper-limit value for solidified improved columns 307.5
	1.0 [1.0%]	188,945	188.9		
	2.5 [2.5%]	104,641	261.6	Natural ground with an *N* value of around 10 110,165	
	5.0 [5.0%]	66,922	334.6		

$$P_{HU} = a_S \cdot q_u \cdot a_p \tag{2}$$

Here, α_S is the correction factor for composite ground in which solidified improved columns are used, and was set as 1.5 as in the calculation for cohesive soil ground in consideration of related physical properties.

The experiment results were examined as described here. First, the modulus of the subgrade reaction in the horizontal direction measured in the large-scale model experiment k was compared with the design value for the upper layer of composite ground with solidified improved columns k'. In Case 1 with natural ground whose N value was 10 for the entire layer, the measured value k roughly corresponded to the design value k' when the permissible horizontal displacement was 1.0% of the pile diameter, which is the standard value set in existing design methods (Japan Road Association 2002, Architectural Association of Japan 2001). In Case 2 where the improvement depth was $1/\beta$ and the unconfined compressive strength q_u was used as the standard strength, the k and k' values were similar for pile displacement at the ground surface when the displacement was 0.5% of the pile diameter (y = 0.5 mm). However, when displacement at the ground surface was 1% or more of the pile diameter, the measured value k did not satisfy the design value k'. While the measured value satisfied the design value at the same displacement in Case 4 where the improvement depth was $1/2\beta$, pile strain increased in the bottom layer of the solidified improved columns because no binding effect could be expected from them in the deep section, and the measured bending moment of piles tended to be underestimated. In Case 3 where the unconfined compressive strength of solidified improved columns q_u was extremely high, the measured value did not satisfy the design value at all displacement levels. In other words, although a certain degree of reaction effect can be expected, the elastic subgrade reaction design method for piles is not feasible if solidified improved columns are very strong.

Accordingly, to enable application of the basic design method for composite ground pile foundations, the improvement depth should always be $1/\beta$, and q_u = 200 kN/m^2 should be set as the standard value for the unconfined compressive strength of solidified improved columns. At the same time, the permissible horizontal displacement of piles used for composite ground pile foundations should be reduced to 0.5% of the pile diameter instead of 1% (or 15 mm) for natural ground.

Next, the measured horizontal subgrade reaction P_H in Cases 2, 3 and 4 was compared with the design value P_{HU}. It can be seen from the table that the measured P_H in Cases 2 and 4 satisfied the design value P_{HU} when pile displacement at the ground surface was up to around 2.5% of the pile diameter (y = 2.5 mm). However, the measured P_H in Case 3 was less than half of the design value P_{HU} at all displacement levels, indicating that the elastic subgrade reaction design method for piles is not feasible when the strength of solidified improved columns is extremely high as seen in the examination of the modulus of subgrade reaction in the horizontal direction.

4 CONCLUSION

Based on the results of a large-scale model experiment, the following findings were obtained in regard to a design verification method for pile foundations used in combination with solidified improved columns (i.e., composite ground pile foundations):

(1) In the basic design method for composite ground pile foundations, specifications for solidified improved columns should be based on engineering grounds, the improvement depth should be based on the characteristic pile length $1/\beta$, and q_u = 200 kN/m^2, with which constitutive laws of soils (Public Works Research Center 2004) can be followed, should be applied as the standard value for the unconfined compressive strength of solidified improved columns.

(2) While the limit state of damage to solidified improved columns in composite ground pile foundations is assumed to be reached within the range of pile deformation to around 2.5% of the pile diameter, it should be verified that the design horizontal subgrade reaction P_{HU} calculated as a product of the design pile displacement y and the design value k' is smaller than the passive earth pressure strength of composite ground given by solidified improved columns to provide inner stability and ensure column soundness. The use of this index is expected to help prevent cracking in improved columns and other types of damage caused by pile behavior in normal conditions and during Level-1 earthquakes.

(3) To sustain the reaction effect and ensure the external stability of solidified improved columns in composite ground pile foundations, the permissible horizontal displacement of piles in normal conditions and during storms and Level-1 earthquakes should be reduced to 0.5% of the pile diameter instead of 1% (or 15 mm) for natural ground. The elastic subgrade reaction design method for piles can be considered feasible when the above design verification method is applied.

In this paper, a new design verification method for composite ground pile foundations with consideration for the limit state of solidified improved columns was presented based on past results from research on pile foundations used in combination with solidified improved columns. Using these results and the outcomes of discussions by a technical exploratory committee consisting of foundation engineering experts from the government, universities and industries, guidelines on design and construction methods for composite ground pile foundations have been established (Civil Engineering Research Institute for Cold Region 2010).

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