Seismic strengthening technique for existing pile foundations in soft ground and liquefiable ground

Technique sismique fortifiante pour les fondations de piles existantes dans le sol mou et la terre liquéfiable

Koichi Tomisawa, Satoshi Nishimoto
Civil Engineering Research Institute for Cold Region, Public Works Research Institute Department, Japan, ko-tomsw@ceri.go.jp

Makoto Kimura
Department of Civil and Earth Resources Engineering, Kyoto University, Japan

ABSTRACT: Seismic reinforcement of existing pile foundations is not often conducted because it is difficult to apply seismic reinforcement on many construction sites, and required seismic performance and seismic diagnosis method of existing pile foundations has not been clarified. However, it is essential for existing pile foundations to implement seismic strengthening work, as well as the superstructures and substructures. In particular, large deformation of pile foundations in soft and liquefiable ground during earthquakes is a concern. In this research, seismic strengthening technique for the existing pile foundations, in which seismic resistance is improved by applying ground improvement around the existing pile foundations (hereinafter called "Composite pile method"), is examined. Composite pile method is an effective reasonable technique under limiting condition for construction. A patent for the method has been obtained and registered in “New Technology Information System” in Japan. In this paper, usefulness on a practical level is verified by reviewing the typical dynamic excitation experiment results on this method.

RÉSUMÉ : Le renforcement sismique des fondations de piles existantes n'est pas souvent conduit parce qu'il est difficile d'appliquer le renforcement sismique sur beaucoup de chantiers de construction, et, la performance sismique nécessaire et la méthode de diagnostic sismique de fondations de pile existantes n'a pas été clarifiée. Du point de vue de la prévention de désastre, il est essentiel pour des fondations de piles existantes de mettre en œuvre le travail fortifiant sismique, aussi bien que les superstructures et les infrastructures. Particulièrement, la grande déformation de fondations de piles dans le sol doux et liquéfiable pendant des tremblements de terre est une préoccupation. Dans cet article, la technique fortifiante sismique pour une telle sorte de fondations de piles existantes dans lesquelles la résistance sismique est améliorée en appliquant l'amélioration moulue autour des fondations de pile existantes ("la méthode de pile Composite ci-après appelée"), est examinée. La méthode de pile composite est une technique raisonnable efficace dans la limitation de conditions pour la construction. Dans cette présentation, l’utilité sur un niveau pratique est vérifiée en passant en revue les résultats d'expérience d'excitation dynamiques typiques sur cette méthode.

KEYWORDS: multiple steel pipes bridge pier integrated with pile foundation, damage control design, footing-less, pile foundation.

1 INTRODUCTION

In recent years, large-scale earthquakes occur frequently in countries around the world. Serious damage or deterioration due to aging has occurred in many existing bridges. Therefore, for bridges whose earthquake resistance was not enough, seismic reinforcement of the superstructures and substructures has been implemented. However, seismic reinforcement of existing pile foundations is not often conducted because it is difficult to apply seismic reinforcement on many construction sites, and required seismic performance and seismic diagnosis method of existing pile foundations has not been clarified. From the point of view of disaster prevention, it is essential for existing pile foundations to implement seismic strengthening work, as well as the superstructures and substructures. In particular, large deformation of pile foundations in soft and liquefiable ground during earthquakes is a concern.

In this paper, seismic strengthening technique for such kind of the existing pile foundations, in which seismic resistance is improved by applying ground improvement around the existing pile foundations (hereinafter called "Composite pile method"), is examined. Composite pile method is an effective reasonable technique under limiting condition for construction. A patent for the method has been obtained from the fact that engineering validity has been confirmed by experimental and analytical research and it has been registered in “New Technology Information System” in Japan. In this article, usefulness on a practical level is verified by reviewing the typical dynamic excitation experiment results on this method.

2 OVERVIEW OF DESIGHN AND CONSTRUCTION CONCEPT OF "COMPOSITE PILE METHOD"

Seismically strengthening an existing foundation by using additional piles, consecutive underground walls, steel pipe sheet pile foundation and caisson foundation are considered as conventional construction methods to reinforce an existing foundation. However, overburden removal and shutting the road to all traffic is needed because reinforcing material are directly installed to the existing foundation in such kind of strengthening methods, resulting in that their application is subject to constraints on the construction conditions. In addition, clear design standards for reinforcing methods have not been codified because dynamic mechanical behavior is complicated by applying additional structures which differ existing foundations. Therefore, seismic strengthening technique for the existing pile foundations in soft clay and liquefiable sand ground, in which seismic resistance is improved by applying ground improvement around the existing pile foundations (Composite pile method), has been proposed as shown in Fig. 1.

The design concept of the composite pile method is different from that of the other conventional reinforcement method in a

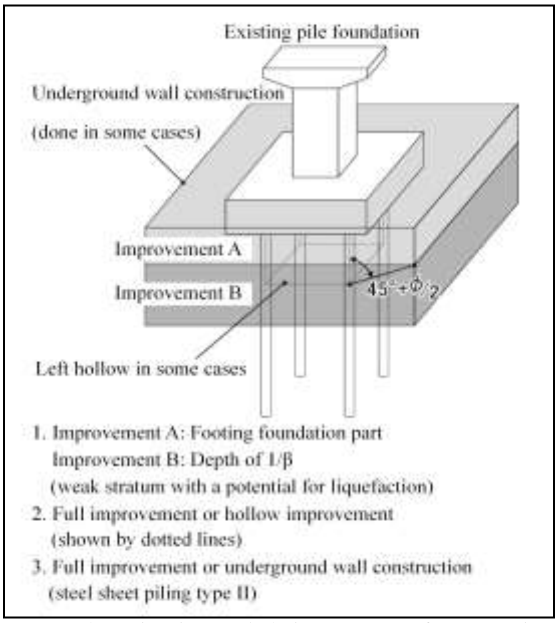


Figure 1. Schematic view and design concept of "Composite pile method".

fundamental way. It is able to reduce large-scale earthquake-induced displacement of the pile by improving soft clay and liquefiable sand ground with cement because mechanical behavior of pile foundations is influenced by relative stiffness of pile foundation to ground (Wei and Randolph, 1997), even if required seismic performance is not satisfied in conventional reinforcement methods and the cost is high to meet required seismic resistance. In other words, it aims to energy absorption during earthquakes by artificial ground around existing piles, the greatest feature of this method is to improve seismic resistance of not only existing pile foundation but also an entire structure. In the seismic design of this method, seismic intensity method is used to know mechanical behavior of the structure subjected to Level 1 ground motion. And horizontal capacity method, dynamic response analysis and non-linear finite element analysis is conducted using actual seismic waves to know dynamic mechanical behavior of the structure against Level 2 ground motion. The shear strength (uniaxial compressive strength q_u) of the soil improvement material, in order to evaluate behavior of improved ground using constitutive models for artificial ground, is set to be approximately 300 kN/m^2. However, it has been mandated to reconfirm mechanical behavior of the structure against Level 1 and Level 2 ground motion while confirming the variation in the strength of the improved body 28 days after construction completion.

This method has been already applied into the pile foundation newly constructed in special ground, where design criteria is not satisfied using a normal pile foundation (Tomisawa and Miura, 2007). All area including the inner ground between the piles is improved to obtain the necessary passive earth pressure as the piles can be installed after the ground improvement in this case. However, the inner ground between piles are not improved in the case that this method is used as seismic reinforcement method for existing pile foundation. As the results, the improved body is forming hollow shape.

The feature on the construction of this method is that it can be applied for any specification of piles even in narrow and low-ceilinged site (approximately 2 m). Besides, it is also the feature that there is no impact to the existing pile foundation in the process to apply the intermediate and deep ground improvement method for the peripheral part after improving the adjacent part using the low-displacement type ground improvement method. Sand compaction pile method (SCP), which is often used as liquefaction countermeasure, is not suitable for this reinforcement method because there is somewhat impact to the existing pile foundation in the process.

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 θ= (45° + ϕ/2) (ϕ: angle of soil shear resistance) from the depth of the characteristic length of piles $1/\beta$ as shown in Fig. 1 (Tomisawa and Miura, 2013). It is possible to improve the subsurface ground with the intermediate ground improvement method (Improvement A) and deeper area with the deep ground improvement method (Improvement B) at the same time. As the results, this method, compared with a conventional construction method for seismically strengthening a foundation by using an additional pile, can reduce construction cost of about 40% and shorten construction period of about 50%.

3 OUTLINE OF SHAKING TABLE TESTS

From a sequence of model experiments and numerical analysis in the previous research (Tomisawa & Miura, 2007), it is confirmed that the required horizontal subgrade reaction and passive resistance are performed against repeated load of static superstructure inertial force by improving with cement around pile foundation in soft ground which has too small shear strength, resulting in the improvement of the yield strength of the piles. Although the subgrade reaction force acting on the piles is not continuously performed in the plastic ground, it is possible to ensure the initial stiffness of the improved ground by re-solidifying with chemical grouting in case that cracks are generated in the improved body due to unexpected large deformation of the piles.

In this paper, large-scale shaking table tests are conducted in order to investigate dynamic behavior and seismic strengthening effect of the composite pile method in the soft peat and liquefiable sand ground subjected to Level 2 large-scale ground motions. Fig. 2 shows the laminar shear box on the shaking table used in this research. The laminar shear box, which measured 1200 m in width, 800 mm in length and 1000 mm in height, consists of 15 stages. The shaking direction of the shaking table is limited to one direction.

The steel pipe, which measured 1000 mm in length, 27.2 mm in diameter and 2.8 mm in thickness, is used to model a bearing pile with the scale of 1/30. The weight of 500 kg, which corresponds to the superstructure reaction force was fixed on the footing plate. In addition, in order to understand the deformation of the pile and the soil on the ground level during shaking in detail, the protruding length of the piles is set up as 10cm. The pile spacing is set up as $3D$ (D is the pile diameter). Fig. 3 shows the schematic view of the model tests named as Case-3, in which the peat ground is improved with cement around the piles except with the inner area. Table 1 shows the test cases.

The model ground consists of three layers; a) soft peat ground (Case-1 to 3) or liquefiable sand (Case-4 and 5) as the subsurface ground, b) natural ground as the intermediate layer and c) the bearing layer. The peat ground is prepared by mixing peat moss and kaolin clay in the ratio of 1:1 by dry weight and adding water as the water content is 200%. The saturated liquefiable sand with a relative density of 40% is prepared using Hamaoka sand. The natural ground and bearing layer is prepared by mixing Toyoura sand and bentonite to model the sandy soil with N-value of 10 and 30, respectively. The subsurface ground is not improved for Case-1 and 4, fully improved for Case-2 (full improvement) and partially improved around the piles except with the inner for Case-3 and 5 (hollow improvement). The improved area is 510 mm in width, 510 mm in length and 200 mm in depth as shown in Fig. 3. The improved ground is prepared with cement and clay as the uniaxial compressive strength q_u is 300 kN/m^2.

Fig. 4 shows the input wave used in the peat ground case (Case-1, 2 and 3), which is the 2011 Tohoku-Pacific Ocean Earthquake ground motion that is classified as a plate boundary Level 2 earthquake ground motion (Type I ground motion, Max acceleration 692gal, duration time 240sec). Sin wave with maximum acceleration amplitude of 500 gal, which is equivalent to Level 2 earthquake is used for the liquefiable sand case named as Case-4 and Case-5.

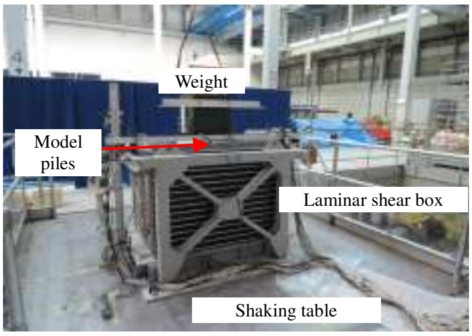


Figure 2. Setup of the laminar shear box apparatus.

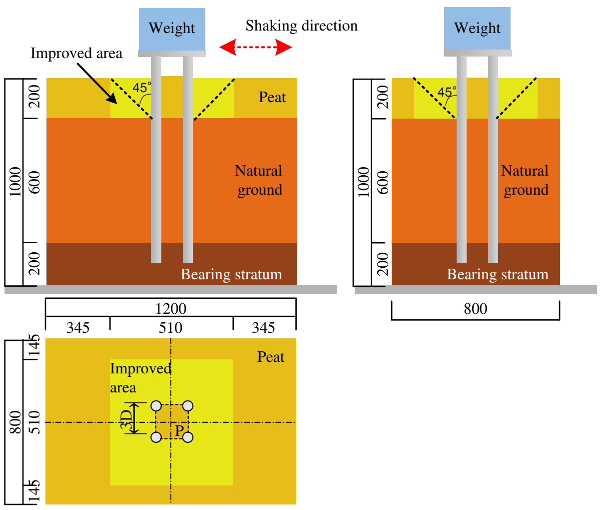


Figure 3. Schematic view of the shaking table tests (Case-3).

Table 1. Test cases.

	Soil type of surface	Ground improvement
Case-1	Peat	Unimproved
Case-2	Peat	Full improvement
Case-3	Peat	Hollow improvement
Case-4	Liquefiable sand	Unimproved
Case-5	Liquefiable sand	Hollow improvement

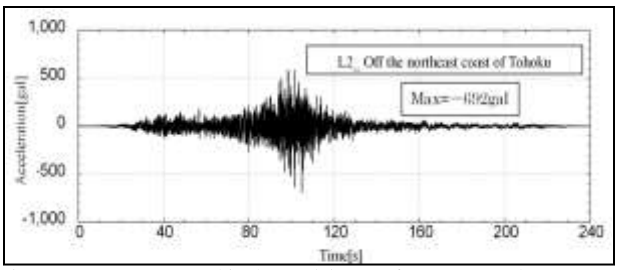


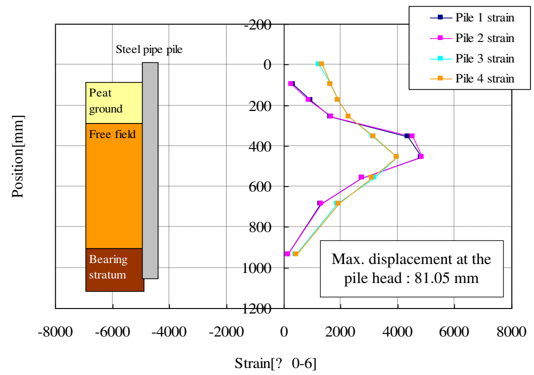
Figure 4. Input wave used in the model tests of Case-1, 2 and 3.

4 TEST RESULTS AND DISCUSSION

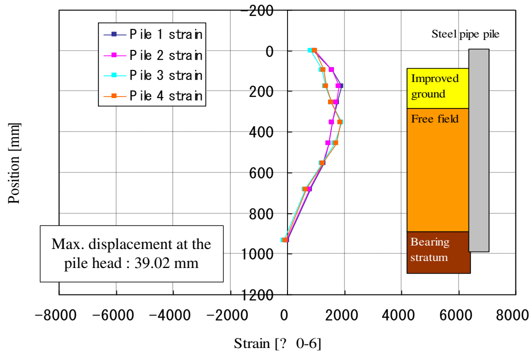
4 .1 *Peat ground case (Case-1, 2 and 3)*

The maximum displacement at the pile head during shaking is 81.05 mm, 39.02 mm and 44.78 mm, respectively. It is recognized from this fact that there is not large difference of reinforcement effect between Case-2 (full improvement) and Case-3 (hollow improvement).

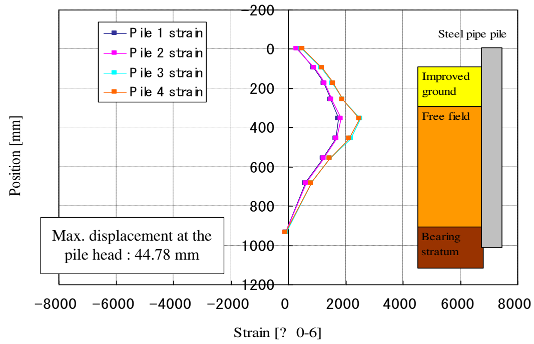
Fig. 5 shows the maximum bending strain distribution generated on the piles during shaking in the peat ground case (Case-1, 2 and 3). In Case-1 (unimproved type) the maximum bending strain exceeds 2000 $\mu\varepsilon$ which is general yield strain of the steel and reaches approximately 5000 $\mu\varepsilon$. On the other hand, the maximum bending strain in Case-2 (full improvement) and Case-3 (hollow improvement) is suppressed below 2000 $\mu\varepsilon$, which is half of the bending strain generated in Case-1. The serious difference between Case-2 and Case-3 are not seen in the maximum bending strain. Thus it is considered that the hollow improvement type has as enough seismic strengthening effect as the full improvement type (Tomisawa and Kimura, 2015).



(a) Case-1



(b) Case-2



(c) Case-3

Figure 5. Maximum bending strain distribution generated on the pile.

Fig. 6 shows the pile deformation after the test in Case-1 (unimproved type). The plastic bending deformation happens at the location where the maximum bending strain is observed as shown in Fig. 5(a). Conversely, as can be seen from the Fig. 7, the damage to the pile and ground improvement is not observed even in Case-3 because the displacement of the pile head is reduced.

4 .2 *Liquefiable sand case (Case-4 and 5)*

Fig. 8 shows the relationship of the response acceleration - displacement at the pile head for the liquefiable sand case (Case-4 and 5). It is confirmed that sand layer is fully liquefied in Case-4 (unimproved type), based on the observation that the excess pore water pressure ratio in the unimproved sand layer reaches 1. On the other hand, in Case-5 (hollow improvement type) the excess pore water pressure is suppressed below 0.8 even in the unimproved sand layer beneath the footing, which is surrounded by the improved area, resulting in decrease of lateral displacement at the pile head during shaking.

5 CONCLUSIONS

The following conclusions are obtained based on the experimental results;

1) Composite pile method has been proposed as seismic strengthening technique for existing pile foundations, in which seismic resistance is improved by applying low-strength ground improvement (uniaxial compression strength q_u = 300 kN/m^2) around the existing pile foundations through a depth of the pile characteristic length $1/\beta$. Unlike other approaches to integrate the existing foundation and a reinforcing material, the main purpose of the proposed method is to enhance seismic subgrade reaction of ground surrounding existing piles. This method, compared with a conventional construction method for seismically strengthening a foundation by using an additional pile, can reduce construction cost of about 40% and shorten construction period of about 50%.

2) According to the dynamic excitation experiment results for the pile foundations in peaty soft ground subjected to the great earthquake of plate boundary type (Level 2, Type I, Maximum acceleration 692 gal, Duration time 240 sec), the proposed method can reduce the maximum response displacement and strain of the existing piles during the ground motion almost by half.

3) According to the dynamic excitation experiment results for the pile foundations in liquefiable ground subjected to the great earthquake (sin wave with the maximum acceleration of 500 gal), the proposed method can reduce the maximum response displacement and strain of the existing piles less than a quarter of those for the case without the strengthening technique, and depress excess pore water pressure in the ground under the footing during the ground motion.

From the above, the effect of the seismic strengthening technique for existing pile foundations in peaty soft ground and liquefiable ground (composite pile method) has been verified. In order to contribute to the development of science and technology, it is expected to apply this proposed method based on the discussions with the relevant agencies.

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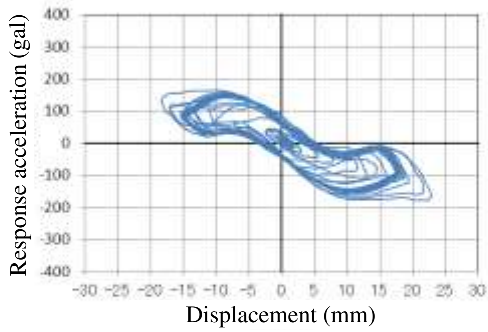
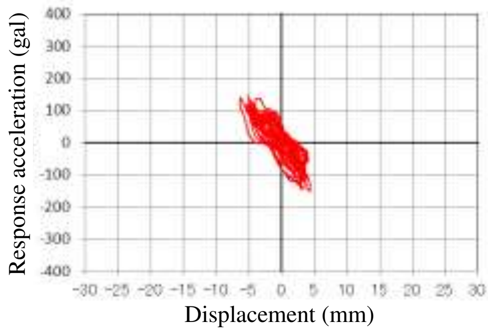
Figure 6. Pile deformation after the test in Case-1.

Figure 7. Pile and ground deformation after the test in Case-3.



(a) Case-4



(b) Case-5

Figure 8. Relationship between response acceleration and displacement of pile head obtained in Case-4 and 5.