A Study on Seismic Evaluation for Pile-Supported Building with Reusing Existing Piles

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SUMMARY
Reusing existing piles has advantages, but it is uncommon to replace a building with reusing the piles because of difficulties in seismic evaluation. Seismic response of the building may be significantly affected by the reuse methods of the piles. When the rigidity of existing pile heads are smaller than the rigidity assumed in seismic design because of construction method of pile head connection, new piles may be excessively loaded laterally. By setting the appropriate rigidity of new pile heads instead of increasing the number of piles, both new and existing piles are loaded reasonably. When it is difficult to connect existing piles directly to a raft because of piles arrangement and architectural planning, the piles are efficiently reused by improving the soil shallowly between the piles and the raft. This paper presents the findings about the appropriate strength and depth of improved soil under the reuse condition.

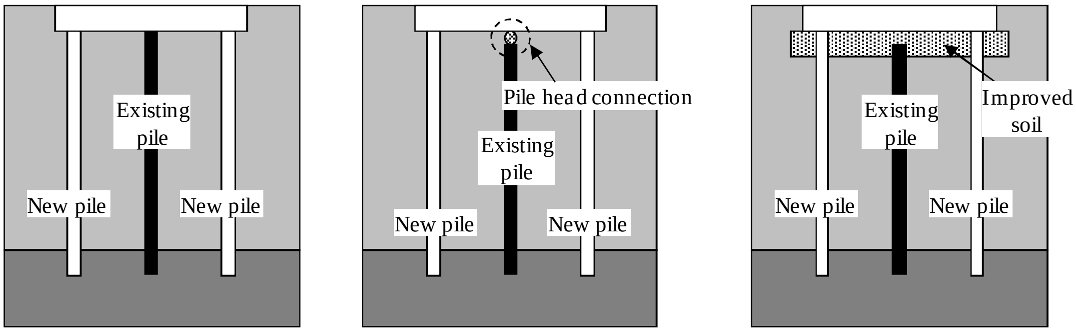
Keywords: Existing pile, Seismic evaluation, Finite element method, Rigidity of pile head, Improved Soil

1. INTRODUCTION

When replacing a building, reusing existing piles left in the soil is required in urban areas. Reusing the piles has advantages as shortening construction periods and reducing construction costs. In addition, it leads to reduction of construction waste and contributes to global environment conservation. In fact, it is uncommon to reuse the piles because of difficulties in non-destructive integrity evaluation for the piles and seismic evaluation for the building. Seismic response of the building may be significantly affected by the reuse methods of the piles. The purpose of this study is to investigate the effect of the methods on the behavior of the building and pile stresses under earthquakes.

Reuse methods of existing piles are divided into 3 classes (Fig. 1). When the piles have the same horizontal bearing capacity as new piles, both piles are connected to a mat slab directly (Fig. 1a). When the capacity is less than the capacity of new piles, the piles are connected to a raft with some kind of pile head connection (Fig. 1b). In Fig. 1a, both new and existing pile head conditions are assumed to be fixed in seismic design. In fact, when connecting existing piles, it is difficult to choose the same construction method of pile head connection as new piles because of the piles arrangement and the horizontal gap between the superstructure column and the pile. Thus, there is a strong presumption that the rigidity of existing pile head decreases. Figure 2 shows the summary of previous studies on the rigidity of pile head by construction methods. The rigidity increases with axial force increasing by seismic overturning moment, but is less than 1. At first, seismic response analyses were conducted to investigate the effect of the decrease of rigidity of existing pile head on seismic response.

It can be difficult to connect existing piles directly to a raft because of piles arrangement and architectural planning. One of the authors presented, by lateral loading tests, that the piles are efficiently reused by improving the soil shallowly between the piles and the raft (Fig. 1c). Secondary, seismic response analyses were conducted to investigate the appropriate strength and depth of improved soil under the reuse condition.



(a) Mat slab (b) Pile head connection (c) Improved soil

Figure 1. Reuse methods of existing piles

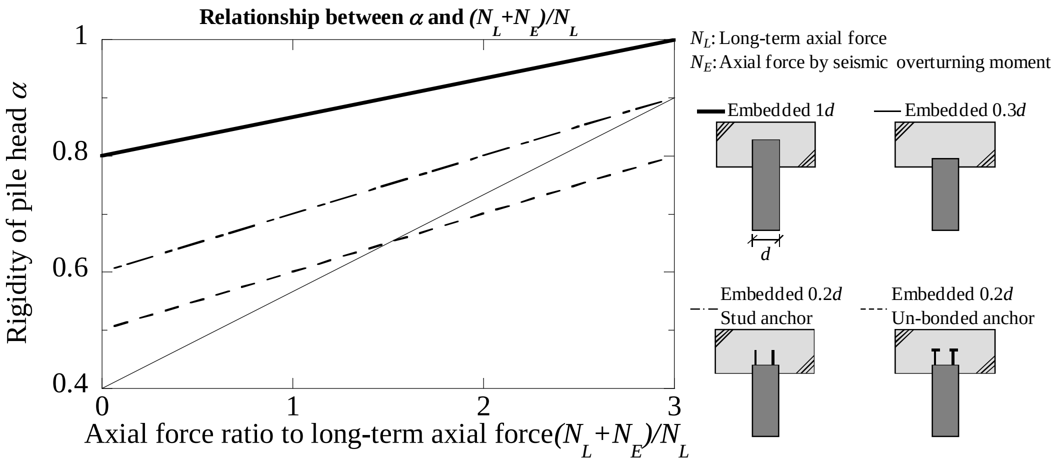


Figure 2. Rigidity of pile head by construction methods of pile head connection

2. EFFECT OF RIGIDITY OF PILE HEAD ON SEISMIC RESPONSE

2.1. Analytical method

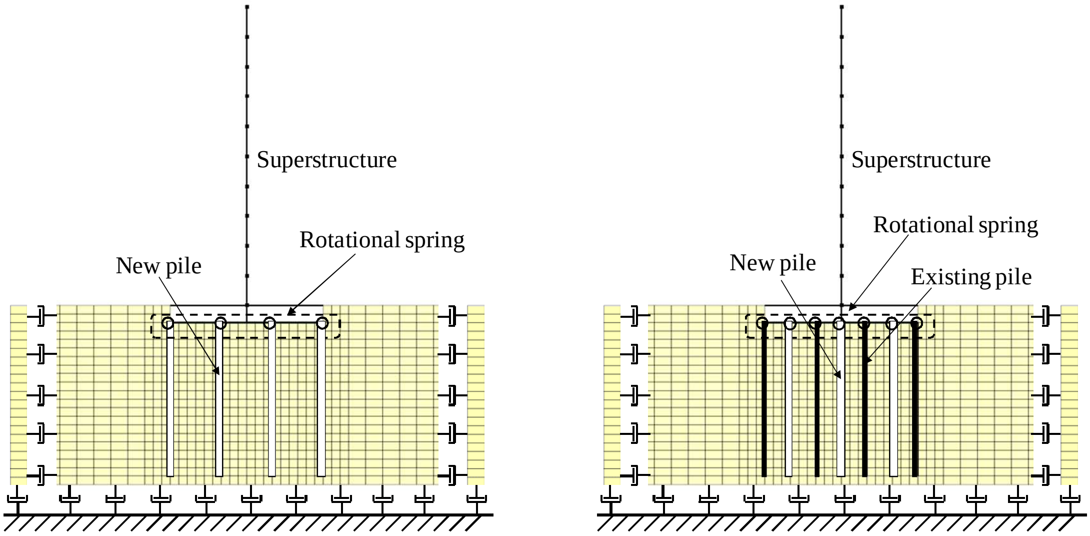
Analyses were conducted under the condition that cast-in-place concrete piles were left in the soil, where old 5-stories building was pulled down and replaced by new 10-stories building. Finite element models are shown in Figs. 3, 4. Analysis cases are shown in Table1. As shown in Fig. 3a, existing piles were ignored. 24 new piles (ϕ1500) were driven into the ground and arranged in a square 4x6. As shown in Fig. 3b, 24 existing piles (ϕ1100) were reused and arranged in a square 4x6. 12 new piles (ϕ1500) were driven into the ground to increase the vertical bearing capacity of pile foundation, and arranged in a square 3x4 between the existing piles. The distance between piles was 6 m and the depth of embedment was 2 m. Viscous boundaries were set at the sides and bottom of the model.

Superstructure was modelled as a lumped mass system with nonlinear shear spring elements. The material properties of superstructure are summarized in Table 2. The initial shear stiffness k_i was calculated from the following equations, and T was 0.8 sec.

$$k_i = \frac{k_n A_i (n-i+1)}{A_n} \tag{2.1}$$

$$A_i = 1 + \left(\frac{1}{\sqrt{\alpha_i}} - \alpha_i \right) \times \frac{2T}{1+3T}, \quad \alpha_i = \frac{w(n-i+1)}{wn} \tag{2.2}$$

where A_i=the distribution of seismic shear force coefficient along the height of building, T=the first natural period of building (sec), w=the floor weight (t), n=the number of stories. The damping of superstructure was proportional to the initial stiffness, and the damping factor h was 3 percent for the first natural period.



(a) Only new piles (b) Reusing existing piles

Figure 3. 2-dimensional finite element model

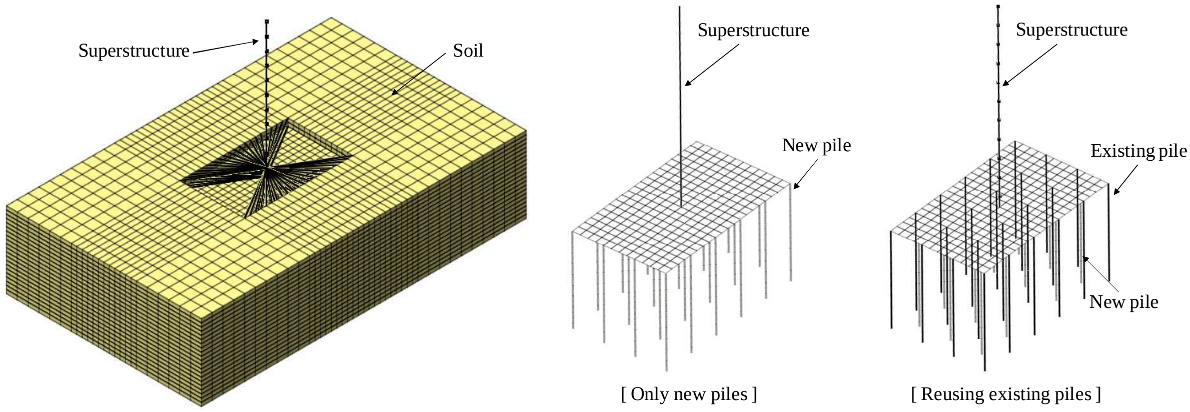


Figure 4. 3-dimensional finite element model

Table 1. Analysis cases

Case		(a) Only new piles	(b) Reusing existing piles
New Pile	Pile type	Cast-in-place concrete pile ϕ1500×24	Cast-in-place concrete pile ϕ1500×12
	Pile head condition	Fixed	Fixed
Existing pile	Pile type	-	Cast-in-place concrete pile ϕ1100×24
	Pile head condition	-	Rigidity of pile head α=0～1

Table 2. Material properties of superstructure

Rectangular plane shape of floor	18 m × 30 m
Floor height	3.5 m
Floor weight	1.2 t/m^2 (base: 1.5 t/m^2)
Hysteresis characteristics	Normal Tri Linear
Stiffness reduction ratio	α_c=0.25, α_y=0.01
Yield load Q_y / Crack load Q_c	3
Deformation angle at yield point	1/200

Soil was modelled as linear plane strain element for 2-D, as linear solid element for 3-D. The material properties of soil are summarized in Table 3. As shown in Fig. 5, the dynamic deformation properties of soil was expressed as following R-O model.

$$\frac{G}{G_0}\left\{1+\alpha\left(\frac{G}{G_0}\frac{\gamma}{\gamma_{ref}}\right)^{\beta-1}\right\}=1 \tag{2.3}$$

$$\alpha = 2^{\beta-1} \tag{2.4}$$

$$\beta = \frac{2+\pi h_{\max}}{2-\pi h_{\max}} \tag{2.5}$$

$$h = h_{\max}\left(1-\frac{G}{G_0}\right) \tag{2.6}$$

where G_0=the initial shear modulus of soil, γ_{ref}=the reference strain (G/G_0=0.5), h_{max}=maximum damping factor. The initial shear wave velocity of soil V_s was proportional to the one-fourth power of confining pressure, and the minimum value of V_s was 80 m/s. The equivalent shear wave velocity of soil V_{se} was determined from the nonlinear analysis for free field by using V_s and the preceding R-O model. The damping of soil was proportional to the linear combination of the mass and the equivalent stiffness, and the equivalent damping factor h_e was the value shown in Table 3 for the first and second natural periods of soil.

Table 3. Material properties of soil

GL (m)	ρ (t/m^3)	V_s (m/s)	V_{se} (m/s)	h_e
～-4	1.6	150 on average	56	0.163
～-8			65	0.187
～-12			78	0.180
～-16			94	0.167
～-20			108	0.155
-20～	1.8	350	350	0.020

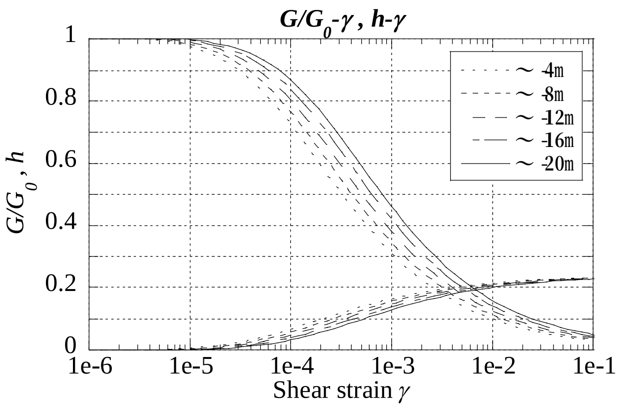


Figure 5. Dynamic deformation properties of soil

Piles were modelled as linear beam elements. The Young's modulus and the unit weight of piles were 24700000 kN/m^2, 2.5 t/m^3. Top of the pile beam element was connected to the footing element by using the rotational spring. Rotational rigidity of the spring K_θ was calculated from the following equations suggested by 'Recommendation for the Design of Building Foundations'.

$$\alpha = K_\theta/(EI\beta + K_\theta) \tag{2.7}$$

$$\beta = [k_h B/(4EI)]^{1/4} \tag{2.8}$$

where α=the rigidity of pile head, E=the Young's modulus of pile (kN/m^2), I=the moment of inertia of pile (m^4), k_h=the coefficient of horizontal subgrade reaction (kN/m^3), B=pile diameter (m).

Footing was modelled as linear beam element for 2-D, as linear shell element for 3-D. The Young's modulus of footing was excessively larger than the modulus of other element. Figure 6 shows the input earthquake motion that occurs extremely rarely. The acceleration response spectrum of the motion conformed to a value stipulated in the notification No. 1461 of the Ministry of Construction.

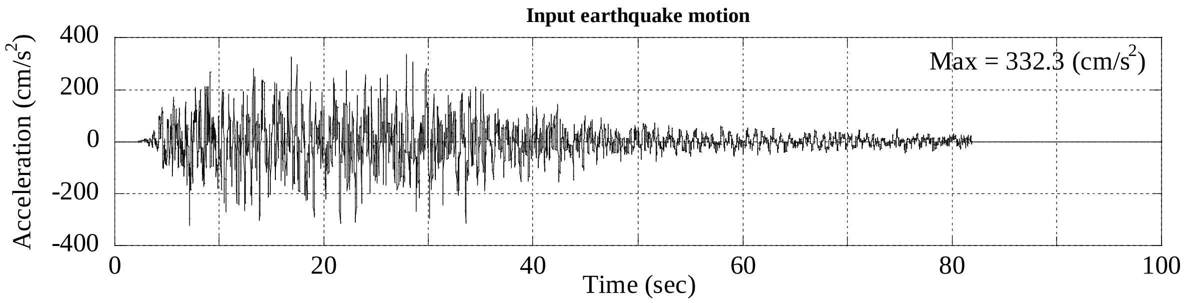
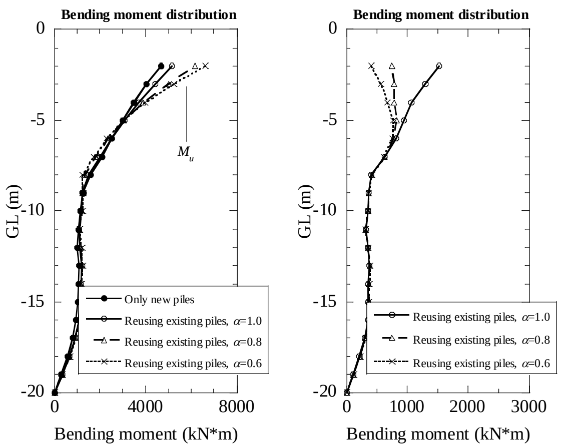


Figure 6. Input earthquake motion

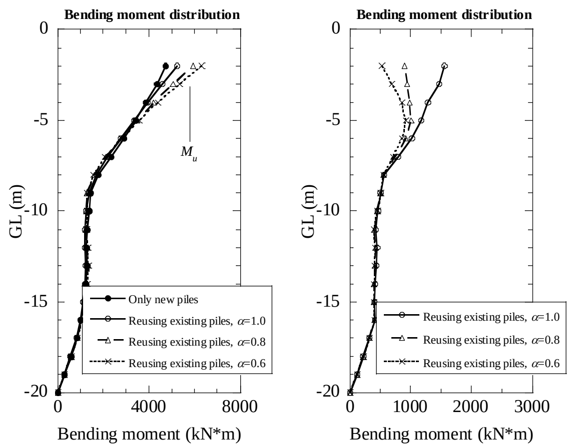
2.2. Decrease of rigidity of existing pile head

Bending moment distributions along each pile are shown in Fig. 7, 8. M_u is the ultimate bending moment of pile. In case of α=1.0, the bending moment of new pile was almost equal to the moment for the case of only new piles, and was smaller than M_u. With α decreasing, the bending moment of new pile head increased and became larger than M_u. This result suggests that when the rigidity of existing pile head is smaller than the rigidity assumed in seismic design, new pile may be excessively loaded laterally.



(a) New pile (b) Existing pile

Figure 7. Bending moment distributions (2-D)



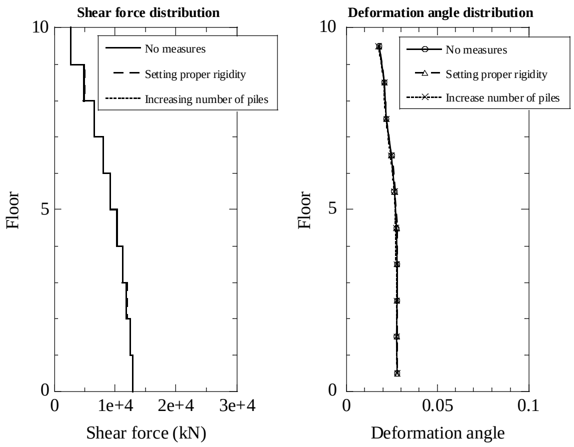
(a) New pile (b) Existing pile

Figure 8. Bending moment distributions (3-D)

2.3. Setting appropriate rigidity of new pile head

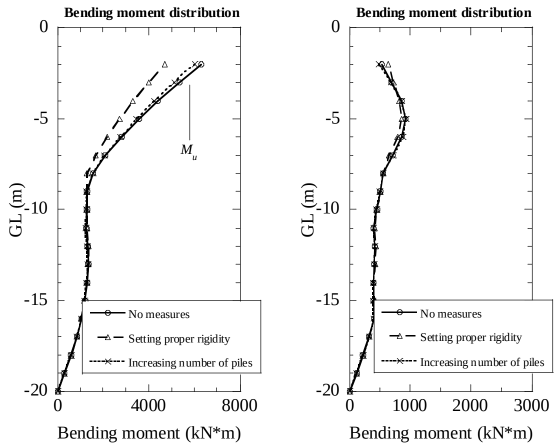
When the rigidity of existing pile head decreases, bending moment of the pile decreases at pile head, but increases at the middle part of pile. As mentioned in section 2.2, because of a large difference of the rigidity of pile head between new piles and existing piles, new piles may be excessively loaded laterally. Therefore, it is important for the piles to be loaded reasonably by setting appropriate rigidity of the pile heads.

Analyses were conducted under the condition that the rigidity of existing pile head decreased (α_e=0.6). Two kinds of measures were taken against the increase of bending moment at new pile head caused by α_e decreasing. One was to set the appropriate rigidity of new pile head (α_n=0.9), and the other was to increase the number of new piles (12 to 15). Seismic response for superstructure and piles for 3-D analyses are shown in Fig. 9, 10. There was little difference in the seismic response of superstructure. In case of increasing the number, the bending moment of new pile was less than the moment for the case of no measures, but was still larger than M_u. On the other hand, by setting the appropriate rigidity, the moment was less than M_u.



(a) Shear force (b) Deformation angle

Figure 9. Seismic response for superstructure



(a) New pile (b) Existing pile

Figure 10. Bending moment distributions

3. EFFECT OF IMPROVED SOIL ON SEISMIC RESPONSE

3.1. Analytical method

2-D finite element model is shown in Fig. 11. Analysis cases are shown in Table 4. Improved soil was modelled as linear plane strain element. The shear wave velocity of improved soil V_{si} was determined from the previous research by ASAKA and Katsura (2005), which presented the relation between V_{si} and q_u of cemented soil (Fig. 12). Considering the material non-linearity of improved soil, the equivalent shear modulus was one-half of the initial shear modulus calculated from V_{si}. Other analytical conditions were mentioned in section 2.1.

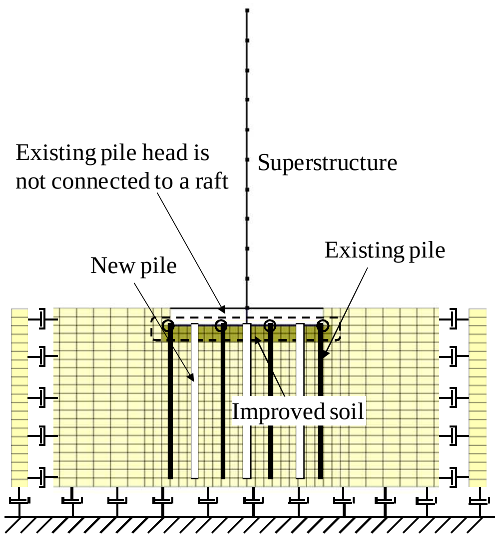


Figure 11. 2-dimensional finite element model

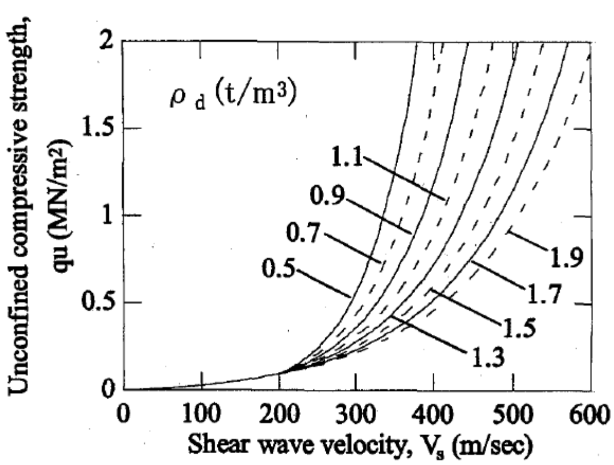


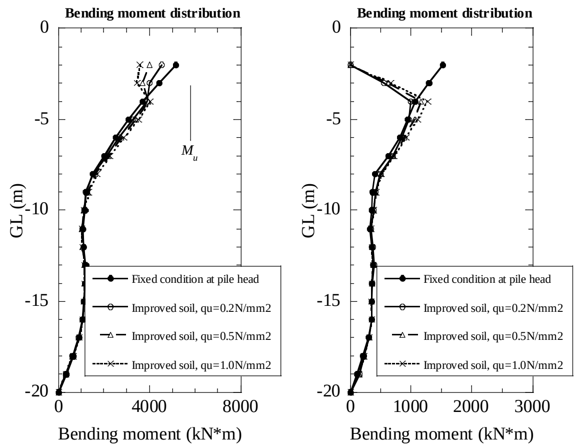
Figure 12. Relation between V_{si} and q_u of cemented soil (ASAKA & Katsura, 2005)

Table 4. Analysis cases

New pile	Pile type	Cast-in-place concrete pile ϕ1500×12
	Pile head condition	Fixed
Existing pile	Pile type	Cast-in-place concrete pile ϕ1100×24
	Pile head condition	Not connected to raft
Improved soil	Unconfined compressive strength q_u	0.2, 0.5, 1.0 N/mm^2 (V_{si}=290, 390, 480 m/s)
	Depth	GL-2〜-3, -2〜-4, -2〜-5 m (H=1, 2, 3m)
	Unit weight	1.7 t/m^3

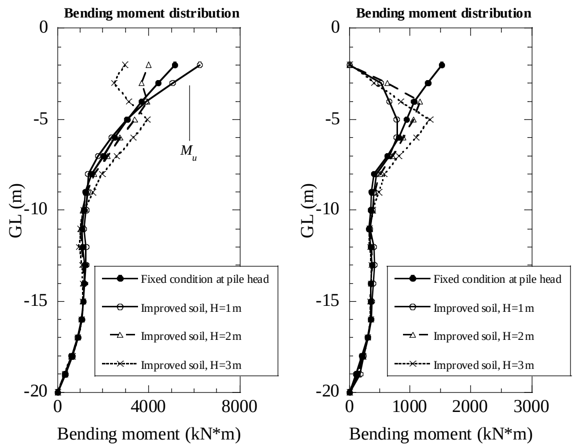
3.2. Appropriate strength and depth of improved soil

At first, analyses were conducted under the condition that H was 2m. Bending moment distributions along each pile are shown in Fig. 13. With the strength increasing, the bending moment of new pile decreased at pile head, but slightly increased at the middle part of pile. This result suggests that there is an appropriate strength of improved soil to obtain the uniform distribution of pile bending moment among the improved soil. Secondary, analyses were conducted under the condition that the strength was 0.5 N/mm^2. Bending moment distributions along each pile are shown in Fig. 14. In case of H=1m, the bending moment of new pile was larger than the moment for fixed condition at pile head. This result suggests that when the soil is improved too shallowly, existing piles are slight loaded laterally.



(a) New pile (b) Existing pile

Figure 13. Effect of strength of improved soil



(a) New pile (b) Existing pile

Figure 14. Effect of depth of improved soil

4. CONCLUSION

Reusing existing piles has advantages, but it is uncommon to replace a building with reusing the piles because of difficulties in seismic evaluation. Seismic response of the building may be significantly affected by the reuse methods of the piles. When the rigidity of existing pile head is smaller than the rigidity assumed in seismic design because of construction method of pile head connection, new pile may be excessively loaded laterally. By setting appropriate rigidity of new pile heads instead of increasing the number of piles, both new and existing piles are loaded reasonably. When it is difficult to connect existing piles directly to a raft because of piles arrangement and architectural planning, the piles are efficiently reused by improving the soil shallowly between piles and the raft. This paper presents the findings about the appropriate strength and depth of improved soil under the reuse condition.

REFERENCES

Sugimura, Y. and Hirade, T. (1987). Experimental study on degree of restraint for rotaion and failure strength of prestressed high strength concrete pile-footing joint. *Journal of Structural and Construction Engineering,* Architectural Institute of Japan. **373**, 111-120. (in Japanese)

AIJ Kinki Branch. (2003). Design for Friction Pile, AIJ Kinki Branch, Osaka, Japan.

Silver, M. L. and Seed, H. B. (1971). Deformation characteristics of sands under cyclic loading. *Journal of the Soil Mechanics and Foundations Division, ASCE*. **97:8**, 1081-1098.

AIJ. (2001). Recommendation for the Design of Building Foundations, AIJ, Tokyo, Japan.

Shoji, M., Kashiwa, H., Inoue, W., Suita, K. and Hayashi, Y. (2009). Experimental study on lateral resistance mechanism of composite foundation of pile with reusing existing piles. *Journal of Structural and Construction Engineering,* Architectural Institute of Japan. **74:644**, 1751-1758. (in Japanese)

Asaka, Y. and Katsura, Y. (2005). Effect of dry density on the relationship between shear wave velocity and unconfined compressive strength of cemented soil. *Summaries of Technical Papers of Annual Meeting,* Architectural Institute of Japan. 755-756. (in Japanese)