EXPERIMENTAL INVESTIGATION ON THE IMPROVEMENT OF BEARING CAPACITY OF SURFACE FOOTING WITH MICROPILES

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ABSTRACT

The development of the effective method for reinforcing existing footings is an urgent problem to improve the stability of urban highway facilities, such as overpasses and bridges. Micropile, which is a cast in place mortar pile of small diameter, is one of the most promising methods for reinforcing footings and improving their bearing capacity during earthquake. The aim of this study is to clarify the mechanism of bearing capacity of spread footings reinforced with micropiles.

A series of loading tests were carried out on the model micropile foundations on level sand ground. Three types of micropiles with different bending stiffness and skin friction were prepared. Rigid circular footing with a diameter of 40mm was reinforced with micropiles of 2mm in diameter with various arrangements; the number, length and inclination angle of micropile were parametrically changed. The micropile foundations placed on sand grounds with three different relative densities were loaded, where the load were controlled with a computer-aided control-monitoring system.

From the comparative examination of the observed behaviors of micropile foundations, the influence of some factors on the mechanism and improvement of bearing capacity of footing is discussed. The density of sand ground, skin friction, bending stiffness and arrangement of micropiles are concerned as main influence factors. The marked interaction between footing and micropile group was recognized in the observed behavior. In the case of dense ground, bearing capacity is improved remarkably; ground material beneath the footing is confined effectively by the footing and micropile group due to the dilatant behavior of the material. As a result, the base pressure of the footing and the friction on micropiles are increased. Regarding this interactive behavior, the performance of micropile foundation is examined under monotonic loading conditions.

1. INTRODUCTION

Micropile is a small-diameter, cast-in-place replacement pile, which is built in a drilled borehole with reinforcement and grout. Micropiles are generally used both for structural support and for in situ earth reinforcement. Inherent in their genesis and application is the precept that micropiles are installed with the technique which causes minimal disturbance to structure, soil and environment. The principle is conceived in Italy [Lizzi, 1971, 1978], and micropiles are widely used in the world for various purposes [Bruce, et al., 1995; US. Department of Transportation, 1997; Schlosser and Frank, 1998; Tsukada, 1998]. Since main infrastructures were extensively damaged in 1995 Hyogoken-Nambu Earthquake, the improvement of bearing capacity of existing footings is one of the urgent engineering problems for upgrading infrastructures against earthquakes in Japan. Micropile is expected as a promising solution for this problem in Japan.

Micropiles can withstand axial and/or lateral loads, and may be considered as either one component in a composite soil/pile mass or a small-diameter substitute for a conventional pile, depending on the design concept. They can sustain sufficient skin friction due to grouting technique with pressurized materials. Due to their flexibleness as small-diameter piles, however, the behavior of micropile group is important to understand the mechanism of bearing capacity and to propose a rational design method. In the case of footing reinforced with a group of micropiles, the interaction between micropile group and footing plays a more important role, especially when the foundation is subjected to critically large loads with perceptible displacement such as under destructive earthquake. Therefore the design of micropile foundation must be considered in the concept of piled raft foundation especially for reinforcing existing foundations [Cooke, R. W., 1986]. Although the applications of micropiles are increasing in various situations, the mechanism of bearing loads is not clarified sufficiently. The aim of this study is to reveal some aspects of the mechanism based on comparative examination of the observed behaviors in loading tests.

In order to clarify the mechanism of bearing load with micropiles, loading tests on the model footings reinforced with a micropile group were carried out by some researchers: e.g., Lizzi (1978) and Francis et al. (1996). They showed the importance of the group effect in micropiles, and discussed the influence of arrangement of micropiles on the bearing capacity. In this study a series of model loading tests was carried out on the footings reinforced with micropiles on sand ground, regarding the interaction among micropiles, footing and ground material. Two types of micropiles, made of stainless steel and plastic, were employed with different surface roughness. And various types of micropile arrangements were prepared; the number, length and inclination angle of micropiles were varied parametrically. Observed behavior of the micropile foundations under vertical are examined comparatively, and the influence factors on the bearing capacity are discussed.

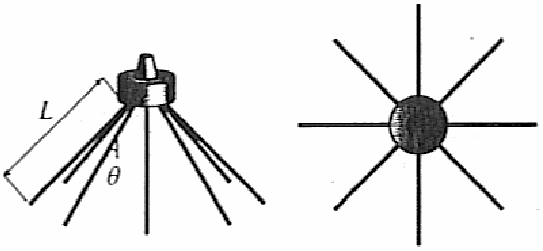


Fig. 1. Model micropile foundation; n=8, L=100mm, θ=45deg.

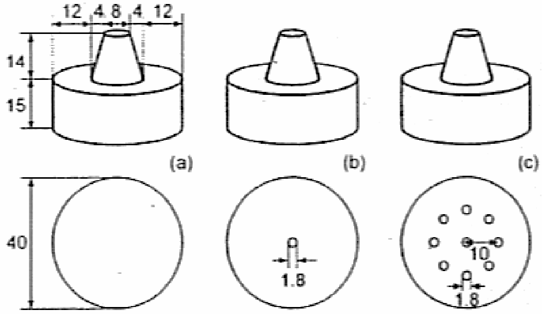


Fig. 2. Model footings, unit in mm; (a) not reinforced, (b) reinforced with single micropile (n=1), (c) reinforced with micropiles (n=2-8)

2. METHOD FOR MODEL LOADING TESTS

(1) Model Micropile Foundation

A typical model micropile foundation employed in this study is shown in Fig. 1. The model is a circular footing made of stainless steel with a diameter of 40mm, which is reinforced with a group of micropiles; the number and length of micropiles and their inclination angle from vertical direction are designated as n, L and θ, respectively. According to the number n and angle θ, the footing was selected from the list shown in Fig. 2.

Three types of model micropiles shown in Fig. 3 were prepared for this study. Two types, S-S-type and S-R-Type, are made of stainless steel with high bending stiffness of $EI=1.28\text{x}10^{-1}\text{Nm}^2$ ($E=2.1\text{x}10^5\text{MPa}$); and the other type, P-R-Type, is made of plastic with low bending stiffness of $EI=2.50\text{x}10^{-3}\text{Nm}^2$ ($E=3.1\text{x}10^3\text{MPa}$) [Tsubokawa, 1999]. Two rough surface types, S-R-Type and P-R-Type, were coated with thin sand layer so as to mobilize sufficient skin friction with ground; sand grains were glued to the micropile surface. From the comparison of the observed behavior of micropile foundations with three different micropiles, the influence of bending stiffness and skin friction of micropiles can be assessed.

The model micropile foundation was set up on the surface of model sand ground formed in a mold; see Fig. 4. Oven dried silica sand was deposited through the air with a nozzle, and tapped with rubber hummer so as to obtain prescribed three different relative densities: dense, medium, and loose grounds. The model micropile footing is suspended in the course of deposition of sand as shown in Fig. 4, to minimize the disturbance of sand ground around micropiles and unnecessary prestress in micropiles and grounds.

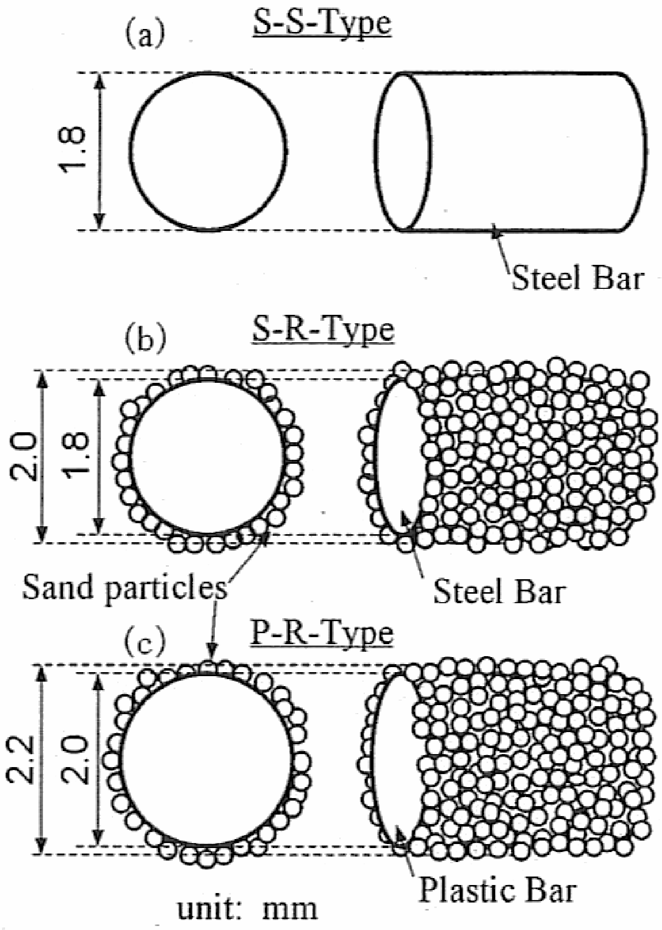


Fig. 3. Model micropiles: (a) S-S-Type; (b) S-R-Type; (c) P-R-Type

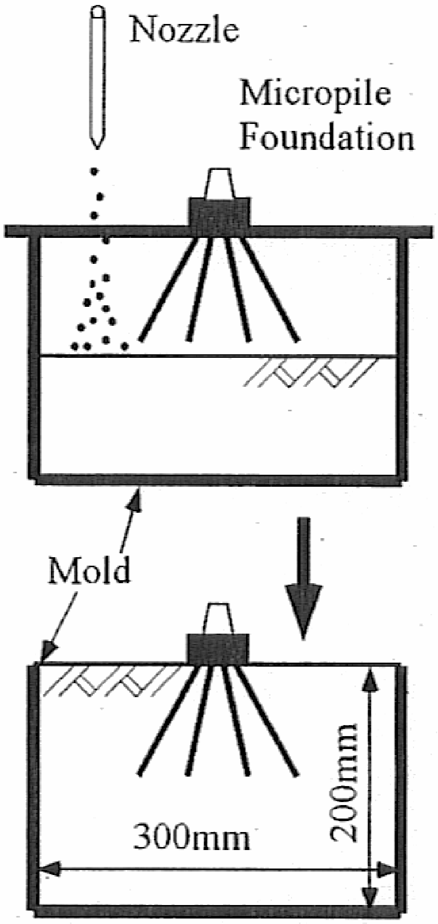


Fig. 4. Preparation method of sand ground with micropile foundation

Table 1. Physical and mechanical properties of sand ground.

Grain density: $\rho_s = 2.717$ g/cm^3	The angle of internal friction, ϕ_d (deg.);	
Max. and Min. dry densities;	Dense ground, Dr=95±2%;	38.5
$\rho_{dmax} = 1.610$, $\rho_{dmin} = 1.255$ g/cm^3	Medium ground, Dr = 65±2%;	36.2
Mean grain size; $D_{50} = 0.18$mm, Uniformity coefficient; $U_c = 1.82$	Loose ground, Dr=50±2%;	34.8

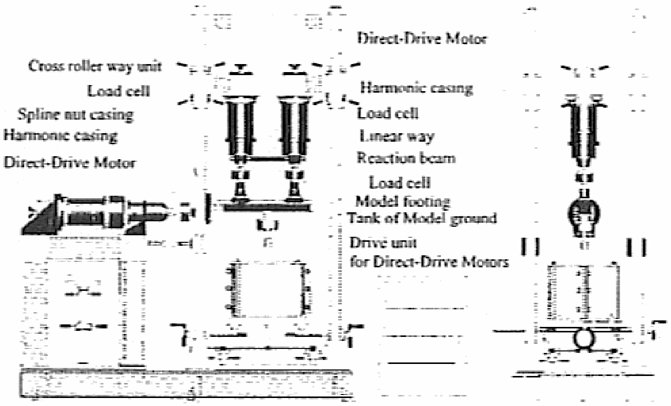
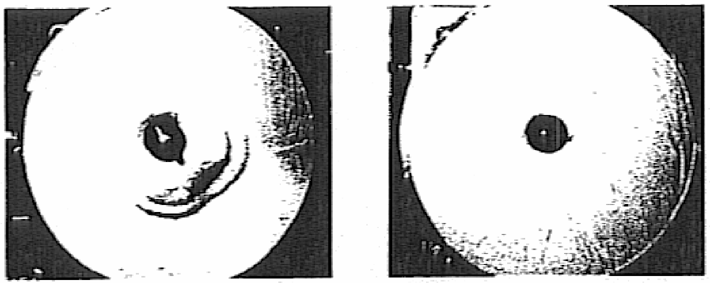


Fig. 5. Loading apparatus, and computer-aided monitoring and controlling system

(2) Loading Apparatus

The loading apparatus, and computer-aided monitoring and controlling system used in this study are shown in Fig. 5. Three loading rams equipped with direct-drive motor and a load cell are mounted on the frame, two are in vertical, one in horizontal. With these three independently operatable rams, three components of the motion of micropile foundation can be controlled, where displacements in vertical and horizontal directions and rotation are concerned. The inclina-



(a) general shear failure in dense ground

(b) local shear failure in medium sand

Photo. 1(a, b) Shear failure patterns observed on the surface at the relative displacement S/D = 0.20 in FT-Test series

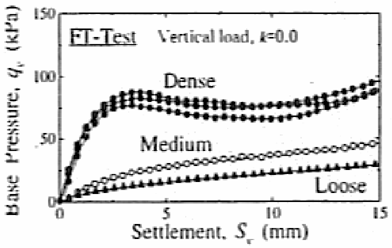


Fig. 7. Base pressure q_v vs. displacement S_v relationship under vertical loading in FT-Test series; k=0.0.

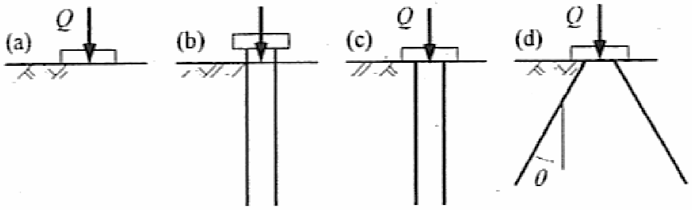


Fig. 6. Loading test series; (a) FT-Test, (b) MP-Test, (c) MP-FD-Test with vertical MPs, (d) MP-FD-Test with inclined MPs

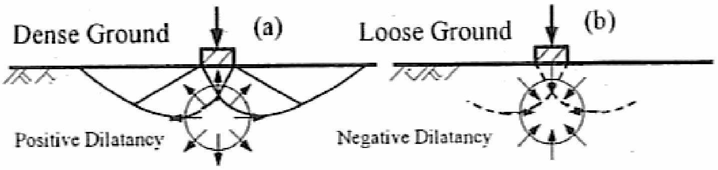


Fig. 8. Illustration of shear failure pattern due to the subsidence of surface footing, (a) general shear failure in dense ground, (b) local shear failure in loose ground

tion angle and eccentricity can be monitored. The accuracies are $5.0\text{x}10^{-7}$mm and $9.2\text{x}10^{-3}$N for displacement and load, respectively, [Tsubokawa, 1999].

3. TEST RESULTS AND DISCUSSION

The loading tests conducted in this study consist of three test series, as illustrated in Fig. 6. First, the behavior of surface footing without reinforcement is observed in FT-Test series. Then, the behavior of micropiles was observed in MP-Test series, where the footing was freestanding, clear from ground surface. The bearing capacity mechanism of micropile foundation was investigated in MP-FD-Test series. The application point of load is maintained at the center of footing on ground surface, throughout the entire test series, as shown in Fig. 8.

(1) Bearing Capacity Characteristics of Surface Footing on Sand Ground.

The behavior of spread footing observed under vertical load in FT-Test is shown in Fig. 7 in the form of base pressure q_v vs. displacement S_v relationship. Typical shear failure patterns appeared on ground surface are shown in Photo. 1. In the case of dense ground, the load-displacement behavior is typical general shear type; base pressure q_v has peak and shear failure plane appeared on the surface. On the other hand, the behavior observed on the medium ground and loose ground is local shear type; shear failure plane was not recognized clearly on the surface. This difference in the load bearing behavior and the failure pattern is due to the relative density dependent dilatancy properties of ground material, sand, as illustrated in Fig. 8. Dilative behavior of dense ground material beneath footing enhances shear failure plane to extend toward ground surface; on the other hand, contractive behavior of loose ground material restrains the extension of shear failure plane. This remarkable effect of relative density of ground through the dilatancy behavior, is recognized in the behaviors of footings reinforced with micropiles.

(2) Bearing Capacity Characteristics of Micropiles in Sand Ground

Shown in Fig. 9 is the observed behavior of a group of 8 vertically installed micropiles of S-R-Type, which was subjected to vertical load. The observed load-length relationships are fitted with parabolas; Q_v is proportional to the square of L; this means that not point bearing but skin friction is main factor and is proportional to depth z; see Fig.10. Due to insufficient space in this paper, further data cannot be

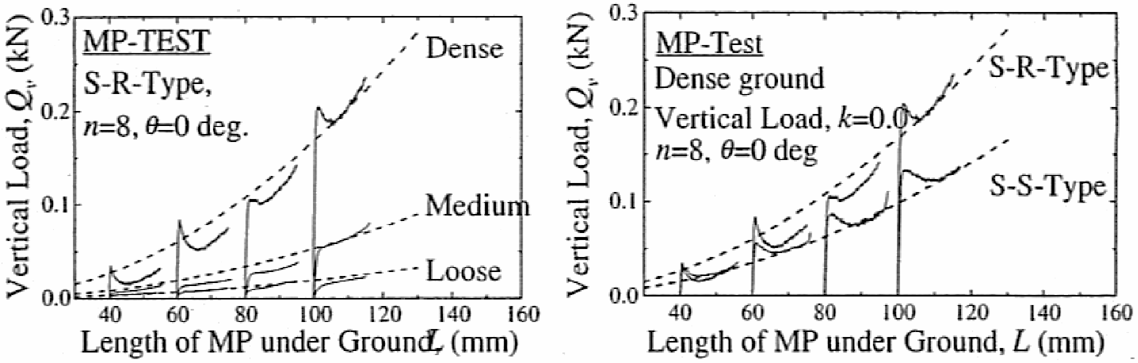


Fig. 9(a, b). Load Q_v vs. length of MP L relationship under vertical loading in MP-Test; (a) S-R-Type, n=8, θ=0 deg., (b) dense ground, n=8, θ=0 deg.

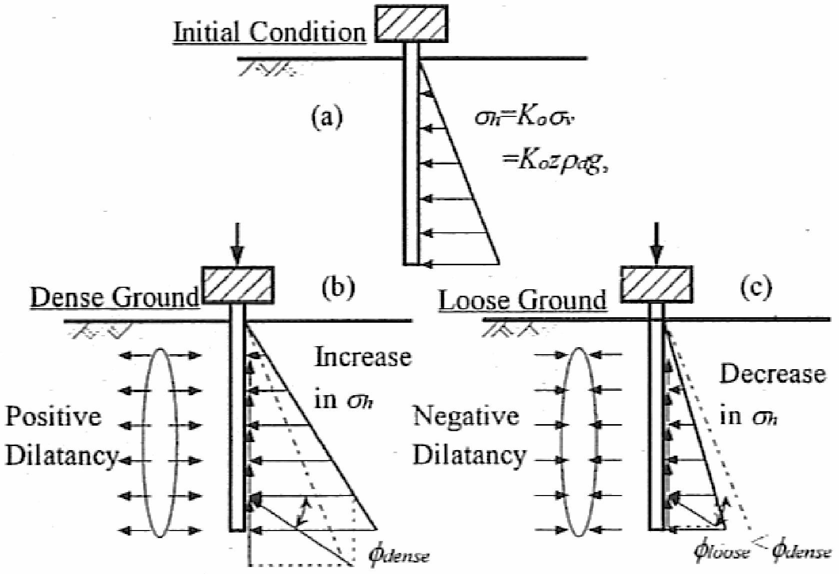


Fig. 10(a-c). Illustration of the change in underground stress condition due to dilatancy behavior; (a) initial Condition, (b) increase in bearing capacity in dense ground, (c) decrease in bearing capacity in loose ground.

presented on the influence of number of micropiles; however, in this test condition (see Fig. 1.), conventional group effect was not perceptible [Tsukada, et al. 1999; and Tsubokawa, 1999]. As shown in Fig. 9(a) the bearing capacity of micropiles is remarkably dependent on the relative density of the ground. The difference of the angle of internal friction listed in Table 1. is not enough to explain this difference in skin friction. Then the effect of dilatancy induced by the deformation of ground associated with penetration of micropiles must be considered. Fig. 10 illustrates the effect of relative density on the bearing capacity of micropiles. In the case of dense ground horizontal stress, which confines micropiles, increases due to the dilative deformation behavior of ground material. On the other hand, in loose ground, the horizontal stress may be reduced. This change of horizontal confining stress is considered to be responsible for the remarkable dependence of bearing capacity of micropile on relative density.

The influence of surface roughness on bearing capacity is also noticeable in Fig. 9(b). The bearing capacity seems to be increased by about 50% due to improvement of the fitness of micropiles with ground material as shown in Fig. 3.

(3) Bearing Capacity Characteristics of Micropile Foundation on Sand Ground

The typical observed behaviors of micropile foundations are shown in Fig. 11. Notable influence of the inclination angle of micropiles is recognized. As shown in Fig. 12 the influence of the inclination angle is clearer in dense ground. At small subsidence of S_v/D=5%, the bearing capacity tends to become maximal with inclination angle of micropiles of θ=30deg; at large subsidence of S_v/D=20%, with low inclination angle of about θ=15 deg. Also bearing capacity is much dependent on the relative density of ground especially with small inclination angle of micropiles θ. The bearing capacity in dense ground is

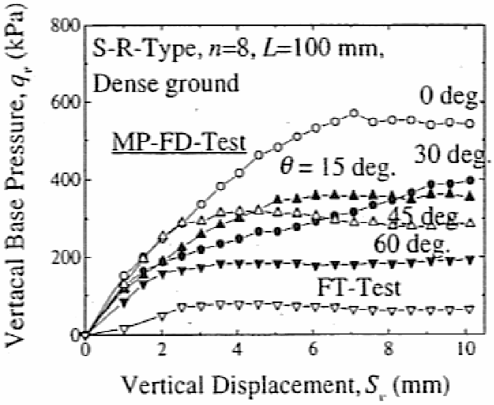


Fig. 11. Base pressure q_v vs. displacement S_v relationships for micropile foundations (S-R Type, n=8, L=10cm) on dense ground.

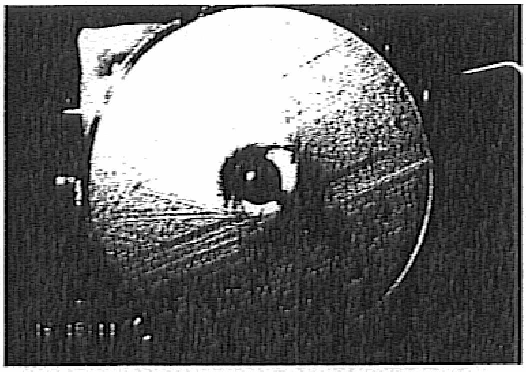


Photo. 2. Local shear failure shear failure observed in MP-FD Test at S_v/D=20%; S-R-Type, n=8, q=0deg., dense ground.

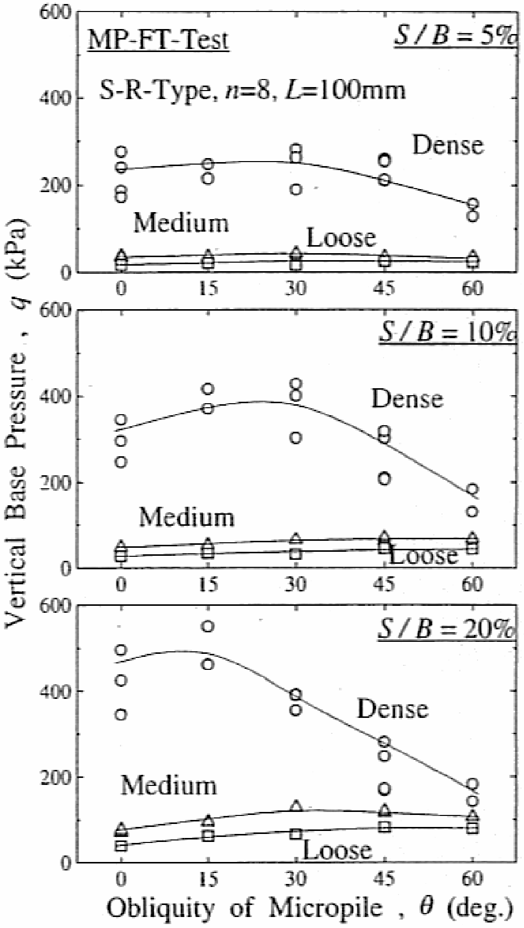


Fig. 12. Influence of relative density of ground on the improvement of bearing capacity.

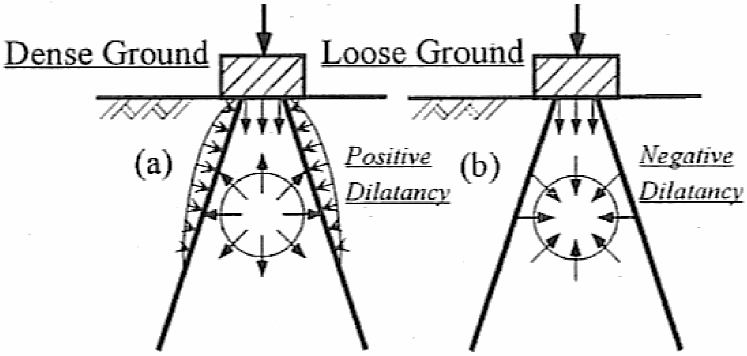


Fig. 13. Improvement of bearing capacity due to the confining effect on ground material beneath footing; (a) in dense ground confining stress increases due to its dilatant behavior, (b) in loose ground confinement is not effective due to negative di-

notably high compared with those in medium and loose grounds. In the case of vertically installed micropile foundations (θ=0deg), ground failed in local shear type as shown in Photo. 2. The contrast with the general shear failure type observed in surface footing (Photo. 1(a)) suggests the confining effect with a group of micropiles on the ground material beneath footing. As explained in Fig. 13, the confinement by the interaction between footing and a group of micropiles becomes effective with dilatant behavior of dense soil material beneath the footing.

The behavior of micropile foundation reinforced with different types of micropiles is also shown in Figs. 14. In the case of the footings reinforced with vertically installed micropiles (θ=0 deg.) the effect of bending stiffness is rather smaller than the effect of skin friction. The effect of skin friction decreases with

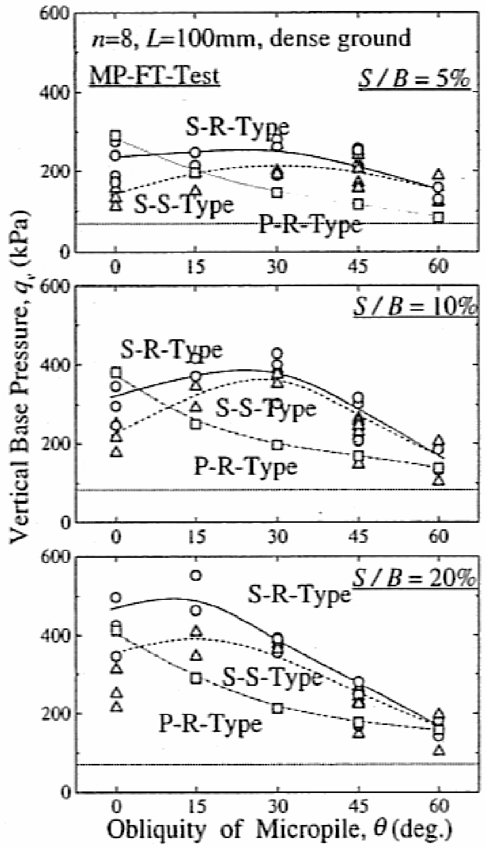


Fig.14. Effect of mechanical properties of micropiles on bearing capacity of micropile foundations

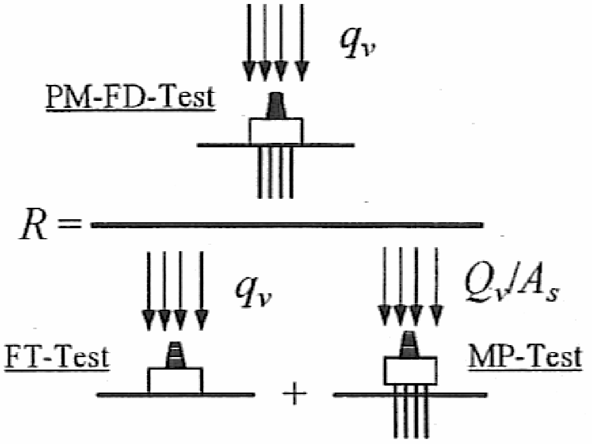


Fig. 15. Definition of improvement coefficient for bearing capacity of micropile foundation.

increasing the inclination angle of micropiles. The effect of bending stiffness is maximal around the inclination angle of θ=30 deg. Even in the case of vertical loading, the bending stiffness is necessary to confine the ground material effectively under rather large settlement. With increasing the inclination angle of micropiles θ, the bearing capacity is reduced in vertical direction (Fig. 16).

(4) Improvement of Bearing Capacity of footing with a Group of Micropiles

To assess the degree of improvement of the bearing capacity with micropiles quantitatively, the improvement ratio R was introduced (Fig. 15). The R of unity means that the bearing capacity of the footing reinforced with micropiles is equal to the summation of those for each surface footing and a group of micropiles. If the confining effect by the interaction between footing and a group of micropiles is effective, and the bearing capacity is improved, the value of R becomes large. In Figs. 16 and 17 the improvement of bearing capacity with the reinforcement with micropiles are presented.

The degree of improvement is remarkably dependent on the relative density of ground (Fig. 16). For dense ground the improvement ratio R is at most more than 2 under relatively large subsidence. It seems that the dilatant behavior raised confining stress beneath footing, then base pressure at the bottom of footing

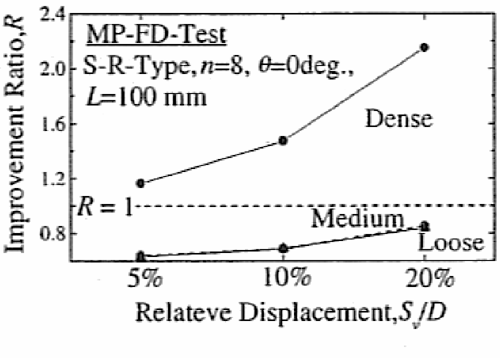


Fig. 16. Effect of relative density of ground on improvement of bearing capacity

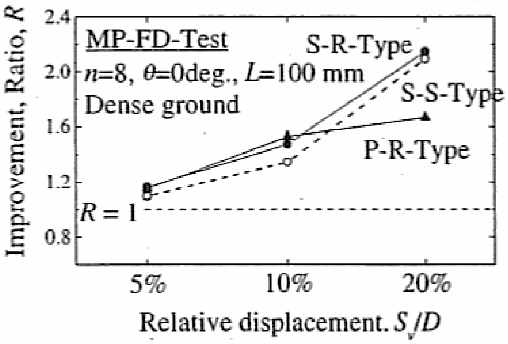


Fig.17. Effect of mechanical properties of micropiles on the improvement of bearing capacity.

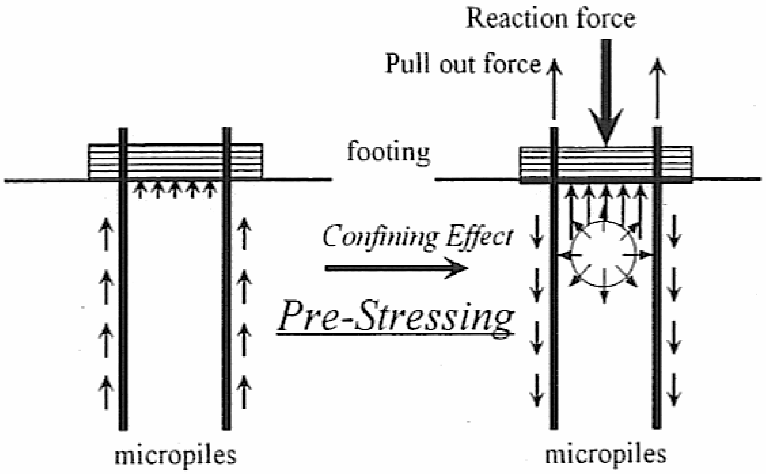


Fig.18. Prestressing for mobilizing confining effect on the ground material beneath footing.

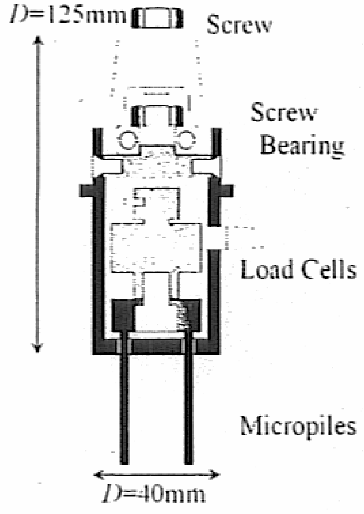


Fig.19 New type model footing for the separate measurement of the load beard by micropiles

was increased and also the confining stress on micropiles was also increased. On the other hand, *R* is less than unity for medium and loose grounds; this suggests that negative dilatancy in loose ground material beneath footing induced a decrease in confining stress and base pressure (see Fig. 13(b)). The improvement is more effective under relatively large subsidence, and in this condition bending stiffness is necessary to confine soil material as shown in Fig. 17; skin friction is less important compared with bending stiffness.

(5) Effect of Prestress in Micropiles on the improvement of bearing capacity

As shown in Figs 16 and 17, it was clear shown that the bearing capacity is efficiently improved by the interaction between footing and a group of micropiles for confining ground material beneath the footing. However, for the appearance of the confining effect rather large settlement is needed. In order to generate confining effect and improve the bearing capacity of micropile foundation, prestress was induced to micropiles in some test cases of MP-FT-Test as illustrated in Fig. 18. Prestress was induced by pulling out micropiles on the footing, and the reaction force was applied to footings. Then the ground material was confined at initial stage. To clarify the effect of the prestressing, new type of the footing was prepared; where the a group of vertical micropiles were pulled out by minute amount with screws, and the force component Q_{mp} beard by micropiles was measured with small load cell; see Fig. 19.

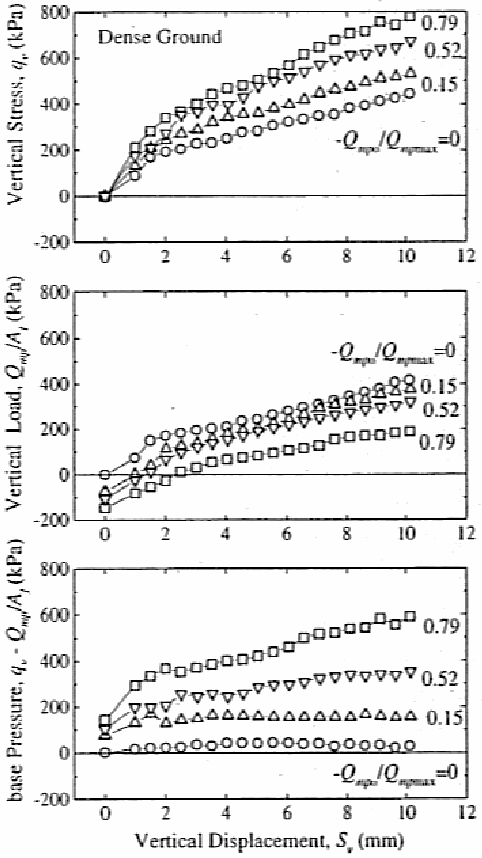
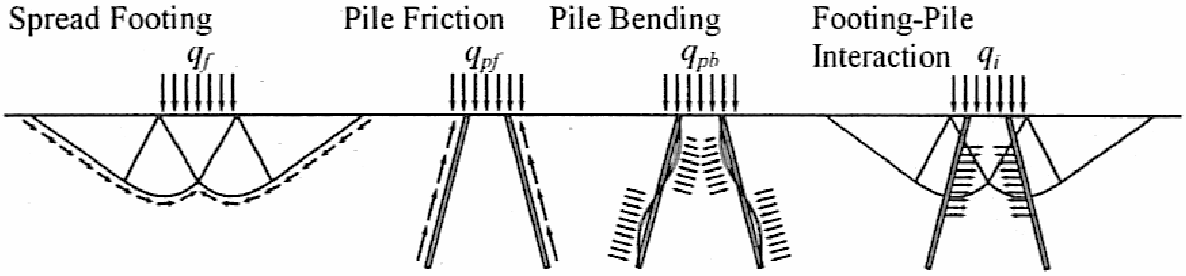


Fig. 20, the effect of prestress on the improvement of bearing capacity of micropile foundation.

Test results are shown in Fig. 20, where Q_{mpo} is initial pull out force applied to a group of micropiles and Q_{mpmax} is maximum bearing capacity of micropiles measured in MP-Test. Initial pull out stress was applied in the range up to 79%. As shown in the figure, Prestressing increased the base pressure and totally bearing capacity of micropile foundation was improved at most 100%, in this test condition.



	D_r	θ	n	L	Friction	Bend Stifness
q_s	++ ◢	—	—	—	—	—
q_{pf}	++ ◢	◣ −	+ ◢	++ ◢	++ ◢	0 ▭
q_{pb}	++ ◢	++ ◢	+ ◢	+ ◢	0 ▭	++ ◢
q_i	++ ◢	◣ −−	++ ◢	++ ◢	0 ▭	++ ◢

Fig.20 Influencing factors on the improvement of bearing capacity of footing with micropiles.

4. CONCLUDING REMARKS

To clarify the mechanism of improvement of bearing capacity of footing reinforced with a group of micropiles, a series of model loading tests were carried out. The circular footings were reinforced with a group of micropiles with variety of the arrangement of micropiles, and were subjected to vertical load. Based the comparative examinations of the observed load-displacement behaviors, the influence factors on the improvement of bearing capacity were discussed. The influence factors are listed and evaluated its role in the mechanism of the improvement of bearing capacity in Fig. 20. The following concluding remarks were drawn, as results.

- The significant effect of the relative density on the bearing capacity was recognized, in the tests of surface footing, a group of micropiles and foundation reinforced with micropiles, respectively. In dense ground, due to the dilatant behavior of ground material, bearing capacity was remarkably high compared with those in medium and loose grounds. In the case of surface footing, only in dense ground was the shear failure plane generated freely and observed on the surface. Because of the increase in confining pressure on the surface of micropiles due to the dilatant behavior of dense ground material, the skin friction of micropiles is remarkably increased.
- An interaction was recognized between footing and a group of micropiles, and this interaction was significantly effective on the confinement of ground material and on the improvement of the bearing capacity of footing. Due to the confinement, the base pressure of footing was increased and the confining pressure on the surface pressure was also increased. In the case of the footing reinforced with a group of vertically installed micropiles, the bearing of the foundation was more than twice the summation of bearing capacities with each of surface footing and a group of micropiles.
- The skin friction and bending stiffness of micropiles are effective on an increase in bearing capacity. The bending stiffness was necessary to enhance the improvement of bearing capacity with the interaction between footing and a group of micropiles.
- The effect of prestressing was examined in some test cases. Tension was applied to micropiles and confining stress to ground material beneath footing, and then base pressure was increased and to totally

bearing capacity was improved. At most 100% of bearing capacity was increased, in this test condition on dense ground.

5. ACKNOWLEDGEMENT

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NOTATION

D; Diameter of footing (D=40mm).
EI; Bending stiffness of micropiles.
E; Young's modulus of the material of micropiles.
L; Length of micropiles (L=100mm).
n; Number of micropiles (n=1-8).
Q_v; Vertical load.
q_v; Vertical averaged base pressure ($q_v=Q_v/(\pi D^2/4)$).
R; Improvement ratio for bearing capacity.
S_v; Vertical displacements.
θ; Inclination angle of micropiles (θ=0, 15, 15, 39, 45, 60 deg.).