BEARING CAPACITY DURING EARTHQUAKE OF THE SPREAD FOOTING REINFORCED WITH MICROPILES

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SUMMARY

The development of the effective method for the reinforcement of 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 under the loading seismic condition.

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 obliquity and eccentricity of 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 is increased. Regarding this interactive behavior, the performance of micropile foundation is examined under monotonic and cyclic loading conditions.

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 infrastructures were extensively damaged in 1995 Hyogoken-Nambu Earthquake, the improvement of bearing capacity of existing

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footings is one of the urgent engineering problems for upgrading infrastructures against earthquakes. 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 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 an important role, especially when the foundation is subjected to critically large loads with perceptible displacement under destructive earthquake. Therefore the design of micropile foundation must be considered in the concept of piled raft foundation especially for reinforcing existing foundations. 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 the comparative examination of the observed behaviors in the 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 on 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 and inclined loads are examined comparatively, and the influence factors on the bearing capacity are discussed.

METHOD FOR MODEL LOADING TESTS

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=1.28x10^{-1}Nm^2 (E=2.1x10^{5}MPa); and the other type, P-R-Type, is made of plastic with low bending stiffness of EI=2.50x10^{-3}Nm^2 (E=3.1x10^{3}MPa) [Tsubokawa, 1999]. Two rough surface types, S-R-Type and P-R-Type, were covered with thin sand layer so as to mobilize sufficient skin friction; sand grains were glued to the surfaces of micropiles. From the comparison of the observed behavior of micropile foundations with three different micropiles, the influence of bending stiffness and skin friction can be assessed.

The model micropile foundation was set up on the surface of model sand ground formed in a mold; see Figs. 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.

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 inclination angle and eccentricity can be monitored. The accuracies are 5.0x10^{-7}mm and 9.2x10^{-3}N for displacement and load, respectively, [Tsubokawa, 1999].

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 supported in the air with vertical micropiles, detached from ground surface. The bearing capacity mechanism of micropile foundation was investigated in MP-FD-Test series. Even in the cases where footings were subjected to inclined load, the application point of load is maintained at the center of footing on ground surface, throughout all the test series

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 a 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 on the surface. This difference in the load bearing behavior and the failure pattern is due to the relative density dependent dilatancy properties, as illustrated in Fig. 8. Dilative behavior of dense ground material beneath footing extends shear failure plane toward ground surface, on the other hand, contractive behavior of loose ground material restrains the extension of shear failure plane.

The behavior of surface footing subjected to inclined load is shown in Fig. 9. The base pressure tend to reduce with increasing load obliquity. And the direction of footing displacement tends to shift from loading direction to vertical downward; this means stiffness is lager in horizontal direction than in vertical direction, in the case of surface footing under the loading condition of $k < 0.9$.

Bearing Capacity Characteristics of Micropiles in Sand Ground

Shown in Fig. 10 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.11. Due to insufficient space in this paper, further data cannot be 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. 10(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, and the change in horizontal stress due to dilatancy effect induced by the deformation of ground associated with penetration of micropiles. The influence of surface roughness on bearing capacity is noticeable in Fig. 10(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.

The behavior of a group of 8 vertically installed micropiles (S-R-Type) under inclined load is shown in Fig. 12. The bearing capacity tends to reduce with increasing load obliquity. The direction of movement of micropiles shift from loading direction to horizontal. Then, it can be said that the stiffness of a group of vertically installed micropiles is higher in vertical direction, with a contrast of those of surface footing as explained in previous section.

Bearing Capacity Characteristics of Micropile Foundation on Sand Ground

The typical observed behaviors of micropile foundations are shown in Fig. 13. Notable influence of the inclination angle of micropiles is recognized. As shown in Fig. 14. the influence of the inclination angle is more clear in dense ground. The bearing capacity tends to become maximum with low inclination angel of about 15 deg. Also bearing capacity is much dependent on the relative density of ground, the bearing capacity in dense ground is much high compared with those in medium and loose grounds. In the case of vertically installed micropile foundations, ground failed in local shear type as shown in Photo. 2. The contrast with the general shear failure type 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. 15, the confinement by the interaction between footing and a group of micropiles becomes effective with dilatant behavior of soil material beneath the footing..

The response of micropile foundations is also shown in Figs. 16 and 17. With increasing the inclination angle of micropiles θ, the veering capacity is reduced in vertical direction (Fig. 16). The effect of skin friction is recognized only in the case of vertical loading; however, the effect of bending stiffness is more important in inclined loading (Figs. 17(a, b)).

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. 18). The *R* of unity means that the bearing capacity of the footing reinforced with micropiles is equal to the summation of those of the 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. 19-21 the improvement of bearing capacity with the reinforcement with micropiles are presented.

The degree of improvement is remarkably dependent of the relative density of ground (Fig. 19). 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 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. 15(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. 20; skin friction is less important compared with bending stiffness. Under inclined loading the improvement of the bearing capacity is also recognized in Fig. 21. However, the improvement becomes less effective with increasing obliquity of load applied to the foundation.

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 and inclined loads. Based the comparative examinations of the observed load-displacement behaviors, the influence factors on the improvement of bearing capacity was discussed. The following concluding remarks were drawn, as results.

- The significant effect of the relative density on the bearing capacity was recognized, for surface footing, a group of micropiles and foundation reinforced with micropiles. 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, shear failure plane was generated freely and observed on the surface only in dense ground. An increase in confining pressure on the surface of micropiles due to the dalatant behavior of dense ground material raised remarkably the skin friction of micropiles.
- 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 on footing was increased and the confining pressure on the surface of micropiles 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 of a surface footing and a group of micropiles.
- The skin friction and bending stiffness of micropiles are effective on the 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.
- Bearing capacity was decreased with increasing the inclination angle of load the footings were subjected to. Footing showed higher resistance to horizontal component of the load than to the vertical component. On the other hand, micropiles installed vertically can resist more in horizontal direction.
- Improvement of the bearing capacity was recognized also under inclined loads. The interaction between footing and a group of micropiles was not so effective under inclined loading compared with under vertical loading.

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REFERENCES

Bruce, D. A., DiMillo, A. F. and Juran, I. (1995): "Introduction to Micropiles: An International Perspective," *Foundation Upgrading and Repair for Infrastructure Improvement, ASCE*, GSP 50, pp.1-26.

Francis, R., Canou, J., Dupla, J.-C., and Belmont, G. (1996): "Group effects of model micropiles in sand," *Australian-New Zealand Conference on Geomechanics*, Vol.7, No.1, pp.620-625.

Lizzi, F. (1971): "Special Patented Systems of Underpinning and more Generally, Subsoil Strengthening by Means Of Pali Radice (Root Piles) with Special Reference to Problems Arising from the Construction of Subways in Built-up Area," *Special Lecture given at university of Illinois at Urbana-Champaign, etc.*

Lizzi, F. (1978): "Reticulated Root Piles to Correct Land Slides," *Proc. of ASCE Conference, Chicago, Illinois, October 16-20*.

Schlosser, F. and Frank, R. (1998): "Review of French FOREVER Project," *Proc. of 1st International Workshop on Micropiles*, pp.2229-264.

Tsubokawa, Y. (1999): *Experimental Study on the Bearing Capacity Characteristics of the Foundation Reinforced with Micropiles*, submitted to Hokkaido University for Master Degree of Engineering.

Tsukada, Y. (1998): "State-of-the-Art: Application of Micropiles in Japan," *Proc. of 1st International Workshop on Micropiles*, pp.265-279.

Tsukada, Y, Miura, K. and Tsubokawa, Y. (1999); "Model Loading Tests on Micropile Foundation on Sand Ground," *Japanese Geotechnical Society*, *Tsuchi-to-kiso*, Vol.47, No.1, pp. 35-38, (1999), in Japanese

US. Department of Transportation, Federal Highway Administration (1997): *Drilled and Grouted Micropiles: State-of Practice Review*, Vols. 1-4.

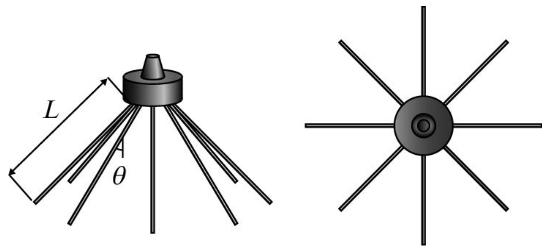


Fig. 1. Model micropile foundation; n=8,L=100mm, =60deg.

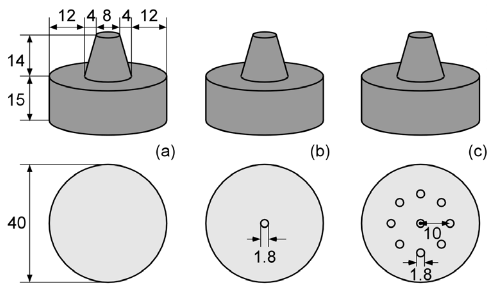


Fig. 2.Model footings, unit in mm; (a) not reinforced, (b) reinforced with single micropile,(c)reinforced with micropiles (n=2-8)

Table 1. Physical and mechanical properties of sand ground.

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

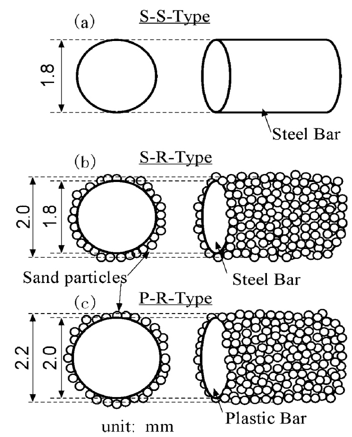


Fig. 3. Model micropiles: (a) S-S-Type; (b) S-R-Type; (c) P-R-Type

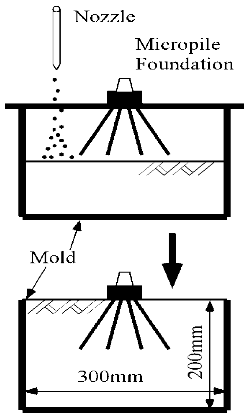


Fig. 4. Preparation method of sand ground with micropile foundation

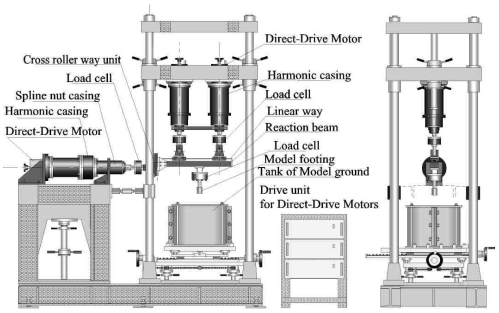


Fig. 5. Loading apparatus, and computer-aided monitoring and controlling system.

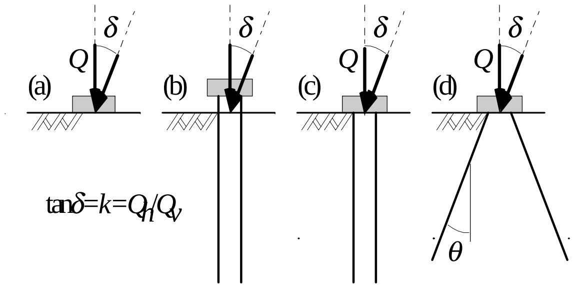


Fig. 6. Loading test series; (a) FT-Test, (b) MP-Test, (c) MP-FD-Test with vertical MPs, (d) MP-FD-Test with inclined MPs

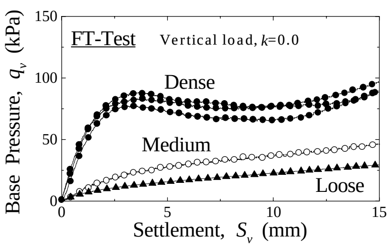


Fig. 7. Base pressure qv vs. displacement Sv relationship under vertical loading in FT-Test series; k=0.0.

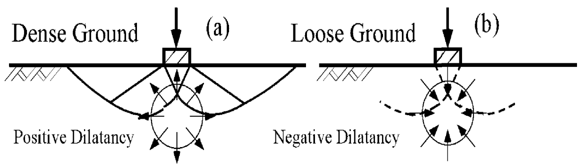


Fig. 8. Illustration of shear failure pattern due to the subsidence of surface footing, (a) general shear failure in dense ground, (b) local shear failure in loose ground

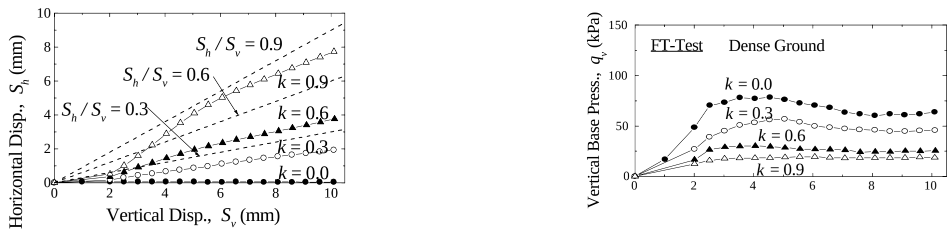


Fig. 9(a, b).Behavior of surface footing under inclined loading in FT-Test series (dense ground);(a)qv vs.Sv, (b)Sh vs. Sv

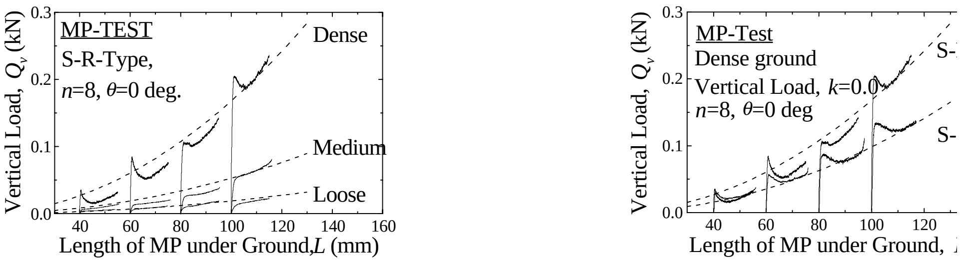


Fig. 10(a, b). Load Qv vs. length of MP L relationship under vertical loading in MP-Test; (a) S-R-Type, n=8, =0 deg., (b) dense ground, n=8, =0 deg.

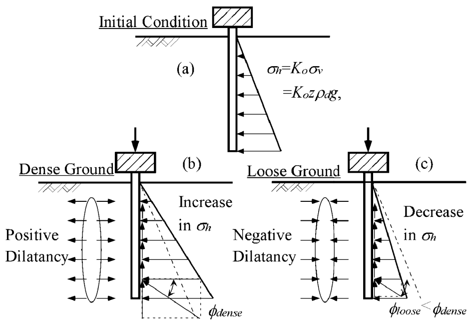


Fig. 11(a-c). Illustration of the change in underground stress condition due to dilatancy behavior; (a) initial Condition, (b) increase in bearing capacity in dense ground, (c) decrease in bearing capacity in loose ground.

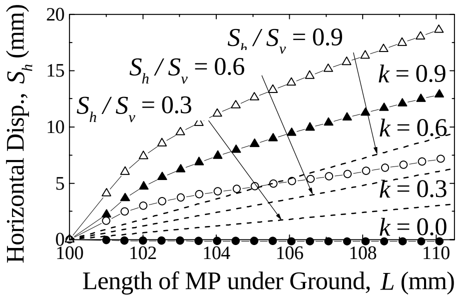


Fig. 12(a, b). Behavior of micropile group under inclined loading MP-Test (dense ground, S-R-Type, n=8, =0 deg.); (a) Qv vs. Sv, (b) Sh vs. Sv.

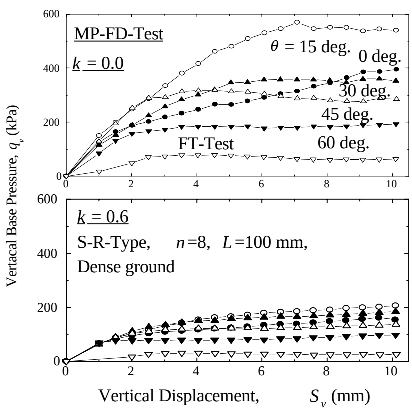


Fig. 13. Base pressure qv vs. displacement Sv relationships for the micropile foundations (S-R-Type, n=8, L=10cm) on dense ground; (a) under vertical load, k=0.0, (b) under inclined load, k=0.6.

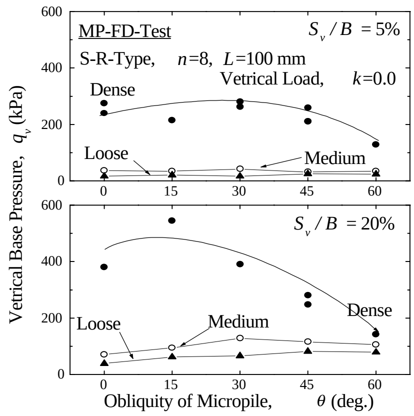


Fig. 14. Influence of Relative density of ground on the improvement of bearing capacity.

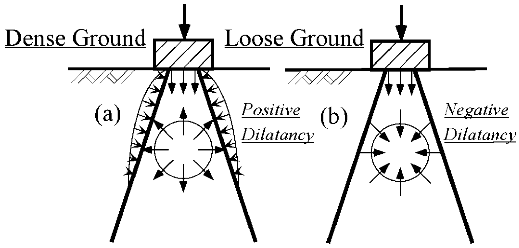
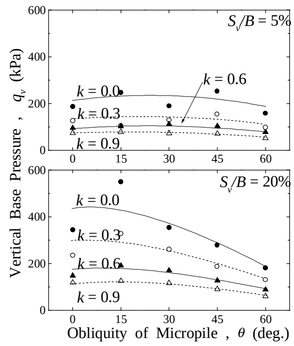


Fig. 15. Improvement of bearing capacity under inclined loading conditions.



16. Effect of inclined load on the bearing capacity of

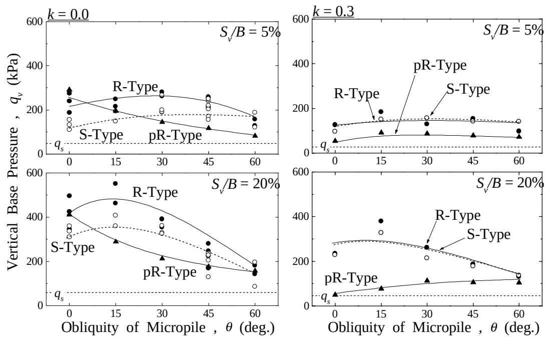


Fig. 17(a, b). Effect of mechanical properties on bearing capacity of micropile foundations

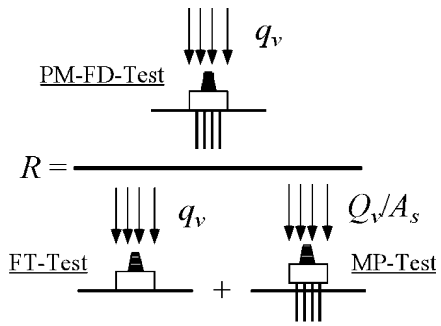


Fig. 18. Definition of improvement coefficient for bearing capacity of micropile foundation.

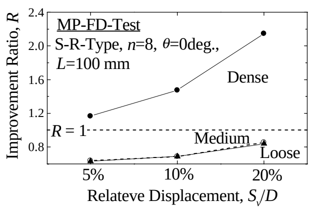


Fig. 19. Effect of relative density of ground on improvement of bearing capacity

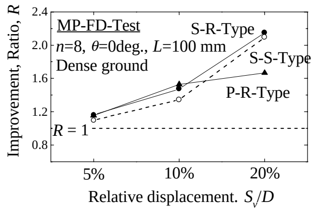


Fig.20. Effect of mechanical properties of micropiles on the improvement of bearing capacity.

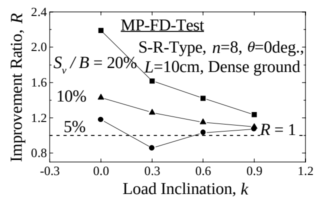


Fig. 21. Improvement of bearing capacity under inclined loads.