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Model loading tests on the footing reinforced with prestressed micropiles

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ABSTRACT: To investigate the mechanism of the bearing capacity of footing reinforced with a group of micropiles, a series of loading tests were carried out on the model footings with and without micropiles. To mobilize the network effect appropriately and improve the bearing capacity, a tensile stress was induced in the micropiles at the beginning of the loading process in this series of model loading tests. As a result, the bearing capacity was improved more than 100% with the prestress of 70% of the pullout resistance, not only in dense and dilative ground, but also in the loose and contractive ground. The network effect of a group of micropiles on the bearing capacity is mobilized positively with the appropriate confinement of the ground material beneath the footing. In this process the micropiles not only provide load bearing capacity directory through their skin friction, but also raise the base pressure on the footing with the confinement.

1 INTRODUCTION

Micropiles are now widely used both as structural supports in foundations as well as for in-situ earth reinforcement. Pioneered by Lizzi (1971, 1978) in Italy, micropiles now enjoy worldwide recognition (US Development of Transportation, 1997, & Tsukada, 1997). Micropiles are claimed to cause minimum disturbance to structures, subsoil and the environment. Furthermore, they can be cast-in-place replacement piles with small diameters and can be easily installed in pre-drilled boreholes containing steel rods as reinforcement and grouted under pressure. It is thus not surprising that micropiles are considered as promising foundation elements in improving the bearing capacity of existing foundations which are deteriorating for one reason or another. The Hyogoken-Nambu earthquake in 1995 in Japan caused extensive damages to the foundations of bridges and this in turn has triggered research and development on the use of micropiles in strengthening foundations.

Additionally, the design concept of micropiles offers a wide range of flexibilities by which they can withstand axial and/or lateral loads. They can be considered either as a single component in a composite soil/pile mass or a small diameter substitute in a conventional pile. Micropiles can sustain sufficient load by friction as there are grouted piles installed under controlled pressures. Because of their flexibility and their installation in small diameters, they can be used conveniently as a group in reinforcing spread footings. The interaction between the footing and the micropile group makes it susceptible to large loads and displacements under earthquake type of destruction. In the reinforcement of existing foundations, the micropiles and footing are considered to be a piled-raft foundation in their performance.

Although the applications of micropiles are increasing in various situations, their mechanism of developing the bearing capacity is not yet fully understood. Thus the aim of the series of study on model micropile is to investigate some important aspects which classify and quantify the development of bearing capacity in micropile foundations and to develop new method to improve the performance of micropile foundations. In previous study, the method of the model loading tests has been reported by Y. Tsukada et al. (1999), and the test results on three series of model tests (or, footing test, micropile test, and micropile foundation test) have been reported by Miura et al. (2000). Three types of micropiles with different bending stiffness and surface roughness but without prestress were used in previous study, which hereafter are called non-prestressed micropiles to distinguish them with the prestressed micropiles in this study.

In this study, the model micropiles were vertically installed beneath the footing in the artificial sand ground. And the behavior is observed under some series tests of micropile foundation in dense and medium-dense ground under vertical and inclined loads. To examine the mechanism of the interaction and improve bearing capacity effectively, prestress was introduced into micropiles in the beginning of the model loading tests. The soil material enclosed by the micropile group and the footing was confined due to the prestress, as a result the stiffness of the soil material and base pressure of the footing were increased. The overall bearing capacity was improved in both vertical load and inclined load.

2 METHOD FOR MODEL LOADING TESTS

In this study, a newly developed apparatus for the model micropile foundation test has been introduced to apply prestress onto the micropiles as shown in Figure 1, which also made it possible to measure the load carried by the micropile group and the load by the footing separately. So the mechanism of interaction between the footing and micropiles was examined. The other main characteristics of the tests are summarized below, for the details of the testing method, refer to Y. Tsukada et al. (1999). The model footing is made of stainless steel with a diameter of 40 mm, which is reinforced with a group of micropiles; five types of model footings are available to fit the need of variation of the pile number and pile inclination angle in the micropile group.

Three types of model micropiles were used in previous non-prestressed study. Two types, S-S-type and S-R-Type, are made of stainless steel with high bending stiffness of $EI = 1.28\times10^{-1}$ Nm^2 ($E = 2.1\times10^5$ MPa); and the other type, P-R-Type, is made of plastic with low bending stiffness of $EI = 2.50\times10^{-3}$ Nm^2 ($E = 3.1\times10^3$ MPa). Two rough surface types, S-R-Type and P-R-Type, were coated with thin sand layer so as to mobilize sufficient skin

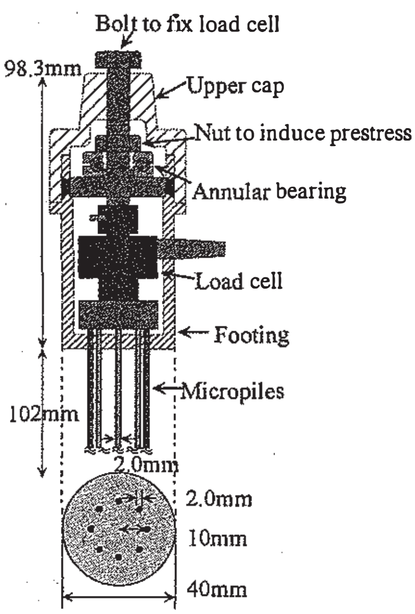

Figure 1. Newly developed device for the inducement of prestress on micropile group.

Table 1. Physical and mechanical properties of sand.

Parameter	Value		
(a) Sand Particles			
Grain density, ρ_s	2.717 g/cm^3		
Max dry density, ρ_{dmax}	1.610 g/cm^3		
Min dry density, ρ_{dmin}	1.255 g/cm^3		
Mean grain size, D_{50}	0.18 mm		
Uniformity coefficient; U_c	1.82		
(b) Grounds			
Type of ground	Dense	Medium	Loose
Relative density, Dr	95 ± 2%	65 ± 2%	50 ± 2%
Angle of friction, ϕ_d	38.5 deg	36.2deg	34.8 deg

friction with ground; and sand particles were glued to the micropile surface. In current study, S-R type micropile was used for prestressed micropile foundation test. The model micropile foundation was set up on the surface of the model sand ground formed in a mold. Oven dried silica sand was deposited through air with a nozzle, and tapped with a rubber hummer so as to obtain prescribed three different relative densities: dense, medium, and loose grounds. The physical and mechanical properties of the model sands are shown in Table 1.

In this study on model micropile foundation, eight S-R type micropiles were used to reinforce the model footing, which were vertically installed. Dense and medium-dense model grounds were used to compare the effect of grounds. Both vertical load and horizontal load were applied in this study. The load ratio k is defined as horizontal load over vertical load. For vertical loading test, $k = 0$. The purpose of applying horizontal load is to model the effect of footing reinforced with micropiles under seismic loading condition. Shown in Figure 2 is a photo of the new device after a loading test.

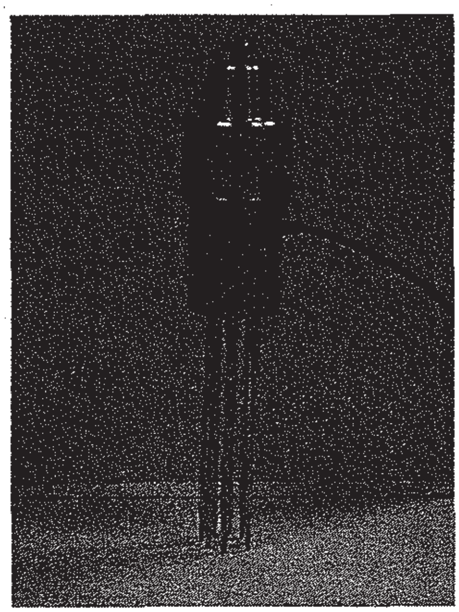

Figure 2. Photo of the test device.

3 TEST RESULTS AND ANALYSIS

To assess the degree of improvement of the bearing capacity with micropiles quantitatively, the network effect index I_{ne} was newly introduced (Fig. 3). The I_{ne} of unit means that the bearing capacity of the footing reinforced with micropiles is equal to the summation of the surface footing and the micropile group. If the confining effect by the interaction between the subsoil, footing and the micropile group is positive, the interaction improves the bearing capacity, and the value of I_{ne} becomes larger than unit.

In the non-prestress micropile model tests, 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. In dense ground, due to the dilatant behavior of ground material, bearing capacity was remarkably high compared with those in medium and loose grounds (Fig. 4). 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. It was found that the confinement of the ground material with the interaction between the footing and the micropile group plays an important role in the improvement of the bearing capacity. The confinement increases the confining stress in the ground material beneath the footing and then the base pressure on the footing as shown in Figure 6. The confining effect is a function of the geometry and stiffness of the micropile group and the mechanical properties of ground material.

$$I_{ne} = \frac{\left[\dfrac{Q_v}{A_s}\right]_{\text{MP-FD-Test}}}{\left[\dfrac{Q_v}{A_s}\right]_{\text{FT-Test}} + \left[\dfrac{Q_v}{A_s}\right]_{\text{MP-Test}}}$$

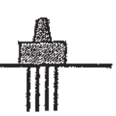

Figure 3. Definition of network effect index for bearing capacity of micropile foundation.

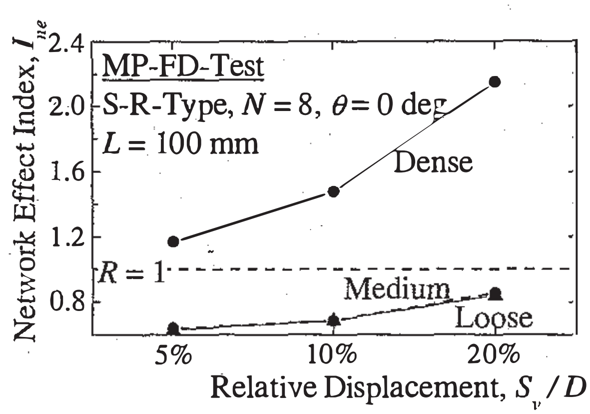

Figure 4. Effect of relative density on network effect index I_{ne}.

However, the improvement of bearing capacity, which is positive effect of the confining effect, was not mobilized in loose and medium grounds and also in the early stage of loading with small displacement in dense ground (Figs. 4&5). To induce the confining effect more effectively even under small displacement, it is necessary to raise the confining stress on the ground material beneath the footing at initial stage. Then, in the series of model loading test on the micropile foundation, some amount of

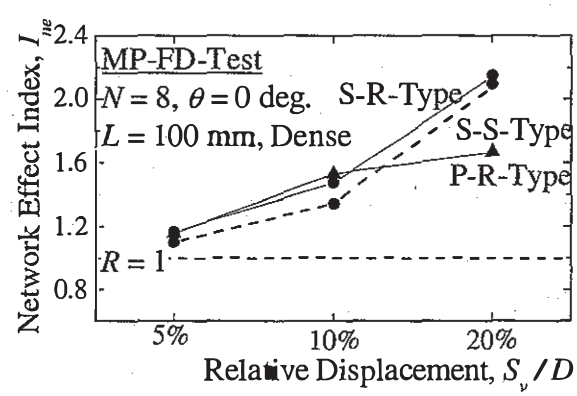

Figure 5. Effect of relative settlement on network effect index I_{ne}.

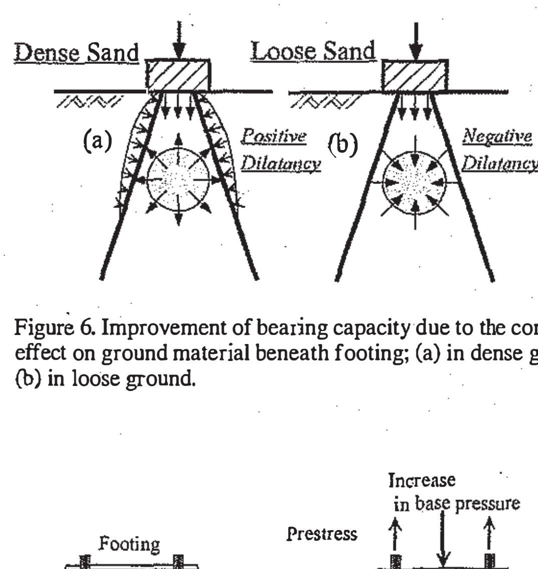

Figure 6. Improvement of bearing capacity due to the confining effect on ground material beneath footing; (a) in dense ground, (b) in loose ground.

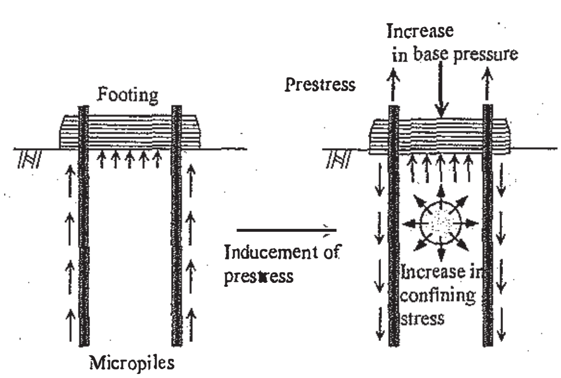

Figure 7. Concept of prestress on micropile group and induce base pressure and confining pressure.

prestress was induced to the micropile group. Shown in Figure 7 is the illustration of how to apply prestress; as a reaction of the prestress, the initial base pressure and confining stress was simultaneously increased.

The prestress test was conducted on the footing reinforced with eight S-R type micropiles on the dense and medium-dense sand. The load on the micropile group could be measured with the load cell inside the model micropile foundation; the base pressure was evaluated from the difference between the total load and the load carried by micropile group. The degree of prestress was indicated with the ratio $-Q_{mp0}/Q_{mpmax}$ of the prestress on the micropile foundation to its ultimate value in micropile test. The inclination of the load is indicated by k.

Under vertical loading condition (k = 0), the observed load-displacement behavior is shown in Figures 8 & 9 for dense and medium-dense ground, respectively; where the averaged base pressure q_v, the equivalent base pressure Q_{mp}/A_f for the load carried by micropiles and the base pressure evaluated as q_f (= q_v - Q_{mp}/A_f) are plotted against settlement S_v. In the case of non-prestressed micropile group ($-Q_{mp0}/Q_{mpmax}$ = 0) the base pressure is rather low and does not increase clearly with displacement on both dense and medium grounds. Due to the induced prestress on micropile the load on micropile group becomes negative and base pressure increases at initial condition. And the base pressure increases notably and as a result the total load increases at a certain displacement. The load carried by micropile group Q_{mp} decreases with the prestress and the micropile group gains the margin until the ultimate condition. Shown in Figures 10 & 11 is the improvement of bearing capacity with the prestress in dense and medium-dense sand grounds, respectively. With the increase of prestress, the load on micropile group was reduced monotonically, on the other hand the base pressure on the footing increased; this trend is recognized at all the levels of displacement until S_v/D = 20%. As a result the base pressure increases with the prestress even under initial stage of loading (S_v/D = 5%). The bearing capacity was increased almost 100% with the prestress equivalent to a half of ultimate bearing load of micropile group.

Under both vertical and horizontal loads, the observed load-displacement behavior in dense sand is shown in Figures 12 & 13 for k = 0.3, 0.6, respectively. The observed variations of load-displacement are similar to those observed in vertical loading test, which demonstrates the effect of prestress on the improvement of bearing capacity under seismic loading condition. Shown in Figures 14 & 15 is the influence of k on the load bearing capacity in dense and medium-dense sand, respectively. It is found that when the k increases the magnitude of improvement induced by prestress decreases.

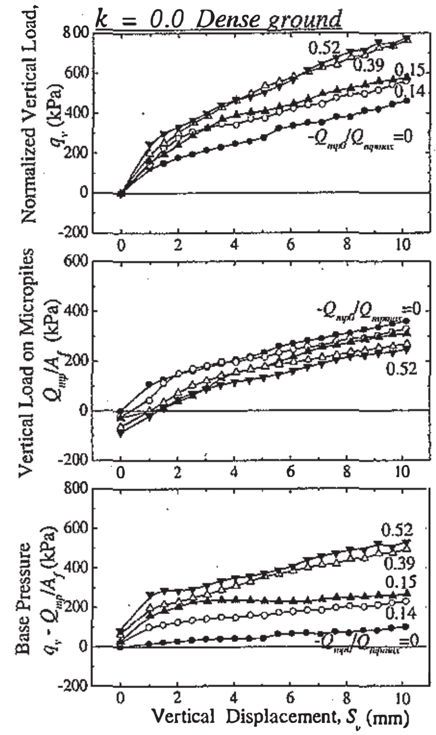

Figure 8. Effect of prestress on the behavior of micro pile foundations on dense ground; (a) total load, (b) load on micropile group, (c) base pressure.

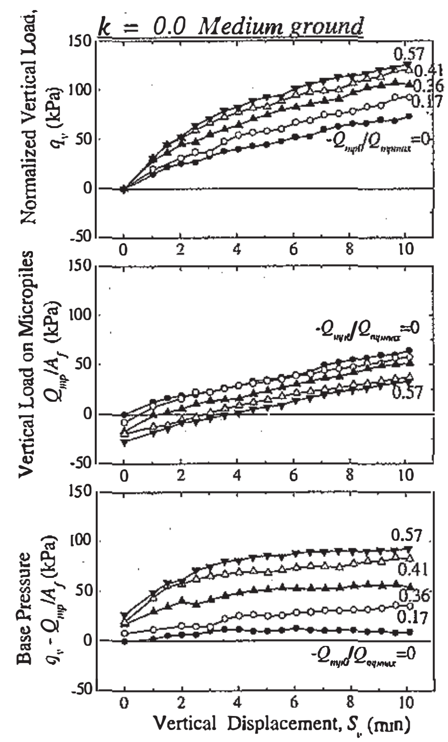

Figure 9. Effect of prestress on the behavior of micro pile foundations on medium ground; (a) total load, (b) load on micropile group, (c) base pressure.

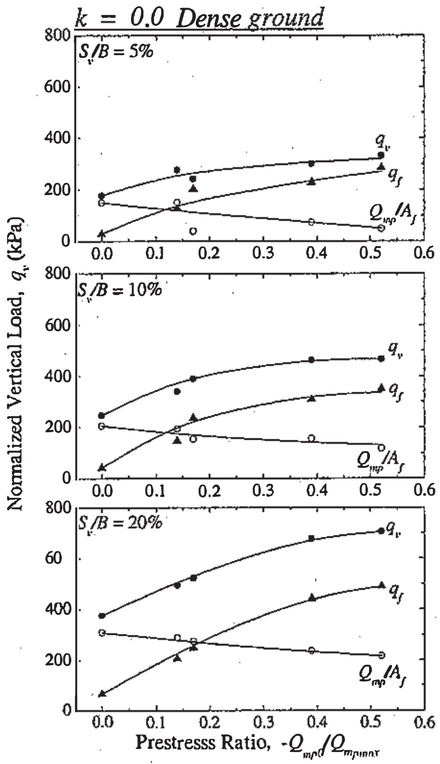

Figure 10. Improvement of bearing capacity with inducement of prestress on micropile group in dense ground.

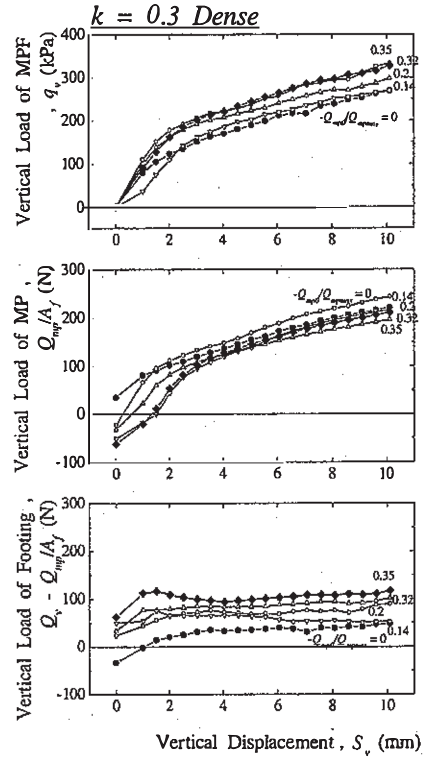

Figure 12. Effect of prestress on the behavior of micro pile foundations on $k = 0.3$; (a) total load, (b) load on micropile group, (c) base pressure.

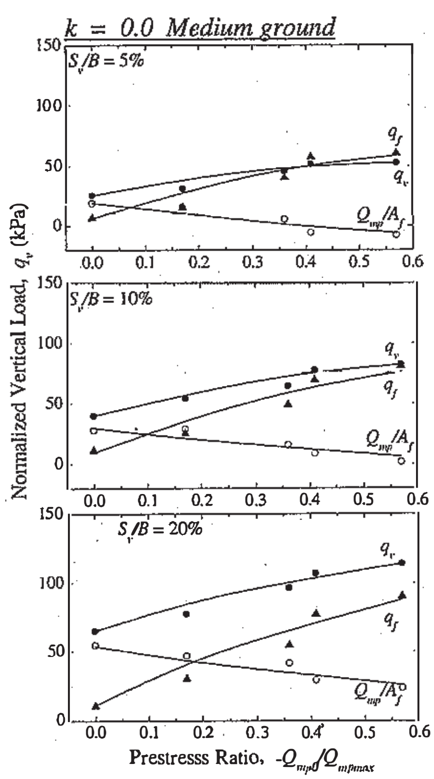

Figure 11. Improvement of bearing capacity with inducement of prestress on micropile group in medium dense ground.

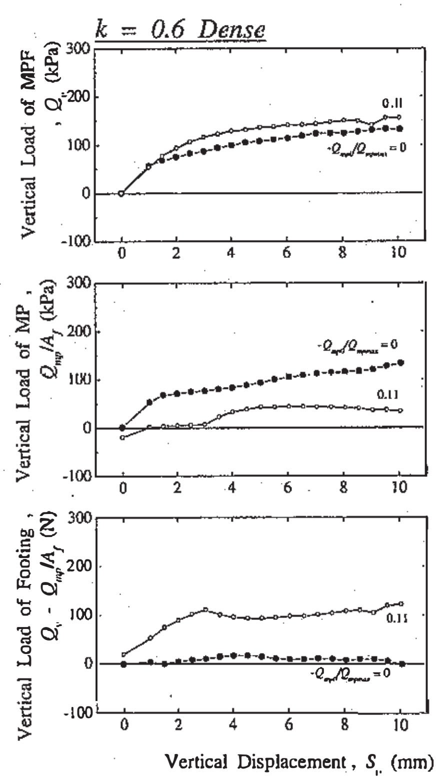

Figure 13. Effect of prestress on the behavior of micro pile foundations on $k = 0.6$; (a) total load, (b) load on micropile group, (c) base pressure.

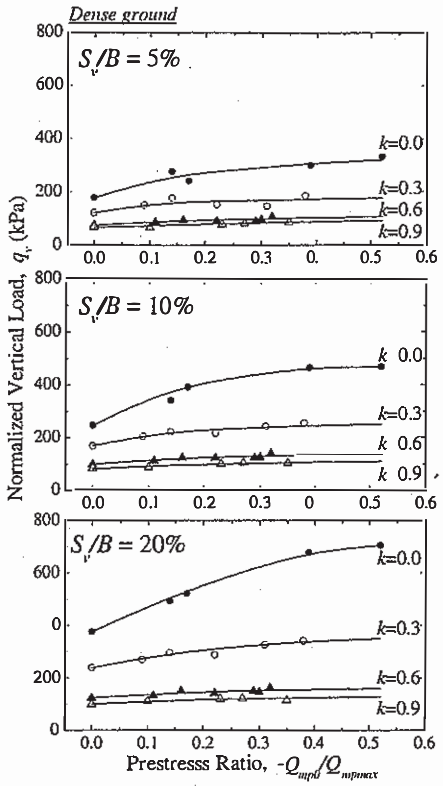

Figure 14. Influence of k on the load bearing capacity in dense sand.

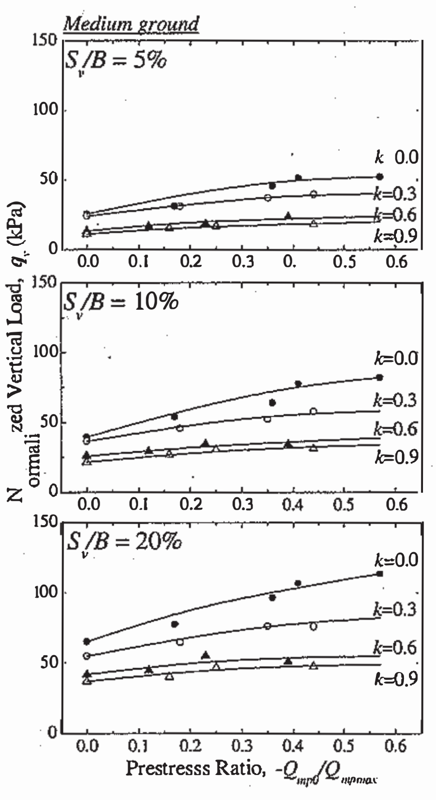

Figure 15. Influence of k on the load bearing capacity in medium-dense sand.

4 CONCLUSIONS

To investigate the effect of prestress on the improvement of the bearing capacity of footing reinforced with a group of micropiles, a series of model micropile foundation tests has been carried out. The circular footings were reinforced with a group of S-R type micropiles, and were subjected to different prestress in both dense and medium-dense sand. Based on the observed load-displacement behaviors from the comparative examinations under different loading conditions, the following concluding remarks were drawn:

Prestress increases the interaction between the footing and the micropile group, and this interaction was significantly effective on the confinement of ground material and on the improvement of the bearing capacity of footing in dense sand.

It was found that the prestress on the micropile group is effective on the improvement of bearing capacity of micropile foundation in both dense and medium sand. It was effective even in initial loading stage with small displacement on both dense and medium sand ground. Under the test condition, the prestress equivalent to a half of the ultimate bearing load on the micropile group increased the total bearing capacity of micropile foundation by 100%.

Prestress increases the overall bearing capacity of micropile foundation, but the load carried by micropile decreases with the prestress. It indicates that the footing is bearing more load with improved contact between footing and soil under high prestress.

Prestress is also effective in increasing bearing capacity of footing under horizontal force.

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