MECHANISM OF BEARING CAPACITY OF SPREAD FOOTINGS REINFORCED WITH MICROPILES

YUKIHIRO TSUKADA\(^{3}\), KINYA MHURA\(^{3}\), YUKITOMO TSUBOKAWA\(^{3}\), YOSHINORI OTANI\(^{3}\) and GUAN-LIN YAO\(^{3}\)

ABSTRACT

The Hyogoken-Nambu Earthquake in 1995 caused extensive damages to the foundations of bridges. Ever since, methods to improve the bearing capacity of existing foundations have become an important aspect of foundation engineering in Japan. Micropiles are considered to provide promising solutions. The mechanism which enhances the bearing capacity of surface footings reinforced with micropiles is the subject of investigation in this study. As an initial phase, model tests were conducted to understand the load-displacement behavior of surface footings with and without micropiles on loose, medium dense, and dense layers of sands. Salient factors which influence the behavior of the footings were selected and their influence on bearing capacity was examined through a comprehensive series of model tests. Notable improvements in the bearing capacity of surface footings reinforced with vertical micropile groups were observed in the case of dense sand which is dilative during shear. To assess quantitatively the degree of improvement in the bearing capacity of surface footings reinforced with micropiles, an index \( R \) called "Network Effect Index" was introduced in this study. The index \( R \) of unity means that the bearing capacity of footings reinforced with micropiles is simply equal to the summation of the individual value of the surface footing and that of the micropile group. An index \( R \) of more than two is achieved in this study where surface footings reinforced with a group of vertical micropiles bear on a dense layer of dilative sand. By contrast, with loose and medium dense sand, which are contractive in nature, the index \( R \) is found to be less than unity.

Key words: bearing capacity, footing, micropile, network effect, reinforcement (IGC: E3)

INTRODUCTION

Micropiles are now widely used for structural supports in foundations as well as for in-situ earth reinforcement. Pioneered by Lazzi (1971, 1978) in Italy, micropiles now enjoy worldwide recognition (see Bruce et al., 1995; US Development of Transportation, Schlosser and Frank, 1998; Tsukada, 1998). 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. As the Hyogoken-Nambu Earthquake in 1995 in Japan caused extensive damages to the foundations of bridges, micropile method was practically used for reinforcement of existing foundations in sites. With practical experiences in the sites, the mechanism of bearing capacity and network effect concerning micropiles has been discussed continuously (see Otani and Hoshiya, 2004; Schlosser, 2004; Tsukada et al., 2004).

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 as 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 suppress 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 (see Cooke, 1986).

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 this study is to examine some important aspects which classify and quantify the development of bearing capacity in micropile foundations. This work reveals the importance of network effect in micropiles as discussed by Lizzi (1978) and Francis et al. (1996). Loading tests were carried out by the authors on a group of micropiles named the Micropile Foundation (MP-Foundation). They have discussed the influence of the arrangement of micropiles in developing the network effect and in enhancing the bearing capacity. Model tests were thus performed by the authors on surface footings with and without micropile reinforcement on layers of sand which are loose, medium dense and dense. Three types of micropiles with different bending stiffness and surface roughness were used. In the model tests, parametric variations of the number, length, and the inclination of micropiles were adopted.

MODEL TESTS

Ideally speaking, centrifugal model tests have superior characteristics under many conditions; nevertheless, ordinary model tests under gravitational force can also contribute to a better understanding of the salient features which enhance the bearing capacity of footings reinforced with micropiles. Model tests are cheaper to perform and thus a large number of tests can be carried out to ensure the repeatability of the data. Additionally, these tests are easy to perform and the fabrication of the equipment and its function are easily verifiable.

**Micropile Foundation**

Figure 1 shows a typical model footing reinforced with a group of micropiles (MP-Foundation). The footing is circular in shape, 40 mm in diameter and is made of stainless steel. It is reinforced with a group of micropiles; $N$ is the number of the micropiles, $L$ is the length and $\theta$ is the inclination of the micropiles to the vertical direction. Depending on the number $N$ and the inclination $\theta$, a footing is selected from those shown in Fig. 2.

Figure 3 and Table 1 contain the details of three different types of model micropiles. Two types, denoted as S-S-Type and S-R-Type, were made of stainless steel with high bending stiffness. The third is denoted as P-R-Type and is made of plastic with low bending stiffness. The stiffness of all three types of micropiles was measured through a series of point loading tests. Sand grains were glued to the surface of the stainless steel and

![Fig. 1. Typical micropile foundation: $N=8$, $L=100$ mm, $\theta=60$ degrees](image)

![Fig. 2. Model circular footings: (a) not reinforced, (b) reinforced with single micropile and (c) reinforced with micropiles ($N=2$–8)](image)

![Fig. 3. Model micropiles: (a) S-S-Type, (b) S-R-Type and (c) P-R-Type](image)

<table>
<thead>
<tr>
<th>Table 1. Mechanical properties of model micropiles</th>
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<tbody>
<tr>
<td>Type of micropile</td>
</tr>
<tr>
<td>(1) Material</td>
</tr>
<tr>
<td>(2) Diameter (mm)</td>
</tr>
<tr>
<td>(3) Bending stiffness, $EI$ (N$\cdot$mm$^2$)</td>
</tr>
<tr>
<td>(4) Young’s modulus, $E$ (kPa)</td>
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</table>
the plastic to make the surfaces rough. Thus the S-R-Type and the P-R-Type have rough surfaces, with a thin sand layer to mobilize the skin friction. The results obtained from the model tests on these piles can be used to examine the effects of surface roughness and bending stiffness of the micropiles. In the model tests with small model scale, relative particle size of soil sometimes induces unfavourable effects on the test result. As the ratio of micropile diameter to the sand particle size is about ten in the model test, the unfavourable scale effect can be considered to be minor in this model test condition: Ovesen (1979) and Miura et al. (2003).

Figure 4 shows the sand container which is made of stainless steel, 300 mm in inner diameter, and 200 mm in depth. The model micropile foundation was suspended in position during the deposition of sand (see Fig. 4). A funnel with a nozzle at the bottom is used to freely deposit the oven-dried sand through the air, inside the container. This procedure is thought to minimize the disturbance of the sand around the micropiles and also avoids the unnecessary prestress both in the micropiles and in the sand. The physical and mechanical properties of the silica sand are listed in Table 2 and the stress-strain behavior observed in conventional drained triaxial tests is shown in Fig. 5. Miura et al. (1998) contains the details of the triaxial tests which were carried out on the sand used in this study.

**Table 2. Physical and mechanical properties of sand**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value 1 (g/cm³)</th>
<th>Value 2 (g/cm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grain density, $\rho_0$</td>
<td>2.717</td>
<td>1.610</td>
</tr>
<tr>
<td>Maximum dry density, $\rho_{max}$</td>
<td>1.255</td>
<td></td>
</tr>
<tr>
<td>Minimum dry density, $\rho_{min}$</td>
<td>0.18 mm</td>
<td></td>
</tr>
<tr>
<td>Mean grain size, $D_{50}$</td>
<td>3.85 deg</td>
<td></td>
</tr>
<tr>
<td>Uniformity coefficient; $U_c$</td>
<td>1.82</td>
<td></td>
</tr>
</tbody>
</table>

(b) Grounds

<table>
<thead>
<tr>
<th>Type of ground</th>
<th>Dense</th>
<th>Medium</th>
<th>Loose</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relative density, $D_r$</td>
<td>95±2%</td>
<td>65±2%</td>
<td>50±2%</td>
</tr>
<tr>
<td>The angle of internal friction, $\phi_i$</td>
<td>38.5 deg</td>
<td>36.2 deg</td>
<td>34.8 deg</td>
</tr>
</tbody>
</table>

Fig. 4. Preparation of the sand with micropile foundation

Fig. 5. Stress-strain-dilatancy behavior of silica sand as observed in conventional triaxial tests

**Loading Apparatus**

Figure 6 illustrates the loading apparatus and the computer-aided monitoring and controlling system used. Three loading rams equipped with a direct drive motor and a load cell were mounted on the frame of the apparatus, two were in the vertical direction and the third was in the horizontal direction. With these three independently adjustable loading rams, the three components of the motion of the micropile foundation can be controlled and
the vertical and horizontal displacements as well as the rotation can all be adjusted. However, in this study, only the vertical load was applied. The least count for the measurements of the displacement and the force are $5 \times 10^{-7}$ mm and $9.2 \times 10^{-3}$ N, respectively. A constant rate of penetration of 1.0 mm/min was maintained in the vertical direction. Detailed information on the preparation of the model micropile foundation and the testing method is described in Tsubokawa (1999).

Test Series

Figure 7 illustrates the three series of loading tests conducted in this study. The first one, denoted as the FT-Test series, contains observations of the load-displacement behavior of surface footings without any reinforcement (Fig. 7(a)). In this series, circular footings placed on the surface of loose, medium dense and dense sand were subjected to vertical loads. The second series of tests designated as the MP-Test series contains observations on the tests conducted on footings reinforced with micropiles, in which the footing was standing free from the ground surface (Fig. 7(b)). In this series, several types and groups of vertical micropiles with different length, number and skin roughness were employed. Finally, in the third series, designated as the MP-FT-Test series, the behavior of footings reinforced with vertical or inclined micropiles was tested (Fig. 7(c)). In this series, similar to the second one, the MP-Tests, several types of micropile groups with different angles of inclination, length, number, stiffness and skin roughness were tested with vertical loads (Fig. 7(d)).

TEST RESULTS AND DISCUSSION

Bearing Capacity Characteristics of Surface Footings on Sand (FT-Test)

The behavior of surface footings subjected to vertical load was observed in FT-Tests. The results are presented in Fig. 8 as the averaged base pressure $q_v$, plotted with respect to the vertical displacement $S_v$. Several test results are presented to indicate the repeatability and reliability of the data. The solid line in the figure is for a different model preparation method where the circular footing was placed after the deposition of sand; it seems that the footing which was suspended during the deposition barely disturbed the sand deposit and did not affect the test results.

The significant effect of the density of the sand layer is seen in the results in Fig. 8. In the case of dense sand, the behavior was of the general shear failure type; the base pressure $q_v$ possessed a peak during the loading and a shear failure plane appeared on the ground surface, as shown in Photo 1(a). By contrast, the behavior in the case of medium dense and loose sand was of the local shear failure type; the shear failure plane did not appear on the surface, as shown in Photo 1(b). These differences in the load bearing behavior and the shear failure mode would be attributed to the dilative properties as a function of relative density, as shown in Fig. 5. As illustrated in
Fig. 9. Shear failure patterns induced by the movement of the surface footing: (a) general shear failure in a dilative sand and (b) local shear failure in a contractive sand

Fig. 9, while the dilative behavior of the dense sand beneath the footing enhances the extension of the shear failure plane towards the ground surface, the contractive behavior of the medium dense and loose sand does not create such a failure mode.

**Bearing Capacity Characteristics of Micropiles in Sand (MP-Test)**

Shown in Fig. 10 are the relationships between the vertical load $Q_x$ versus the embedded length of micropiles $L_e$ as observed in the MP-Test series on the vertically installed micropiles with different initial lengths. The results of the tests on the micropile groups in dense sand with different numbers of S-R-Type micropiles are presented in Fig. 10(a). Only in the case of the group with 8 micropiles, the load-length behavior showed a peak at the early stage of loading. Parabolic curves are shown in this figure, fitting the test data: $Q = 2.1 \times L_e^2$ for $N = 1$ and $Q = 8 \times 2.1 \times L_e^2$ for $N = 8$. These curves suggest that the load bearing is supported mainly by skin friction and not by end bearing. It can be said that the group effect of the micropile group, which is followed by the reduction in the bearing capacity per pile with increasing number of piles, was not recognized. The behavior was not influenced by the limited size of the container or its base.

Indicated in Fig. 10(b) is the effect of the relative density of the sand; the bearing capacity of micropile groups in medium dense and loose sand seems to be only less than half of that in dense sand. This remarkable reduction in the bearing capacity cannot be explained only by the angle of internal friction shown in Fig. 5. The mechanism of bearing capacity development, that is, by skin friction of micropiles, is illustrated in Fig. 11. The reduction in the bearing capacity with lower relative density can be attributed to the reduced values of confining stress around the micropiles as induced both by the contractive volume of the medium dense and loose sand (see Fig. 5), and by the reduced angle of internal friction.

The influence of surface roughness on bearing capacity is noticeable in Fig. 10(c), where the results are presented for the S-R-Type and S-S-Type with rough and smooth surfaces, respectively. The bearing capacity was increased by about 50% due to the improvement in the fixity of micropiles within the sand, as well as a slight increase in the diameter, as shown in Fig. 3 and Table 1.

Fig. 10. Load $Q_x$ versus micropile length $L_e$ in MP-Test series: (a) influence of the number of micropiles (dense sand, S-R-Type), (b) influence of the sand density (S-R-Type, $N = 8$) and (c) influence of mechanical properties of micropile (dense sand, $N = 8$)

Fig. 11. Illustration of the mechanism of micropile bearing capacity with respect to the change in horizontal confining stress: (a) initial condition, (b) increase in bearing capacity in dense sand and (c) decrease in bearing capacity in loose sand
Bearing Capacity Characteristics of Micropile Foundation in Sand (MP-FT-Test)

The observed behavior of micropile foundations reinforced with micropile groups of different angles of inclination θ are shown in Fig. 12 in the case of dense sand. A notable influence of the angle of inclination of the micropiles is recognized. The influence of the relative density of the sand is also shown for an initial stage and a few loading stages in Fig. 13, where $K_{vs0}$ is the initial tangential stiffness. The prominent influence of the relative density can be explained by the dilatative behavior of the sand as illustrated in Fig. 14. That is, the horizontal displacement of the sand would be confined within a group of micropiles in the loading process, and the confinement would change the end bearing and the skin friction of the micropiles. If the sand is dense and dilative, the confining pressure will increase more, otherwise it will decrease. This confining effect of the group of micropiles is called as the network effect of micropiles; see Lizzii, 1978.

Shown in Photo 2 are the failure patterns appeared on the ground surface in the MP-FT-Test in dense sand. Due to the confinement of the sand within the micropile group, the failure mode changed from the general failure type (Photo 1(a)) to the local shear failure type (Photo 2(a)) in the case of the vertical micropiles (θ=0 degree); the general shear failure type (Photo 2(b)) was still seen when the angle of inclination θ was 60 degrees. Thus, it seems that the effect of confinement (or the network effect) was mobilized more in the case of the vertical installation than in the other inclined cases. For dense sand, at a large displacement ($S_v/D = 20\%$) with sufficient deformation of the surface beneath the footing, the bearing capacity was maximum when the angle of inclination

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**Fig. 12.** Base pressure $q_s$ versus displacement $S_v$ for micropile foundations (S-R-Type, $N=8$) in dense sand

**Fig. 14.** Illustrated mechanism of the effect of confinement of sand with micropile group: (a) positive network effect in dense sand and (b) negative effect in loose sand

**Fig. 13.** Influences of relative density of sand and inclination angle of micropile on bearing capacity in MP-FT-Test (S-R-Type, $N=8$): (a) secant modulus $K_{vs0}$, (b) base pressure at $S_v/D = 5\%$, (c) base pressure at $S_v/D = 10\%$ and (d) base pressure at $S_v/D = 20\%$
θ was less than 15 degrees. Since the total reaction force in the loading process is the summation of the base pressure of the footing and the load carried by micropiles, the bearing capacity is rather complicated to interpret as a function of the angle of inclination of micropiles, see Fig. 13.

To examine the effect of the mechanical properties of the micropile group, such as the bending stiffness and surface roughness, several types of MP-Foundations

![Photo 2. Shear failure patterns appeared on ground surface at relative displacement $S_a/D$ of 20% on dense sand in MP-FT-Test (S-R-Type, $N=8$): (a) local shear failure for $\theta=0$ degree and (b) general shear failure for $\theta=60$ degrees](image1)

![Photo 3. Plastically deformed micropile groups in dense sand in MP-FT-Test (P-R-Type, $N=8$): (a) for $\theta=0$ degree and (b) for $\theta=15$ degrees](image2)

![Fig. 15. Influences of stiffness and surface roughness of micropiles on bearing capacity in MP-FT-Test (dense sand, $N=8$): (a) secant modulus $K_{\psi_s}$, (b) base pressure at $S_a/D=5\%$, (c) base pressure at $S_a/D=10\%$ and (d) base pressure at $S_a/D=20\%$](image3)
reinforced with different types of micropiles were vertically loaded in dense sand; the test results are shown in Fig. 15. From the comparison between the S-R-Type and S-S-Type, the effect of surface roughness is found to be largest in the case of the vertical installation of micropiles ($\theta=0$ degree), and the effect decreases with increasing angle of inclination $\theta$. From the comparison between the S-R-Type and P-R-Type, the effect of bending stiffness is largest at an angle of inclination $\theta$ around 30 degrees. The damaged P-R-Type of micropile groups with plastic deformations are presented in Photo 3. This type of plastic deformation suggests that sufficient bearing stiffness of the micropile is needed for the full mobilization of the confinement of the sand.

Shown in Fig. 16 are the results of the vertical loading tests on MP-Foundations reinforced with different numbers of micropiles. There is a clear trend that the bearing capacity increases with the number of micropiles $N_t$; the relationship is not linear due to the network effect of the micropile group. At a larger displacement ($S_v/D = 20\%$), the bearing capacity for vertical installation ($\theta=0$ degree) was higher than that for the inclined installation ($\theta=30$ degrees).

**Improvement of Bearing Capacity of Footing with a Group of Micropiles**

To assess quantitatively the degree of improvement of the bearing capacity with the network effect of the micropile group, the Network Effect Index, designated as $R$, was introduced in Eq. (1).

\[
R = \frac{Q_{v,\text{MP-FT-Test}}}{Q_{v,\text{FT-Test}}} + \frac{Q_{v,\text{MP-Test}}}{A_t,\text{MP-Test}}
\]

The Network Effect Index $R$ of unity means that the bearing capacity of the footing reinforced with micropiles is simply equal to the summation of those of the surface footing and the micropile group. If the network effect is positively mobilized and the sand is confined with the interaction between the footing base and the micropile group, then the bearing capacity is improved positively and the index $R$ becomes larger. In the following discussion, the salient features of the network effect will be examined using Figs. 17 to 19.

The network effect is remarkably dependent on the degree of displacement of the MP-Foundation as illus-
CONCLUSIONS

Series of model tests were carried out to clarify the mechanism for improvement of the bearing capacity of footings reinforced with a group of micropiles. Circular footings were reinforced with a group of micropiles and the arrangement of micropiles was varied as well as the inclination of the micropiles. The load-displacement behavior of the foundations was analyzed and the features that influence the bearing capacity were identified. The following concluding remarks can be made.

The significant effect of the relative density of the sand on the bearing capacity was recognized for surface footings, a group of micropiles, and foundations reinforced with micropiles. In dense sand, the dilatant behavior has remarkable influence in increasing the bearing capacity as compared to the medium dense and loose sand. In the case of surface footing, a shear failure mechanism was generated freely and was observed on the surface only in the case of dense sand. An increase in the confining pressure on the surface of micropiles due to the dilatant behavior of dense sand, raised remarkably, the skin friction of micropiles.

An interaction was recognized between the footing and a group of micropiles, and this interaction had a significant effect on the confinement of the sand and the improvement of the bearing capacity of the footing. Due to the confinement, the base pressure on the footing was increased, as was the confining pressure on the surface of micropiles. In the case of footings reinforced with a group of vertically installed micropiles, the bearing capacity of the foundation was more than twice the summation of the individual bearing capacity of the surface footing and the group of micropiles.

The skin friction and bending stiffness of micropiles are important in increasing the bearing capacity. Sufficient bending stiffness is necessary to enhance the confinement of the ground material and the improvement of bearing capacity through the interaction between the footing and the group of micropiles.

ACKNOWLEDGEMENT

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NOTATION

- $A_c$: Area of the footing base (m$^2$)
- $D$: Diameter of footing (mm)
- $D_{max}$: Mean grain size of sand (mm)
- $D_r$: Relative density (%) 
- $E$: Young's modulus of the material of micropiles (kPa)
- $E_l$: Bending stiffness of micropiles (Nm$^2$)
- $K_s$: Earth pressure coefficient in sand
- $K_{t,5%}$: Initial tangential coefficient for $Q_y$ versus $S_y$ curve (N/m)
- $L$: Length of micropiles (mm)
- $L_e$: Embedded length of micropiles (mm)
- $N$: Number of micropiles ($N = 1-8$)
- $Q_y$: Vertical load (kN)
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