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BEHAVIOR OF MICROPILE FOUNDATIONS UNDER INCLINED LOADS IN LABORATORY TESTS

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ABSTRACT: Subsequent to the model investigation of the load bearing mechanism of micropile foundations in sand under vertical loads, this model study aims to further investigate the load bearing behavior of micropile foundations under inclined loads in sand. Three series of model tests (footing, micropile, and micropile foundation tests, respectively) are conducted in very dense sand (D_r = 95 ± 3%) under three different load inclinations ($k = P_h/P$ = 0.3, 0.6, and 0.9, respectively). The test results under inclined loads are comparatively analyzed using the results of the vertical loading tests (k =0.0), and discussed in terms of displacements, coefficients of subgrade reaction, and the network effect index. It is found that micropiles can effectively improve the bearing capacity of surface footings under inclined loads. However, as expected, the improvement of bearing capacity decreases with the load inclination. A positive network effect is observed in the model tests under inclined loads as in the vertical loading tests in previous studies. The network effect index, R increases gradually with settlement under different load inclinations; at a large settlement, a network effect index of 1.2 is obtained in inclined loading tests. It is found that the footing in the early loading stage tends to move toward the vertical direction in the footing tests under inclined loads, while the opposite results are observed in the micropile tests. The vertical coefficient of subgrade reaction of micropile foundations is higher than those of footings and micropiles, and its horizontal coefficient is more than twice of that of micropiles at k = 0.3. This indicates that the surface footing not only plays a role in load bearing, but also makes a remarkable contribution in positively mobilizing the interaction among footing, micropiles, and subsoil. The bearing capacity of micropile foundations is larger at small battered angles of micropiles under inclined loadings, and it decreases at large battered angles. Consequently, the coefficient of vertical subgrade reaction decreases with the battered angle in micropile foundation tests. On the other hand, the horizontal coefficient increases with the battered angle up to 45°.

Key words: Footing, inclined load, micropile, micropile foundation, model test, network effect, sand

INTRODUCTION

Piles with a diameter of less than 300mm are generally referred to as micropiles (Lizzi 1980; FHWA 1997). Modern micropiles were initiated by Dr. F. Lizzi in the 1950s in Italy, where they were called *pali radice* (root piles) (Lizzi 1964, 1971). Micropiles are now widely used for both structural supports in foundations and in-situ earth reinforcement (Lizzi 1978; Lizzi 1980; Lizzi 1994; FHWA 1997; Tsukada and Ichimura 1997; Mitchell et al. 1999). Micropiles are considered promising foundation elements for improving the bearing capacity or preventing the settlement of existing, deteriorating foundations with minimum disturbance to structures, subsoils, and the environment (Mason 1997; Tsukada et al. 1999). As a response to the destructive Hyogoken-Nambu earthquake in 1995 in Japan, research and development regarding the applications of micropiles in strengthening foundations have been focused on in Japan (Tsukada and Ichimura 1997; Kishishita et al. 1999).

In previous model studies on micropile foundations (surface footings reinforced with a group of micropiles), Tsukada et al. (1999, 2002) have reported the experimental method and results of footing tests (FT-Tests), micropile tests (MP-Tests), and micropile foundation tests (MP-FD-Tests) in different sands under vertical loads. Miura et al. (2000) have analyzed the load-bearing mechanism, key factors affecting bearing capacity, and the network effect of micropile foundations under vertical loads. The network effect refers to the synthetic effect of the footing and micropiles on the bearing capacity of micropile foundations. The purpose of this model study is to further investigate the behavior of micropile foundations under inclined loads using the same models and test apparatus as

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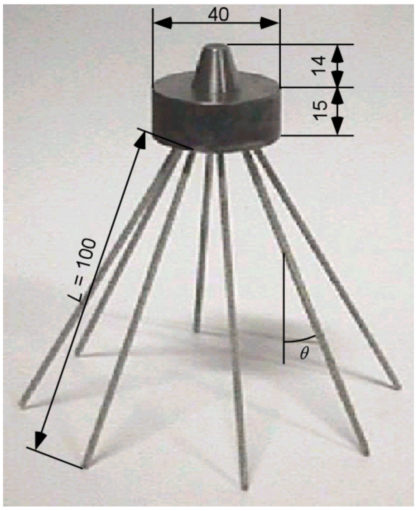

Fig. 1 Photo of a model micropile foundation (S-R-Type, N=8, L=100 mm, θ=30°)

in the vertical loading tests, and its target in the long run is to simulate the performance of micropiles in reinforcing bridge foundations under inclined loading conditions. Three series of tests were conducted under inclined loads in very dense sand, which are also designated as the FT-Test, the MP-Test, and the MP-FD-Test, in order to maintain consistency with the vertical loading tests, of which the FT-Test and the MP-Test are reference tests of the MP-FD-Test.

Prototype tests and centrifugal model tests may have superior characteristics under many conditions, such as scale effect (Vesic 1973; Franke and Muth 1985; Bolton 1986; Adachi 1992; Taylor 1995) and stress concentration (Shibata et al. 1989; Taylor 1995); 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 (Tsukada et al. 2002). Model tests are cheaper and easier to perform and thus a large number of tests can be carried out in order to ensure the repeatability of the data (Franke and Muth 1985; and Tsukada et al. 2002). Therefore, in this study, ordinary 1g models were also employed in the inclined loading tests of footings, micropiles, and micropile foundations.

TEST APPARATUS

The preparation of the model footing, micropiles, micropile foundations and the sand ground, and the test apparatus used for the inclined loading tests are same as those for the vertical loading tests described in previous studies. Below is a brief description of the test apparatus used; for a more detailed description of the test apparatus and preparation of the models, refer to Tsukada et al. (1999), Miura et al. (2000), and Tsukada et al. (2002).

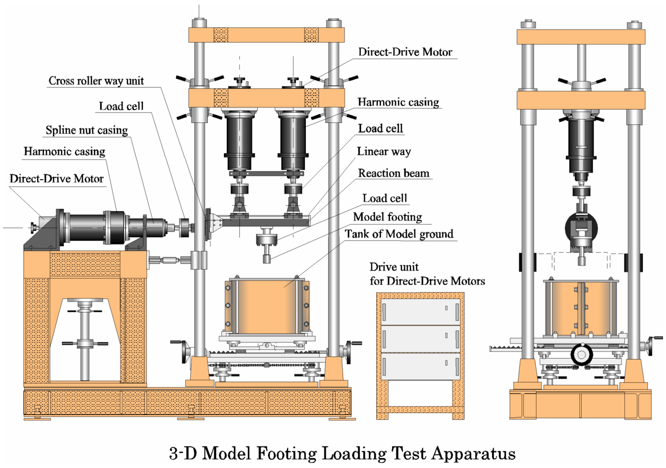

Fig. 2 Loading apparatus used in the inclined loading tests (after Tsukata et al. 1999)

The rigid model footings were made of stainless steel with a rough base, and were circular with a diameter of 40mm and thickness of 15mm (Fig.1). The model micropiles employed were steel rough micropiles (S-R-Type, 2.0mm in diameter). The rough surfaces of the footing base and micropiles were made by sticking sand onto their surfaces. The bending stiffness of steel micropiles is 0.119 (N×m^2). The length of the micropiles (L) is 100mm**.** The model micropile foundations were made by inserting micropiles into the micropile holes in the model footings using high strength industrial glue to fix them together, which may have variations in the number of micropiles (N, N = 8 in this study), in the battered angle of the micropiles (θ, θ = 0°, 15°, 30°, 45° and 60°) and in the types of micropiles installed (S-R-Type micropiles in this study). Shown in Figure 1 is a photograph of a model micropile foundation (S-R-Type, N = 8, L = 100mm, θ = 30°). The model sand ground was made of Japanese No. 7 silica fine sand. It was prepared by means of the air falling method with a relative density of D_r = 95 ± 3% whose physical properties are shown in Table 1. The steel container of sand is 200mm in depth and 300mm in inner diameter. Shown in Fig. 2 is the loading apparatus that can apply inclined loads (Tsukada et al. 1999). The test method used is Constant-Rate-of-Penetration (CRP) with CRP = 1mm/min.

METHOD OF ANALYSES

The load-settlement curve is used to show the observed load-settlement relationship of the surface footing, the micropiles, and the micropile foundations under inclined loads in model tests in sand. The direction of displacement is indicated by its vertical and horizontal components in order to reflect the displacement vector of the foundation.

Table 1 Physical and mechanical properties of sand

Properties	Value
Grain density	$\rho_s = 2.717$ g/cm^3
Maximum dry density	$\rho_{dmax} = 1.610$ g/cm^3
Minimum dry density	$\rho_{dmin} = 1.255$ g/cm^3
Mean grain size	$D_{50} = 0.18$mm
Uniformity coefficient	$U_c = 1.82$
Relative density	$D_r = 95 \pm 3\%$
Frictional angle	$\phi_d = 38.5°$

The coefficient of subgrade reaction is used to depict the early deformation behavior of the surface footings, the micropiles, and the micropile foundations under inclined loading conditions in the model sand (Japanese No. 7 silica sand, D_r = 95 ± 3%). The load bearing behavior of the micropile foundations was then further analyzed according to Network Effect Index (R) (Miura et al. 2000; Tsukada et al. 2002). The terms used in the analyses are defined as follows:

Normalized Settlement and Movement

$$S/B = \frac{S}{B}\times 100(\%) \qquad (1)$$
$$S_h/B = \frac{S_h}{B}\times 100(\%)$$

where

S/B Normalized settlement in percentage;

S_h/B Normalized horizontal movement in percentage;

S, S_h Settlement and horizontal movement, respectively, mm;

B Width (diameter) of the footing, B = 40mm.

Base Pressure, Equivalent Base Pressure, and Average Base Pressure

The bearing capacity is expressed as base pressure, equivalent base pressure, and average base pressure for the FT-Test, the MP-Test, and the MP-FD-Test, respectively. The base pressure of the footing and the equivalent base pressure of the micropiles are the load taken by the footing and the micropiles, respectively, divided by the area of the footing base, while the average base pressure of the micropile foundation is the total applied load divided by the footing area, as follows:

$$q_v = (P - P_{mp})/A_f$$
$$q_{ve} = P_{mp}/A_f \qquad (2)$$
$$q_{va} = P/A_f$$

where

q_v Base pressure of the footing, kPa;

q_{ve} Equivalent base pressure of micropiles, kPa;

q_{va} Average base pressure of the micropile foundation, kPa;

P Applied vertical load, kN;

P_{mp} Vertical load taken by micropiles, kN; In the FT-Tests, $P_{mp} = 0$, and in the MP-Tests, $P_{mp} = P$;

A_f Area of the footing base, m^2.

Load Inclination

To simulate the seismic resistant capacity of the micropile foundations, a series of inclined loading tests were conducted with respect to the model FT-Test, the MP-Test, and the MP-FD-Test. The load inclination is expressed by the ratio k of the horizontal load (P_h) over the vertical load (P), corresponding to the seismic coefficient (k) widely used in geotechnical engineering. Four kinds of inclined loads are employed with $k = 0.0, 0.3, 0.6, \text{and } 0.9$, respectively, where k = 0.0 represents the vertical loading tests in previous studies (Tsukada et al. 1999; Miura et al. 2000).

Coefficient of Subgrade Reaction

Due to its simplicity, the coefficient of subgrade reaction is widely used to approximately predict the deflection of vertically loaded footings and lateral loaded piles (Terzaghi 1955; Robinson 1979; Poulos and Davis 1980; Parikh and Pal 1981; Bowles 1996; Das 1999) under a given load intensity. However, the vertical subgrade reaction is generally used for footings, and the horizontal subgrade reaction is commonly used for laterally loaded piles. The coefficient of subgrade reaction is affected by many factors (Terzaghi 1955; Robinson 1979; Poulos and Davis 1980; Parikh and Pal 1981), such as soil properties, and the depth, location and magnitude of the applied load, and material properties and geometry of the pile and the footing. However, the focus of this study is not to investigate the influencing factors of subgrade reaction. Here we use the vertical and horizontal coefficients of subgrade reaction as an index to indicate the variation or improvement of the vertical and horizontal displacements in different foundations on the ground surface under different test conditions. Therefore, both the vertical and horizontal coefficients of subgrade reaction are based on the observed load-settlement curves of surface footings, micropiles, and micropile foundations for comparisons in this study. Figure 3 illustrates how to determine the load intensity and the corresponding settlement for the calculation, as depicted below.

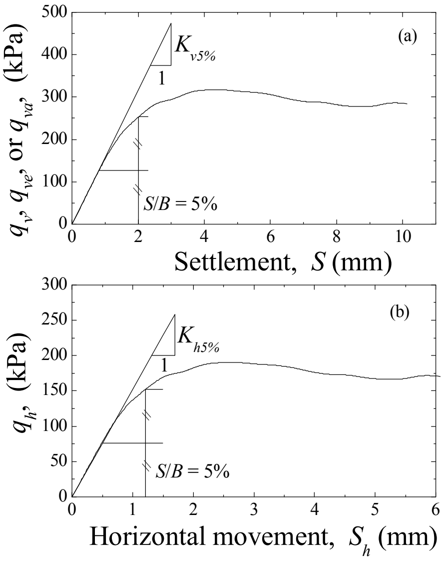

Fig. 3 Definition of the coefficient of subgrade reaction, (a) $K_{v5\%}$, (b) $K_{h5\%}$

The coefficient of the vertical subgrade reaction, denoted as $K_{v5\%}$, is specifically defined as the initial secant slope of the q_v (in the FT-Test, or q_{ve} in the MP-Test, q_{va} in the MP-FD-Test) vs. the S curve as follows and as illustrated in Figure 3a.

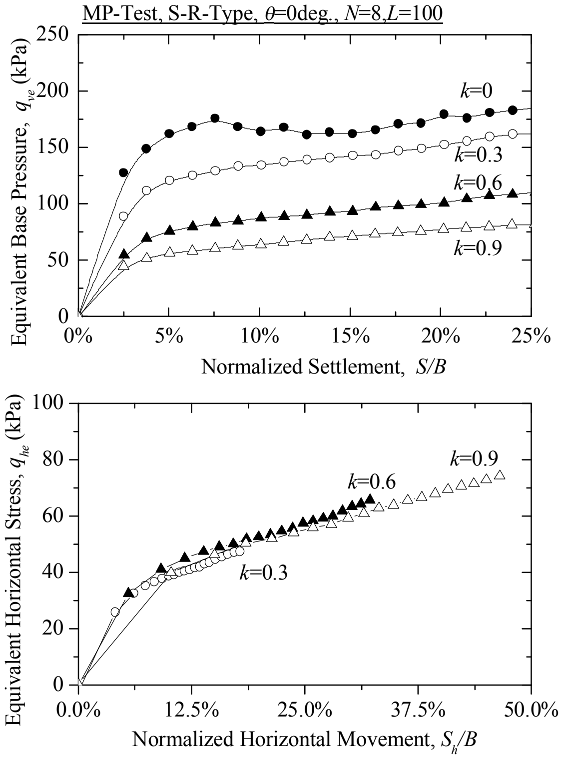

Fig. 7 Effect of inclined loading on the load bearing behavior of micropiles in the MP-Tests

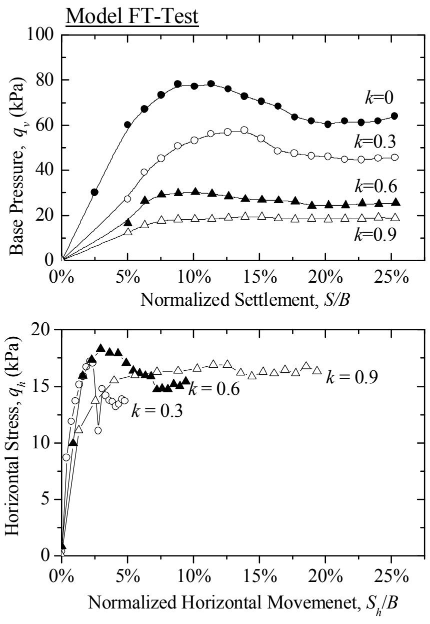

Fig. 4 Effect of inclined loading on the load bearing behavior of the footing

$$K_{v5\%} = \frac{\frac{1}{2}q_v}{S}, \tag{3}$$

where

q_v Base pressure at $S/B = 5\%$, kPa, $q_v = P/A_f$ in the FT-Test;

S Settlement corresponding to $q_v/2$, m.

As well, the coefficient of the horizontal subgrade reaction, $K_{h5\%}$, is similarly defined as the initial secant slope of the q_h vs. S_h curve when the normalized settlement (S/B) reaches 5% (Fig. 3b).

$$K_{h5\%} = \frac{\frac{1}{2}q_h}{S_h}, \tag{4}$$

where

q_h Horizontal stress at $S/B = 5\%$, kPa, $q_h = P_h/A_f$;

S_h Horizontal movement corresponding to $q_h/2$, m.

It should be emphasized that the coefficient of subgrade reaction ($K_{v5\%}$ or $K_{h5\%}$) is defined as the initial secant slope of the load-settlement curve in order to indicate the early deformation (elastic deformation) of the sand surface in different foundation systems. This is of particular interest for micropile applications in underpinning and foundation reinforcement for preventing movement or increasing bearing capacity. However, it should be stressed that the mechanism of developing the subgrade reaction is different in different directions for different foundations, so

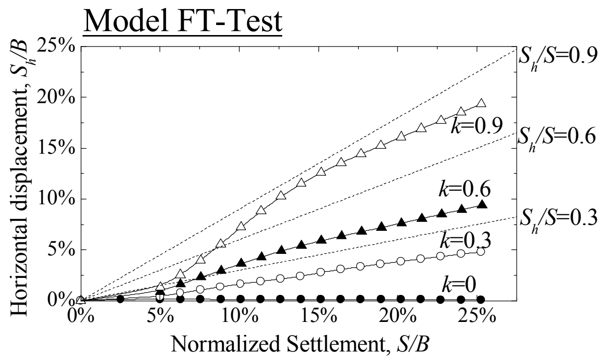

Fig. 5 Effect of inclined loading on the displacement of the footing

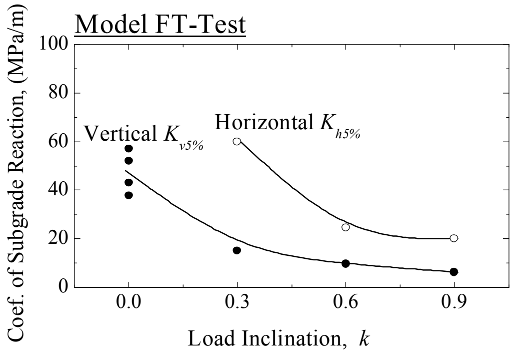

Fig. 6 Effect of load inclination on the coefficients of subgrade reaction in the model FT-Test

interested readers are suggested to refer to the related literature. This paper uses the average load intensity (P/A_f, P_h/A_f) divided by the corresponding settlement at ground surface (S, S_h) to arrive at the coefficient of subgrade reaction ($K_{v5\%}$, $K_{h5\%}$) as defined above; though it might be over-simplified, it is appropriate to the interest of the study to use them as an index to indicate the displacement variations at the ground surface. The reaction stress of P/A_f and P_h/A_f is different for different foundations: for surface footings, it is the normal reaction stress from the sand underlain and the interfacial shear stress along the footing base, respectively. However, for micropiles, it is the shear stress on the micropile-soil interface and the lateral stress normal to the pile; for micropile foundations, it is hybrid for either the vertical or the horizontal coefficient due to the different structural orientations of the footing and the micropile components that contribute to bearing the vertical and lateral loads simultaneously under inclined loading conditions. Though the same term, subgrade reaction, is used for both directions, and should be distinguished according to context.

Network Effect Index

The behavior of micropile foundations is investigated with consideration of the contribution of the surface footing and the interaction between the footing, micropiles, and subsoils. The Network Effect Index, designated as R, is used to quantitatively assess the improvement of bearing capacity under inclined loads. The Network Effect Index is defined as the ratio of the bearing capacity of the micropile foundation to the summation of the bearing capacity of the FT-Test and the MP-Test under the same test conditions as below (Miura et al. 2000; Tsukada et al. 2002):

$$R = \frac{\left[q_{va}\right]_{MP-FD-Test}}{\left[q_v\right]_{FT-Test} + \left[q_{ve}\right]_{MP-Test}} \tag{5}$$

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, then the bearing capacity is improved positively and the R index becomes larger.

TEST RESULTS AND ANALYSES

Model FT-Test under Inclined Loads

In the FT-Tests, the footing base made contact with the ground surface without any embedment at the beginning of the test. Figure 4 shows the behavior of the surface footing subjected to inclined loads in very dense sand. The base pressure of the footing is significantly higher under vertical loading (k = 0) than under inclined loadings (k = 0.3, 06, and 0.9), and it tends to diminish with the load inclination (Fig. 4a). There is an apparent peak in the curves when the load inclination is small, indicating a general shear failure pattern in the shallow foundation. As well, the horizontal bearing load of the surface footing is primarily dependent on the frictional resistance on the base as shown in Figure 4b, and slippage along the base may occur once the applied horizontal load exceeds the frictional resistance as indicated in the case of k = 0.9.

The displacement direction is indicated in Fig. 5, where the horizontal axis is the normalized settlement and the vertical axis is the normalized horizontal movement. The dotted line means that the direction of the displacement is identical to the direction of the inclined load (that is, S_h/S = k). Figure 5 shows that vertical movement is predominant

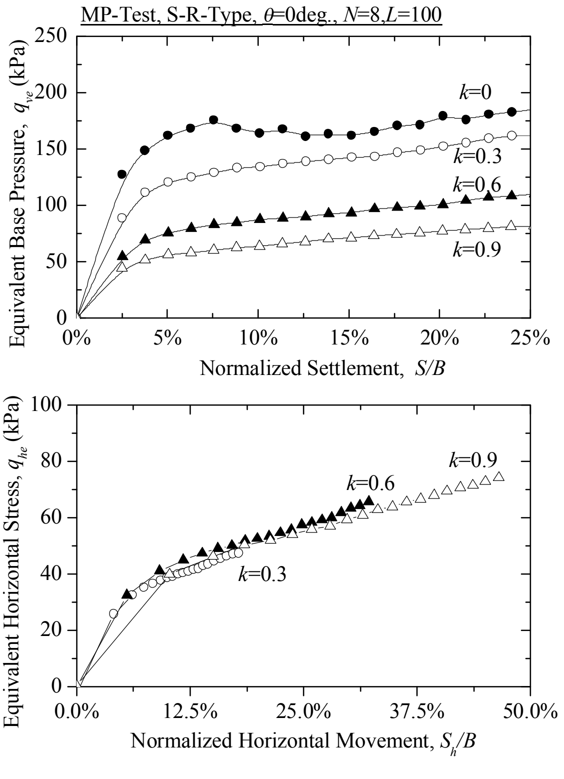

Fig. 7 Effect of inclined loading on the load bearing behavior of micropiles in the MP-Tests

when the normalized settlement is small. In other words, the direction of the footing movement tends to shift from the loading direction to the downward vertical at the early loading stages; this may suggest that the friction between the footing base and the sand underlain has a dominant effect on the displacement of the surface footing in the early loading stage since the lateral movement is not significantly mobilized unless the lateral load exceeds the base friction, while the vertical settlement is comparatively large due to the compression of the sand at this stage.

Figure 6 is plotted with $K_{v5\%}$ and $K_{h5\%}$ vs. k for the model FT-Test in the very dense sand under the inclined loading condition, which indicates that the coefficients of the horizontal and vertical subgrade reactions decrease with the increase of the inclination of the applied load, k. In agreement with the observed behavior of the footing under an inclined load (Fig. 5), the horizontal coefficient is significantly higher than the vertical coefficient under inclined loading conditions (Fig. 6).

Model MP-Test under Inclined Loads

The model micropile was vertically installed around a concentric cycle of 20mm in diameter in the model footing in the MP-Test (θ = 0°), so the micropile was 20mm from the footing edge and 130mm from the wall of the sand container, and the pile tip was 150mm from the container base. The pile spacing is dependant on the number of micropiles used; it is 7.65mm for N = 8 (or, 3.8D, D is the diameter of micropiles). The footing was detached from the sand ground with a clearance of 20mm in the model MP-Test, so the footing functioned as a micropile-holder and a load-transfer element in this case. The behavior of a group of eight vertical micropiles (S-R-Type, L =100 mm) under inclined loads is shown in Figure 7. The vertical bearing capacity (equivalent base pressure, q_{ve}) tends to decrease with the load inclination (Fig. 7a). However, the horizontal load-deflection curves are identical for k =0.3, 0.6, and 0.9 as shown in Figure 7b.

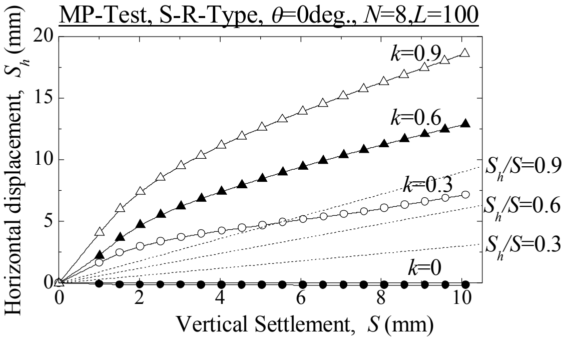

Fig. 8 Effect of inclined loading on the displacement of micropiles in model MP-Test

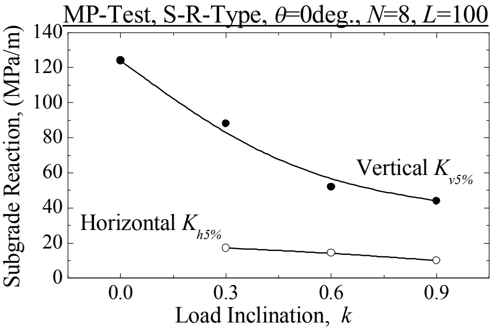

Fig. 9 Effect of load inclination on the coefficients of subgrade reaction in model MP-Test

Figure 8 shows that horizontal movement is predominant when the settlement is small in the model MP-Test, and this deviation increases with the load inclination. In other words, micropiles deflect more easily in the horizontal direction than in the vertical, in contrast to the surface footing as explained in the previous section, which may be attributed to the micropiles' large shaft friction and the small bending stiffness.

Figure 9 indicates that the coefficients of subgrade reaction ($K_{v5\%}$ and $K_{h5\%}$) decrease with the increase of load

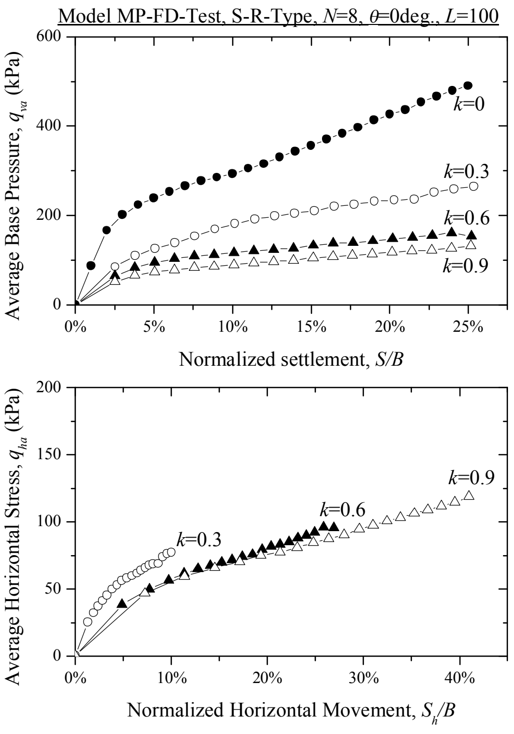

Fig. 10 Effect of inclined loading on the load bearing behavior of micropile foundations

inclination k. However, $K_{h5\%}$ only slightly decreases with k in the MP-Tests. In contrast to the Model-FT test, the $K_{v5\%}$ of micropiles is much higher than its $K_{h5\%}$ due to the large frictional area of the micropile shaft in resisting the vertical settlement. Under an inclined loading condition, the vertical component of the inclined load is mainly borne by the micropiles' skin friction, and the horizontal component is taken by the micropiles' bending stiffness. The small diameter of micropiles results in the lower bending stiffness. Therefore, the vertical subgrade reaction is superior to the horizontal in the MP-Test as shown in Fig. 9.

Model MP-FD-Test under Inclined Loads

Differing from the model MP-Test where the footing was standing free, the footing was in direct contact with the sand surface in the MP-FD-Tests. Eight micropiles were evenly installed around a concentric cycle of 20mm in diameter as in the MP-Tests, but the micropiles might be battered with different angles (θ = 0°, 15°, 30°, 45° or 60°). In the case of installing battered micropiles, a model footing with inclined micropile installation holes was used. The clearance of the micropile tip to the sand container varies with the micropiles' battered angle; it is 130, 104, 80, 59, and 43mm to the wall, and 100, 103, 113, 129, and 150mm to the base, for θ = 0°, 15°, 30°, 45°, and 60°, respectively.

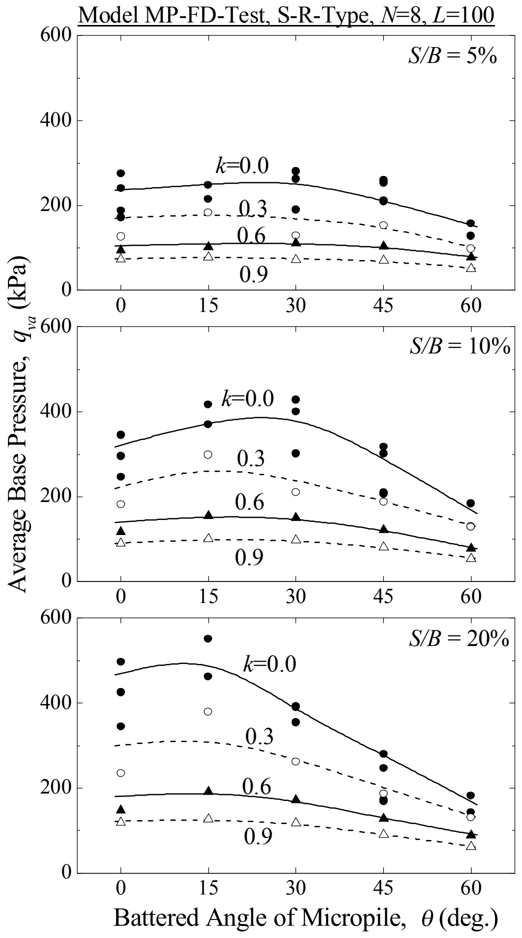

Fig. 11 Effect of battered angle of micropiles on the bearing behavior of model MP-FD under inclined loads

Figure 10 shows the test results of the model MP-FD-Test using S-R-Type micropiles (N = 8, θ = 0°, and L = 100mm) under different load inclinations (k=0.0, 0.3, 0.6, and 0.9). From the figure, the average base pressure of the micropile foundation (q_{va}) decreases with the increase of k, and it is significantly higher under a vertical load (k =0.0) than under inclined loads (k=0. 3, 0.6, 0.9) (Fig. 10a). But the horizontal load-deflection curves are not significantly different for k =0.3, 0.6, and 0.9 as shown in Figure 10b. Under a lower inclined load ratio, the model micropile foundation appears to be slightly stiffer in resisting a horizontal force. In comparison with the MP-Test under an inclined load as shown in Fig. 7 where the load-deflection curves are identical, this may be due to the footing component whose base friction enhanced the horizontal resistance of micropile foundations.

Figure 11 shows the relationship between q_{va} and θ under different load inclinations at S/B = 5%, 10%, and

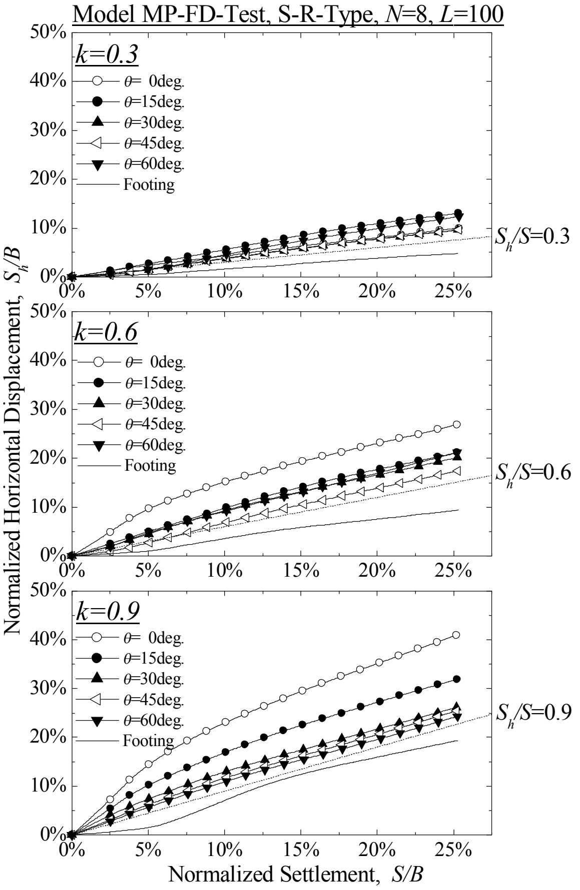

Fig. 12 Effect of inclined loading on the movements in model MP-FD-Test

20%, respectively. Figure 11 clearly indicates that q_{va} deceases with k at each settlement level. In regard to the effect of the battered angle of micropiles, the micropile foundation has a higher average base pressure (q_{va}), or bearing capacity, when $\theta \leq 30°$, and q_{va} decreases when $\theta \geq 30°$, having a lowest value at $\theta = 60°$ since the load bearing behavior is largely affected by the micropiles' lateral loading behavior in such cases.

Figure 12 shows that the movement of the micropile foundation deflects from the $S_h/S = k$ line to the S_h direction; however, the deviation decreases with the micropiles' battered angle in MP-FD-Tests. In other words, micropile foundations deflect more easily in the horizontal direction than in the vertical, similar to the results of the MP-Test but in contrast with those of the FT-Test. So it can be implied that the lateral loading behavior of a micropile foundation is controlled by the micropiles. As expected, the horizontal movement S_h/B increases with k at different θ. Battered micropiles increase the lateral resistance of the micropile foundation; however, there is not a linear relationship between the battered angle and the lateral movement.

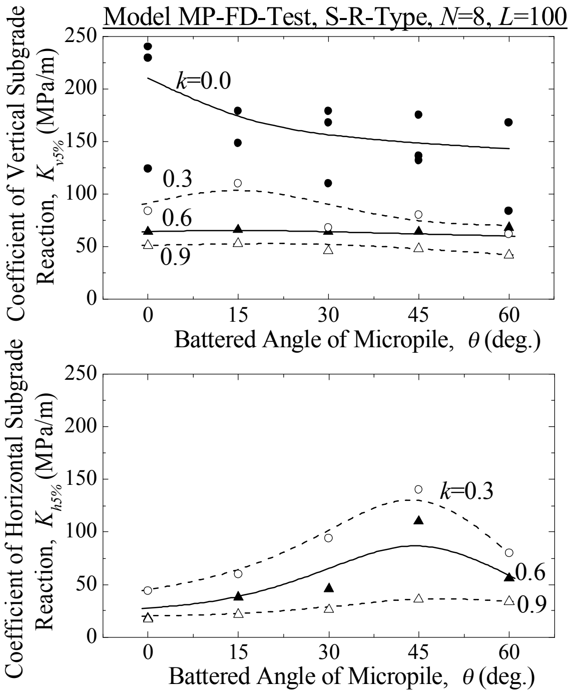

Fig. 13 Effect of battered angle of micropiles on the coefficients of subgrade reaction in model MP-FD-Test under inclined loads

Figure 13 indicates the variation of subgrade reactions with the battered angle of micropiles in the MP-FD-Test. Both $K_{v5\%}$ and $K_{h5\%}$ decrease with the increase of k at different θ. $K_{v5\%}$ generally decreases with the increase of θ under different load inclinations, and the $K_{v5\%}$ is much higher for micropile foundations with vertically installed micropiles. On the other hand, $K_{h5\%}$ increases with the increase of θ up to $\theta = 45°$ for k =0.3, 0.6, and 0.9, and this variation is non-linear.

Figure 14 shows the $K_{v5\%}$ and $K_{h5\%}$ plotted against k from the model MP-FD-Test in very dense sand under the inclined loading conditions with vertical ($\theta = 0°$) and inclined ($\theta = 45°$) micropiles, respectively. $K_{h5\%}$ is much higher in the $\theta = 45°$ case than in the $\theta = 0°$ case. This figure indicates that the micropile foundation with eight battered micropiles of 45° has a very high horizontal subgrade reaction at $k = 0.3$. However, the difference of $K_{v5\%}$ is insignificant for $\theta = 0°$ and $\theta = 45°$ under inclined loading conditions.

Network Effect of Micropile Foundations under Inclined Loads

With reference to Figures 4, 7, and 10 of the model tests under inclined loads, the Network Effect Index (R) is computed by means of equation (5) for the micropile

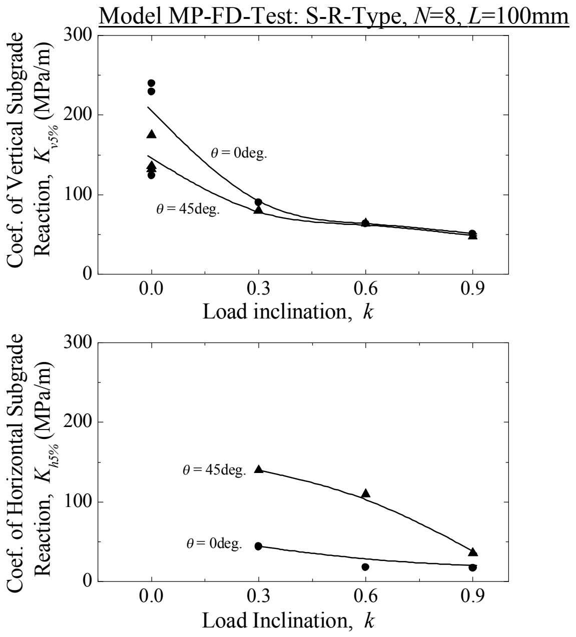

Fig. 14 Effect of load inclination on the coefficients of subgrade reaction of micropile foundations ($K_{v5\%}$, $K_{h5\%}$) (S-R-Type, N =8, $\theta = 0^0$ and $\theta = 45^0$)

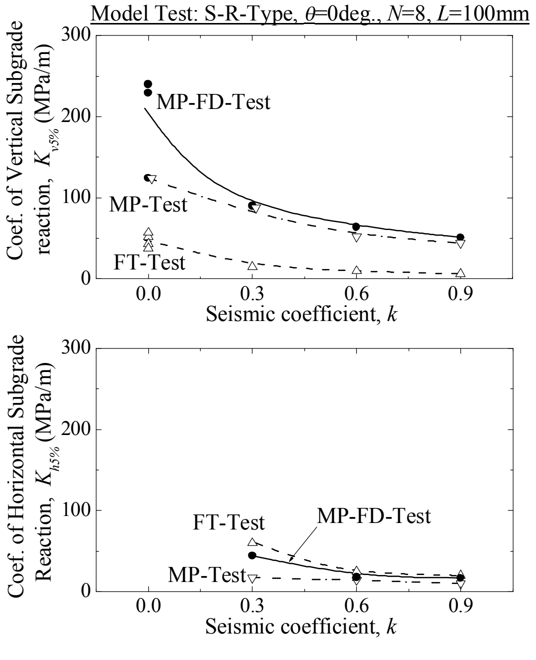

Fig. 16 Effect of load inclination on the coefficients of subgrade reaction of footings, micropiles and micropile foundations ($K_{v5\%}$, $K_{h5\%}$)

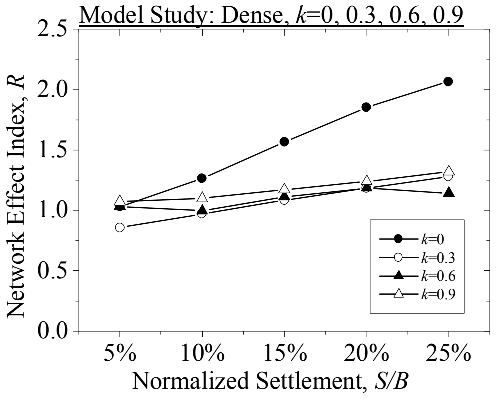

Fig. 15 Effect of inclined loads on the Network Effect Index in model study

foundation with S-R-Type micropiles (N = 8, L =100mm, θ = 0°). From figure 15, R increases gradually with S/B under different load inclinations; the network effect index is significantly higher under vertical loading than under inclined loadings; and there is not an explicit difference in R values for different load inclinations. At S/B = 20%, R is about 1.2 for inclined loads, while it was about 2 for the vertical load.

Figure 16 shows the comparison of the coefficients of subgrade reaction ($K_{v5\%}$ and $K_{h5\%}$) from the model FT-Test, MP-Test, and MP-FD-Test under different load inclinations. $K_{v5\%}$ of the micropile foundation is significantly greater than those of the footing and micropiles, which indicates the effect of micropiles on the reinforcement of the surface footing under the inclined loads. $K_{h5\%}$ in the MP-FD-Test is significantly higher than $K_{h5\%}$ in the MP-Test, where the footing was standing free; in case of k = 0.3, the former is more than twice the latter. This indicates that the surface footing not only plays a role in bearing a vertical load, but also makes a remarkable contribution in positively mobilizing the interaction among the footing, micropiles, and subsoil, which results in the improvement of $K_{h5\%}$ (refer to Figs. 7 and 10).

On the other hand, micropile foundations are a combination of the footing and micropiles, so the coefficients of the vertical and horizontal subgrade reactions should take the advantage of them. The micropile foundation is supposed to enhance the bearing capacity of footings by introducing micropiles, but the horizontal subgrade reaction of micropile foundations is lower than that of the surface footing. The horizontal stiffness of a foundation is dependent on the Young's modulus and Poisson's ratio, and is affected by the size and shape of the foundation, such as base area, dimension, and embedded depth of the footing, and the diameter of the pile. The reasons that the $K_{h5\%}$ of micropile foundations is lower than that of the surface footing might be: 1) since the micropiles bear the major load, the friction on the footing base is not fully developed; 2) the interaction between the footing, micropiles, and subsoil in the composite foundation system, which may decrease the base pressure due to the compression of the subsoil at the early loading stage; and/or 3) $K_{h5\%}$ may be affected by the magnitude of the applied load since the applied load is much higher in the micropile foundation test than in the footing test at S/B = 5%.

CONCLUSIONS

This paper presents the test results of model footings, micropiles, and micropile foundations in very dense sand under inclined loads, and the analyses of load bearing behavior by means of displacements, coefficients of subgrade reaction ($K_{v5\%}$, $K_{h5\%}$), and the network effect index (R). From these analyses, the following conclusions can be made.

Micropiles can effectively improve the bearing capacity of surface footings under inclined loads. This is in accordance with the findings in model tests under vertical loads; however, the improvement of bearing capacity decreases with the load inclination. A positive network effect is mobilized in the model micropile foundation tests under inclined loads in very dense sand. The network effect index, R, increases gradually with settlement; at S/B = 20%, R is about 1.2 for inclined loads, while it was found $R = 2$ for the vertical load test.

Consequently, micropiles are very effective in preventing the displacement of surface footings under inclined loadings. The vertical coefficient of subgrade reaction ($K_{v5\%}$) of micropile foundations is higher than those of footings and micropiles. The horizontal coefficient of subgrade reaction ($K_{h5\%}$) of micropile foundations is more than twice that of a group of micropiles at k = 0.3. This indicates that the surface footing not only plays a role in load bearing, but also makes a remarkable contribution in positively mobilizing the interaction among footing, micropile, and subsoils.

From the analyses of the coefficients of subgrade reaction, both the vertical and horizontal coefficients of footings, micropiles, and micropile foundations decease with the increase of the load inclination. However, the coefficients demonstrate different characteristics: the vertical coefficient of subgrade reaction ($K_{v5\%}$) is significantly lower than the horizontal coefficient ($K_{h5\%}$) in the model FT-Test. But $K_{v5\%}$ is much higher than $K_{h5\%}$ in the model MP-Test, which is attributed to the large frictional area in bearing the vertical load and the small diameter of the micropiles in resisting the bending moment, while $K_{h5\%}$ only slightly decreases with k in the MP-Test. In the MP-FD-Tests, $K_{v5\%}$ is large at a small batter angle of 15°, and $K_{h5\%}$ appears to increase with the battered angle of micropiles up to 45°.

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REFERENCES

Adachi, T. (1992). Model test and its limitation. Tsuchi-to-Kiso. 40(5): 1-4.

Bolton, M. D. (1986). Scaling principles and limitations of models. A preprint of specialty session on centrifuge model tests. Bangkok, Thailand: 1-16.

Bowles, J. E., (1996). Foundation Analysis and Design (5th edition). McGraw-Hill International Editions. Singapore: 1175.

Das, B. M., (1999). Principles of Foundation Engineering (4th edition). International Thomson Publishing Asia. 882.

Franke, E. and Muth, G. (1985). Scale effect in 1g-model tests on horizontally loaded piles. Proc. of 11th International Conference of Soil Mechanics and Foundation Engineering. San Francisco, USA. A. A. Balkema: 1011-1014.

FHWA (Federal Highway Administration, US Department of Transportation), (1997) Drilled and Grouted Micropiles: State-of -Practice Review, Volume I, II, III and IV, Publication No. FHWA-RD-96-018.

Kishishita, T., SAITO, E. and Miura, F., (1999). Dynamic response characteristics of structures with micropile foundation system. Proceedings of the 2ndInternational Workshop on Micropiles. Ube city, Japan: 161-168.

Lizzi, F. (Soc. An. Fondedile, Naples), (1964). Root-pattern piles underpinning. Proceeding of Symposium on Bearing Capacity of Piles. Roorkee, India: 305-320.

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 landslides. A Preprint of ASCE Convention, Chicago, Ill., October: 1-25.

Lizzi, F., (1980). The use of '*Pali Radice*' (root pattern piles) in the underpinning of monuments and old buildings and in the consolidation of historic centers. Naples (Italy): Fondedile S.P.A.: 25pp. (An English imprint of an article published in Italian Technical Magazine, L'INDUSTRIA DELLE COSTRUZIONI, No.110, Dec. 1980 of A. N. C. E.)

Lizzi, F., (1994). The 'reinforced soil' in the future of geotechnics.. In Balasubramniam et al. (Editor), Proceedings of Symposium on Development in Geotechnical Engineering, Balkema, Netherland: 553-563.

Mason, J. A., (1997). Seismic design concepts and issues for reticulated micropile foundation systems. Proceedings of the 1st International Workshop on Micropiles, September, Seattle, Washington, USA: 202-227.

Miura K., Tsukada Y., You G. L., Ishito M., Otani Y. and Tsubokawa Y., (2000). Model investigation on the bearing mechanism of footing regarding the interaction between the footing and a group of micropiles, Proceedings of the 3rd International Conference on Ground Improvement Techniques, Singapore: 255-262.

Mitchell C. L B, Perkins W. J. and Okumatsu T., (1999) Micropile project in US: a bridge seismic retrofit in Seattle, Proceedings of the 2nd International Workshop on Micropiles, Ube city, Japan: 175-176.

Parikh, S.K. and Pal, S.C., (1981). Coefficient of subgrade reaction for pile systems. Proceedings of the 10th International Conference on Soil Mechanics and Foundation Engineering, Vol. 2, Stockholm, Sweden, A. A. Balkema: 209-212.

Poulos, H.G. and Davis E.H., (1980) Pile foundation analysis and sesign, Series in Geotechnical Engineering, Taipei: 397.

Robinson, K.E., (1979) Horizontal subgrade reaction estimated from lateral loading tests. Journal of Geotechnical Engineering, ASCE. 105(6): 520-536.

Shibata, T., Yashima, A. and Kimura, M. (1989). Model tests and analyses of laterally loaded pile groups. Soils and Foundations. 29(1): 31-44.

Taylor R. N. (1995): Geotechnical Centrifuge Technology (Edited). Blackie Academic & Professional, An Imprint of Chapman & Hall, London: 296.

Terzaghi, K., (1955). Evaluation of the coefficient of subgrade reaction. Geotechnique. 5(4): 197-326.

Tsukada, Y. and Ichimura, Y., (1997). Micropiles in Japan: present status and future prospects. Proceedings of the 1st International Workshop on Micropiles, September, Seattle, Washington, USA: 266-278.

Tsukada, Y.; Miura, K.; Tsubokawa, Y.; Ishito, M.; Nishimura, N.; Otani, Y. and You, G. L., (1999). Experimental investigation on the improvement of bearing capacity of surface footing with micropiles. Proceedings of the 2nd International workshop on Micropiles, September, Ube city, Japan: 139-148.

Tsukada Y., Miura K., Tsubokawa Y., Otani Y., You G. L. and Ishito M., Mechanism of bearing capacity of surface footings reinforced with micropiles. Journal of Geotechnical and Geoenvironmental Engineering, ASCE (Approved, 2002).

Vesic, A. S. (1973). Analysis of ultimate loads of shallow foundations. Journal of the Soil Mechanics and Foundations Division, ASCE. 99(1): 45-73.