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FEM analysis of the effect of the prestress induced in micropiles

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ABSTRACT: We have conducted model loading tests and field loading tests on the foundation reinforced with micropiles to reveal the mechanism of load bearing capacity of the foundation. The significance of the confining effects of a group of micropiles on the bearing capacity was clarified through the examination of the test results. And the prestress induced in the micropiles was certified to be effective on the enhancement of the confining effect. We also carried out FEM simulations to examine the confining effect, and discussed the applicability of the FEM analysis in the simulation of the behavior of micropile foundation considering the interactions between soil ground, micropiles and footing.

1 INTRODUCTION

Micropiles, which was pioneered by Lizzi (1971, 1978) in Italy, are now widely used both as structural supports in foundations as well as for in-situ earth reinforcement. Micropiles are considered as promising foundation elements in improving the bearing capacity of existing foundations which are deteriorating for one reason or another with minimum disturbance to structures, subsoil and the environment.

To clarify the mechanism of the bearing capacity and develop new rational method to improve the performance of micropile foundations, a study on model micropile has been conducted by authors continuously. In previous study, the method of model loading tests has been reported by Tsukada et al. (1999, 2006), the test results on three series of model tests (footing test, micropile test, and micropile foundation test) have been reported by Miura et al. (2000), and the effect of prestress on the improvement of bearing capacity has also been investigated in model micropile foundation study by Miura et al. (2001). From these studies, it is found that 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. Large-scaled field loading tests on the footings reinforced with micropiles were also conducted on natural uniform loam ground, and the findings obtained in the series of laboratory model loading tests were observed.

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 by the interaction between the footing and a group of micropiles. Also it was demonstrated that the bearing capacity is improved more efficiently with the prestress, which induces the confinement on the ground material beneath the footing at early stage of the loading process.

In this study, FEM simulations were carried out to examine the confining effect quantitatively, and discussed the potential of the FEM analysis in the simulation of the behavior of micropile foundation considering the interactions between soil ground, micropiles and footing. In the following, the results of the field loading tests are explained briefly, and the results of the FEM simulations are discussed.

2 FIELD LOADING TEST

2.1 *Test method*

The plan layout of the investigation is shown in Fig. 1. Four types of foundations were investigated as follows;

- FT; a footing without micropiles,
- S-MP; a single micropile,

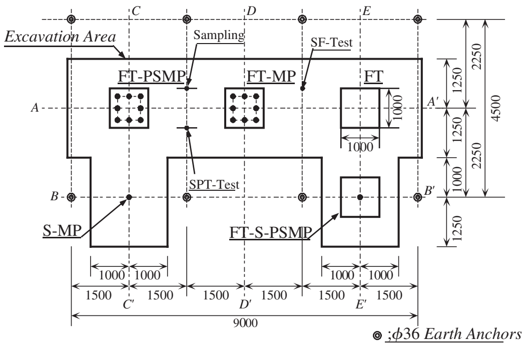

Figure 1. Layout of the field loading test.

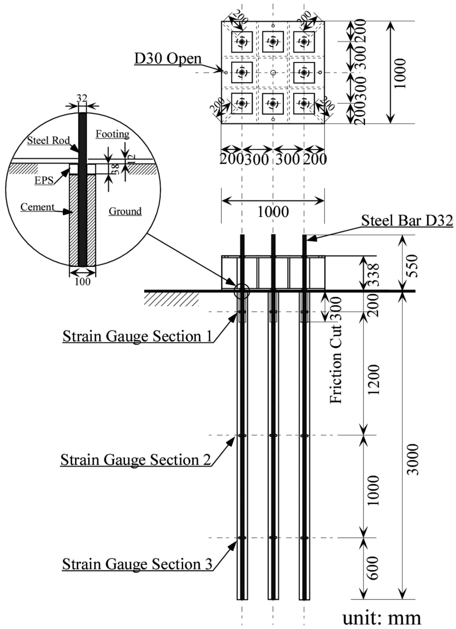

Figure 2. Micropile, footing and their connection (FT-MP and FT-PSMP).

– FT-MP; a footing reinforced with eight micropiles,
– FT-PSMP; a footing reinforced with eight prestressed micropiles.

Figure 2 shows the details of the micropile and the footing. The micropile (MP in short) used was 100 mm in diameter, 3.0 m in length and reinforced with D32 steel core bar. The MPs were instrumented with strain gauges arranged for the bending in two directions at three sections of −0.2 m, −1.4 m, and −2.4 m. The footing (FT in short) used is made of steel and 1000 × 1000 mm square in plane shape. The amount of prestress was 70% of the pullout resistance of the micropiles.

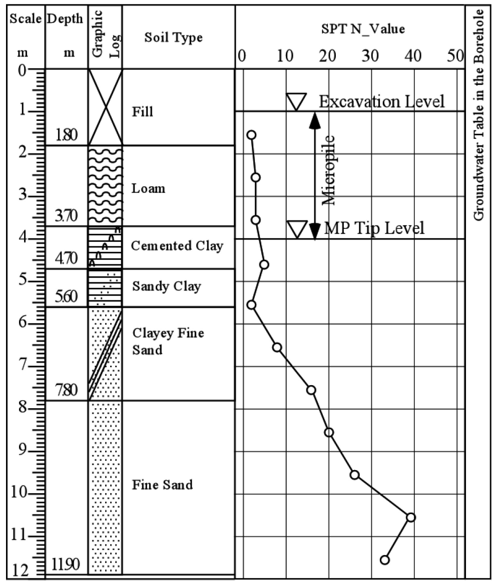

Figure 3. Geotechnical boring log of the test site.

Table 1. Soil properties of the investigation site.

Soils	Loam	Cemented clay	Fine sand
Depth (m)	2.0∼2.8 m	3.7∼4.5 m	8.0∼8.8 m
Wet density ρ_t (kg/m^3)	1.631×10^3	1.721×10^3	1.905×10^3
Dry density ρ_d (kg/m^3)	1.005×10^3	1.144×10^3	1.442×10^3
Water content ω (%)	62.7	50.6	32.2
Total stress c (kN/m^2)	23.54	46.09	42.17
Total stress ϕ (°)	17.6	16.8	43.7
Effective stress c' (kN/m^2)	10.79	7.85	3.92
Effective stress ϕ' (°)	28.4	33.7	37.0
B value	0.92∼0.96	0.94∼0.96	0.92∼0.96

The soil profile and the SPT N-value of the upper 10 m are shown in Fig. 3. The subsoil consisted of fill, loam, cemented clay, sandy clay, and fine sand, in order from ground surface to the 10 m depth. The fill, loam and clay are soft; the N values obtained are less than 5. The soil properties are tabulated in Table 1.

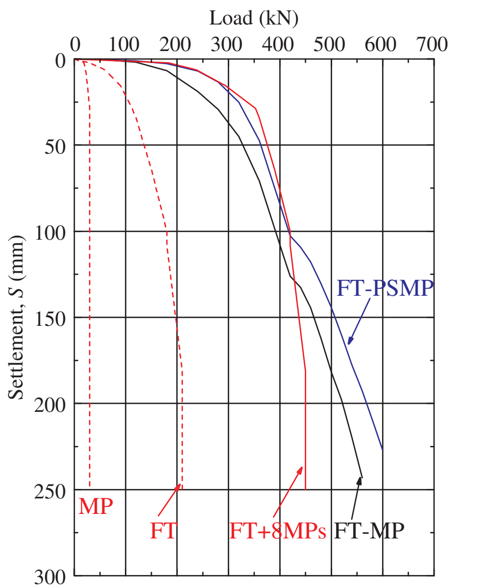

Figure 4. Load-settlement relations of FT, FT-MP, FT-PSMP and FT+8 MPs.

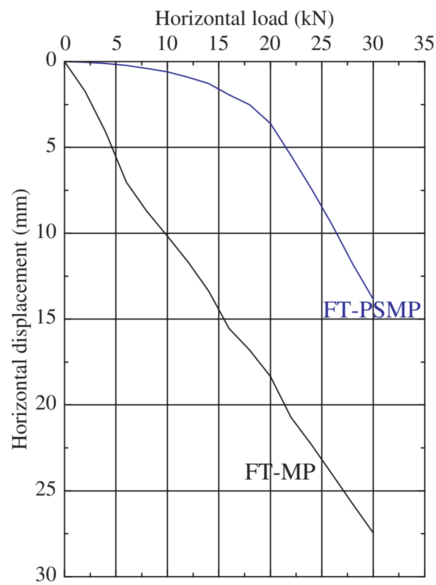

Figure 5. Movement of FT-PSMP and FT-MP under horizontal load.

2.2 *Test results*

2.2.1 *Vertical loading tests*

Figure 4 shows the load-settlement relationships of FT-PSMP and FT-MP. To investigate the MP group effect, the load carried by FT and the load taken by eight MPs are summated (FT+8 MPs). From this figure, MP group effect is not clear at the early loading stage when the settlement is small; the curve of FT-MP is even lower than that of FT+8 MPs, which may be due to loose contact between FT and the ground surface at the early stage. But with the increase of the load, FT-MP and FT-PSMP become higher than FT+8 MPs. From this figure, the curve of the FT-PSMP is always higher than that of the FT-MP. In other words, the coefficients of subgrade reaction were 1.86×10^4 kN/m^3 and 3.97×10^4 kN/m^3 in the tests on FT-PSMP and FT-MP, respectively. This comparison means the settlement was suppressed at the early loading stage and became almost half due to the effect of prestress on MPs.

2.2.2 *Horizontal loading tests*

Figure 5 shows the load-movement relationship of FT-PSMP and FT-MP. The effect of prestress on horizontal movement control is remarkable compared with on settlement control. The movement in the FT-MP seems linearly increased with load. The coefficient of subgrade reaction was 1.01×10^3 kN/m^3 and 17.1×10^3 kN/m^3 in the tests on FT-PSMP and FT-MP, respectively. This clearly showed the remarkable effect of prestress also in horizontal loading.

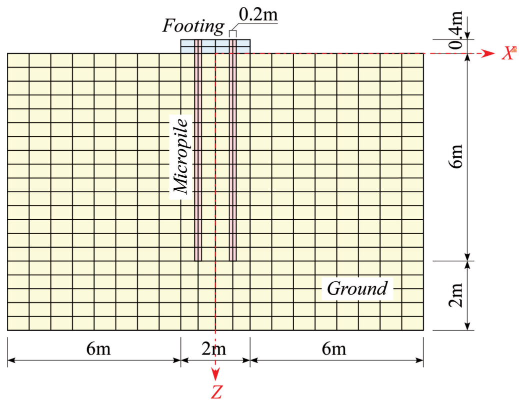

Figure 6. FEM mesh.

3 FEM SIMULATION

3.1 *Outline of FEM simulation*

Figure 6 shows the FEM mesh prepared for the simulation; the mesh consists of footing, micropiles and ground. The footing was reinforced with the micropiles and placed on the horizontal ground surface. The footing is detached with the ground surface in the simulation cases for the bearing capacity without micropiles. On the other hand, the footing contacts with the ground surface in the simulation cases for the bearing capacity with micropiles. Footing was modeled as rigid material where all the nodes on the

Table 2. Input parameters.

	Dense sand	Loose sand	Micropile
ϕ (°)	35	30	
c(kN/m^2)	0	0	
Dilatancy angle Ψ. (°)	10	−10	
Wet density ρ (kg/m^3)	2.00×10^3	1.90×10^3	2.40×10^3
Young's modulus E (kN/m^2)	1.04×10^5	0.35×10^5	70.0×10^5
Shear modulus G (kN/m^2)	1.20×10^5	0.40×10^5	2.69×10^6
Poisson's ratio ν	0.3	0.3	0.3

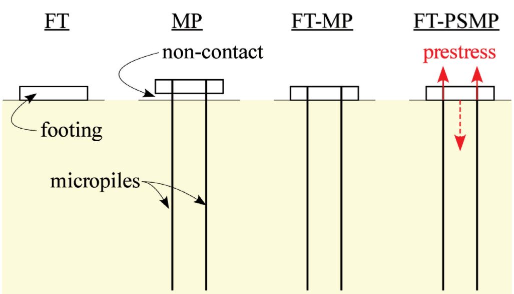

Figure 7. The types of foundations.

footing have the same displacement vector, and the micropiles were modeled as elastic bending material with second-order FEM elements. The ground was modeled with Drucker-Prager Type elasto-plastic model combining the Mohr-Coulomb Criteria for frictional failure and dilatancy. The interface between micropiles and ground is modeled with bi-linear slider elements with initial stress on the interface and internal friction angle of the ground. The mechanical properties, or input parameters for the models, are listed in Table 2. Two types of ground materials, i.e. dense and loose sands, were employed to clarify the effect of density and dilatancy on the bearing capacity. Not only the internal friction angle ϕ but also the dilatancy angle ψ is different with density.

Four types of footings were considered as follows (Fig. 7);

- FT Foundation; a spread footing without micropiles,
- MP Foundation; micropies where the footing was detached with the ground,
- FT-MP Foundation; a footing with micropiles, where the footing was attached with the ground,
- FT-PSMP Foundation; A footing with prestressed micropiles.

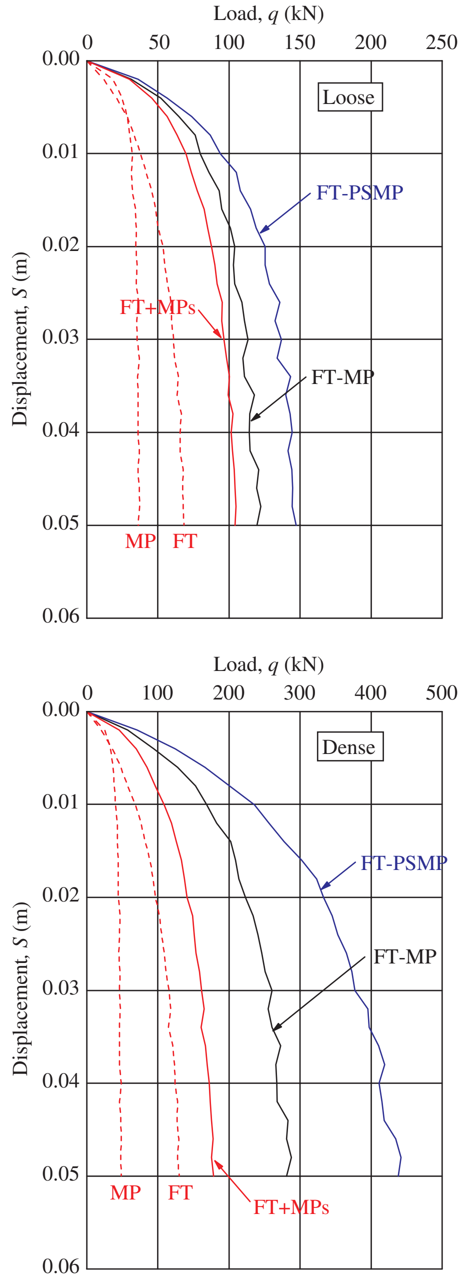

Figure 8. Load-settlement relations under vertical loading condition (loose and dense sand ground).

The prestess was applied before the loading; tension was induced in the micropiles, and the footing was pressed onto the ground at the same time as a reaction of the prestress. The amount of prestress was selected so as to be approximately 30% of the

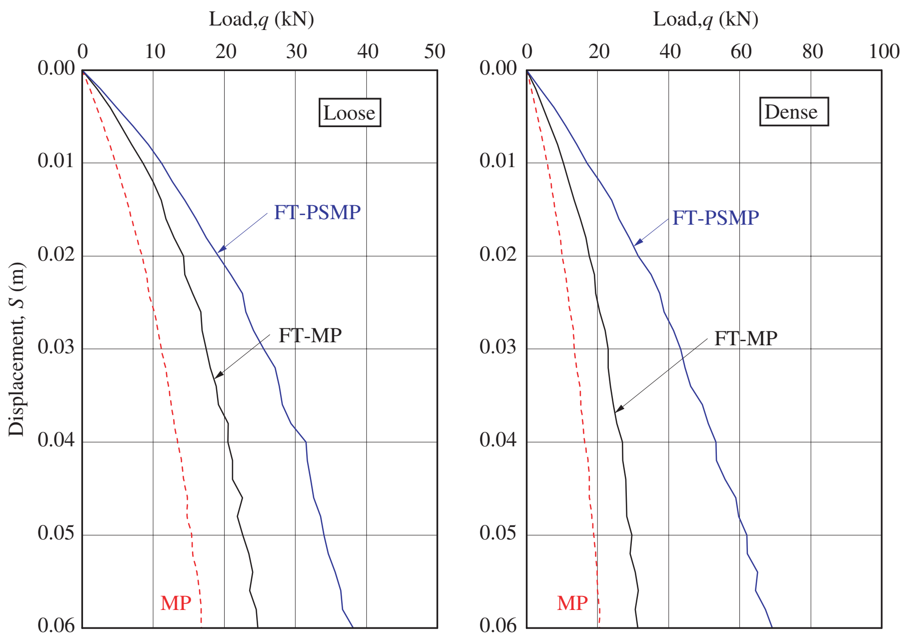

Figure 9. Load-movement relations under horizontal loading condition (loose and dense sand ground).

Table 3. The critical loads borne by the foundations without prestress and the ratio R.

	FT (kN)	MP (kN)	FT+MPs (kN)	FT−MP (kN)	R
Dense sand	124	45	169	307	1.82
Loose sand	64	35	99	123	1.24

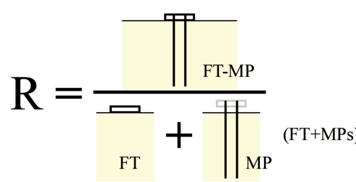

Figure 10. Confining effect ratio R.

bearing capacity of the micropiles. The loadings in two directions were conducted with incremental loading schemes with non-linearity of soil behavior and the interaction between soil and micropiles.

3.2 *Calculation results and discussion*

The calculated behaviors of the foundations under vertical loads are shown in Fig. 8, and those under horizontal loads in Fig. 9. The symbol FT+MPs is for the summation of the loads borne by FT Foundation and by MP Foundation. Table 3 lists the critical loads borne by the foundations without prestress. The ratio R designated for the critical bearing load of FT-MP Foundation to that of FT+MPs, shown in Fig. 10, was calculated and listed in the table. The value of the parameter R which indicates the effectiveness of the confinement of ground material with the footing and micropiles, was 1.82 in the dense sand ground, and 1.24 in the loose sand ground. The difference between the dense ground and loose ground is due to the dilatancy behavior of ground materials; the dense soil shows more dilative behavior compared with the loose sand. This significant effect of the dilatancy in the load bearing capacity was recognized also in the model loading tests (Tsukada, et al., 1999, 2006).

Table 4 shows the comparisons in critical bearing capacity and initial coefficient of subgrade reaction between the foundations with and without prestress: FT-MP Foundation and FT-PSMP Foundation. Remarkable effects of the prestress on both vertical and horizontal load bearing capacity can be recognized in the critical bearing capacity. On the other hand, the effects of the prestress cannot be seen clearly in the initial modulus of subgrade reaction. In the FEM simulation employed in this study, shear failure strength was properly increased with an increase in confining stress through Mohr-Coulomb Criteria. The modification of shear stiffness under confining stress was not sufficiently considered; i.e. the shear modulus of ground material was assumed constant

Table 4. Effect of prestress.

		Vertical loading		Horizontal loading	
		FT-MP	FT-PSMP	FT-MP	FT-PSMP
Dense sand	Critical bearing capacity (kN/m)	307	436	31	67
	Initial coefficient of subgrade reaction (kN/m^3/m)	31000	31000	760	820
Loose sand	Critical bearing capacity (kN/m)	123	156	23	38
	Initial coefficient of subgrade reaction (kN/m^3/m)	19000	20000	630	650

irrespective of the confining stress. The increase in critical load bearing capacity was clearly seen in the FEM simulation both in the vertical loading and horizontal loading. For example, in the case of horizontal loading on the dense ground, the critical load bearing capacity became large by the factor of two due to the prestress on micropiles. This effect of the prestress on the improvement of bearing capacity were recognized common in the model loading tests, field loading tests and FEM simulation.

4 CONCLUSIONS

To clarify the load bearing mechanism of the footing reinforced with micropiles, we conducted loading tests in laboratory and field, and FEM simulations. And the positive effect of prestress on the improvement of the bearing capacity was examined in the loading tests and FEM simulations. The following points were found in this study.

– The confining effects on the ground by the micropiles were clearly observed both in the loading tests and FEM simulations. The effect was remarkable in the case of dense ground which shows dilative deformation behavior,
– The effect of the prestress which induced the confinement on the subsoil by the interaction with footing and micropiles was recognized not only in the loading tests but also in the FEM simulations. The effect of the prestress was clearly seen both in vertical loading and horizontal loading.

The FEM simulation must be modified in order to take sufficiently account of the yielding behavior of ground under the horizontal loading on piles, and the increase in shear modulus of ground due to the confinement, and etc. Also the FEM simulation should be carried out in three-dimensional condition to simulate the network of micropiles and its confining effect on the bearing capacity.

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