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Field loading test on the footing reinforced with prestressed micropiles

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ABSTRACT: To reveal the mechanism of bearing capacity of the footing reinforced with prestressed micropiles, large-scaled field tests were conducted with the experience in the previous series of laboratory model study. A series of loading tests were carried out on uniform medium stiff loam ground on three types of square surface footings (1m × 1m); surface footing, surface footing with eight non-prestressed micropiles of 3m in length, and surface footing with eight prestressed micropiles. In the preliminary loading tests, the bearing capacity and pullout resistance of micropile, and its applicability and durability of the prestress were examined on single micropile. On the surface footings reinforced with micropiles, both horizontal and vertical loading tests were conducted. The performance of footing was improved with the reinforcement of micropiles, and prestress was notably effective on the stabilization of footing. The network effect was recognized in both non-prestressed and prestressed micropile foundation. The prestress raised the base pressure at early stage, and the load bearing capacity in both horizontal and vertical directions.

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. Triggered by the destructive Hyogoken-Nambu earthquake in 1995 in Japan, the research and development on the use of micropiles in strengthening foundations have been focused (Tsukada, 1997).

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), 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. 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, the large-scaled field tests on the footings reinforced with micropiles were conducted on natural uniform loam ground. The purpose is to examine the findings obtained in the series of laboratory model loading tests, and to clarify the mechanism of network effect and the effect of prestress in micropiling.

2 IN-SITU SOIL PROPERIES

The large-scale field tests were conducted inside the factory of Hirose Co. Ltd, N339, Jyoba, Shirai-chyo, Inba-gun Chiba, Japan; the plan layout of the investigation is shown in Figure 1. The soil profile and the SPT N-value of the upper 10 meters are shown in Figure 2. The subsoils consist 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.

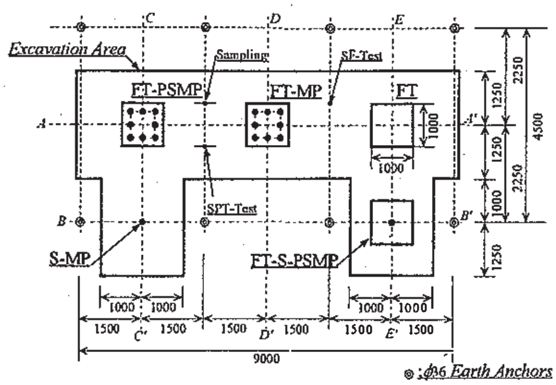

Figure 1. Layout of the large-scale field test

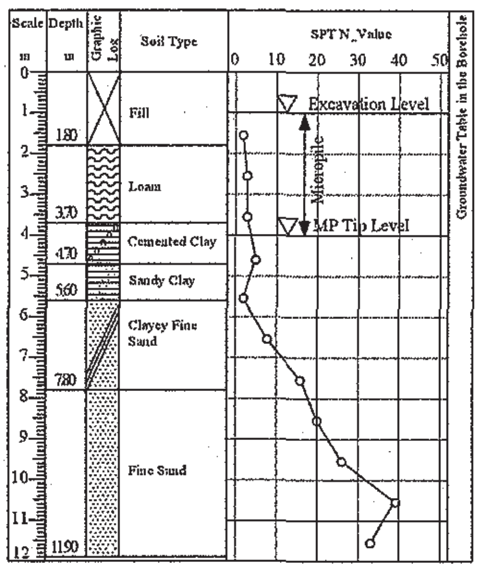

Figure 2. Geotechnical boring log of the test site

Table 1. Soil properties of the investigation site

Soils	Loam	Cemented Clay	Fine Sand
Depth (m)	2.0~2.8m	3.7~4.5m	8.0~8.8m
Wet density ρ_t (g/cm^3)	1.631	1.721	1.905
Dry density ρ_d (g/cm^3)	1.005	1.144	1.442
Water content W_n (%)	62.7	50.6	32.2
Total stress c (kgf/cm^2)	0.24	0.47	0.43
Total stress ϕ (^{0})	17.6	16.8	43.7
Effective stress c' (kgf/cm^2)	0.11	0.08	0.04
Effective stress ϕ' (^{0})	28.4	33.7	37.0
B value	0.92~0.96	0.94~0.96	0.92~0.96

3 TEST METHOD

3.1 *Test apparatus*

The micropile (MP in short) used for Single MP (S-MP) test and Group MP test is same in the specification; the diameter is 100 mm, length 3.0 m and reinforced by D32 steel bar, as shown in Figure 3. 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 (Fig. 3).

The loading apparatus was set up according to the requirements of each of loading tests. Two I-600×190 beams were used as reaction beams in the loading and pullout tests of S-MP. In the prestress test of single MP (FT-S-PSMP), a 50t jack was placed on the footing to apply prestress on the MP. Shown in Figure 4 is the loading apparatus of S-MP test.

The loading apparatus for horizontal test of MP groups is shown in Figure 5. After prestressing the MPs group in the FT-PSMP (footing plus eight prestressed MPs), H-300×300 was used as the load transfer bar. A 50t jack was used to apply horizontal load; a load cell of 200kN in capacity was used to monitor the load.

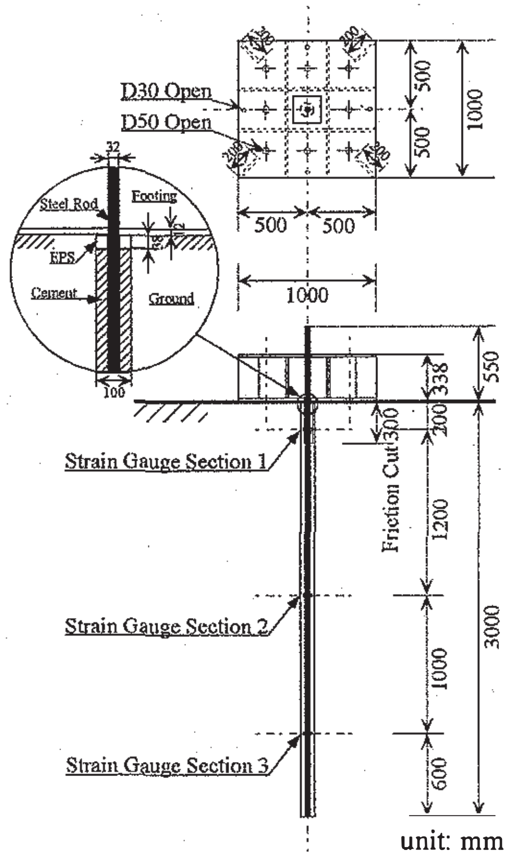

Figure 3. Micropile, footing and their connection

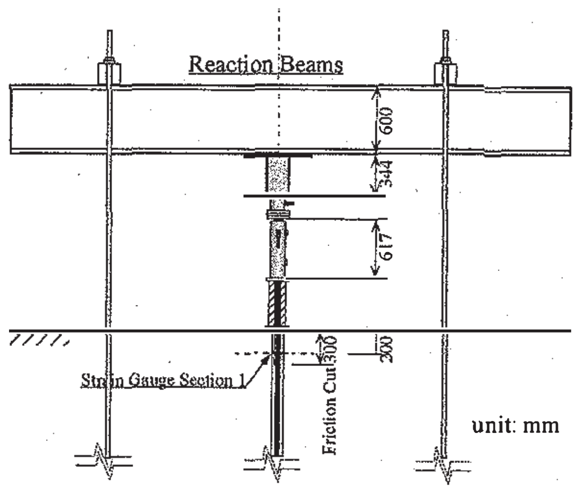

Figure 4. Loading apparatus of S-MP test

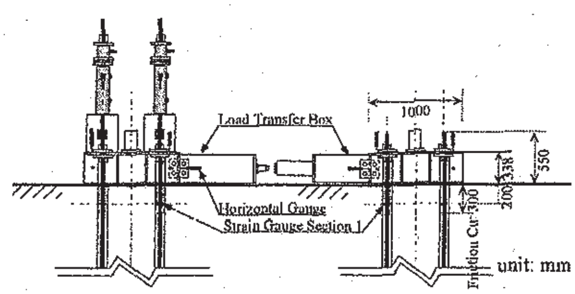

Figure 5. Loading apparatus of horizontal test

3.2 *Measuring system*

Load Measuring: The variation of load was controlled by a hydraulic jack; Monitoring the load was controlled by the highly accurate load cell.

Displacement Measuring: Displacement was measured by a 100 mm DT-100E displacement gauge, whose minimum reading is 1/100 mm. The DT-100E displacement gauge was connected to an ASW-50C automatic exchanger, and recorded by TDS-601 multi-functional digital meter.

Strain Measuring: To measure the stain of MP, the end of the strain gauge was connected to the ASW-50C automatic exchanger, and recorded by TDS-601 multi-functional digital meter. The average value of the two strain gauge reading at the same section was used under each of loads.

Time Recording: Time and the elapsed time were recorded from TDS-601 to a personal computer through the entire tests.

4 TEST RESULTS

4.1 *Preliminary loading tests*

FT Test, S-MP loading and pullout tests were conducted in a preliminary loading test programs. Shown in Figure 6 is the comprehensive test result in the FT test with maximum applied load $P_{max} = 210.0$ kN and settlement $S_{max} = 181.43$ mm. Yielding load is identified as $P_y = 90.0$ kN, and the ultimate load was estimated as $P_u = 313.8$ kN by Weibull curve.

Shown in Figure 7 is the comprehensive test result in the S-MP loading test with maximum applied load $P_{max} = 30$ kN and settlement $S_{max} = 28.69$ mm. Yielding load is identified as $P_y = 16.0$ kN, and the ultimate load is estimated as $P_u = 30.3$. And shown in Figure 8 is the axial force distribution. At section 1, friction cut technology was applied for the need of tensile prestress (refer to Fig. 3).

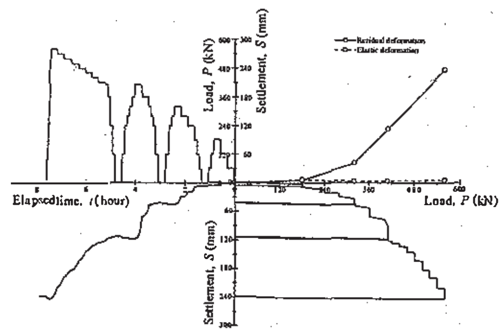

Figure 6. Comprehensive test results in FT test

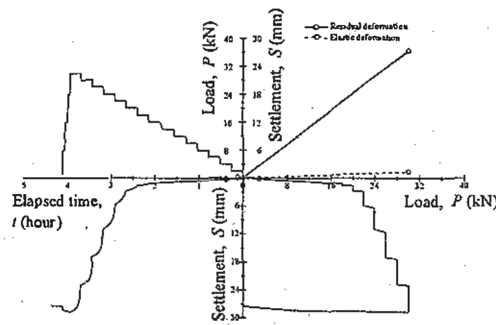

Figure 7. Comprehensive test results in S-MP loading test

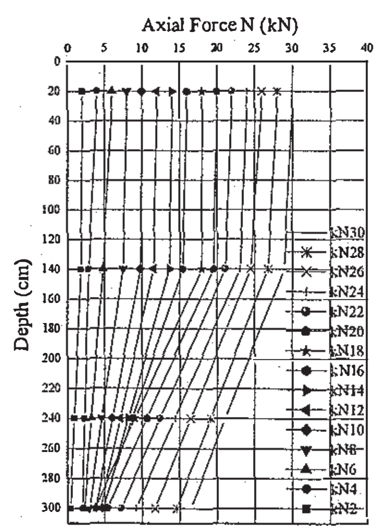

Figure 8. Axial force distribution along MP in S-MP loading test

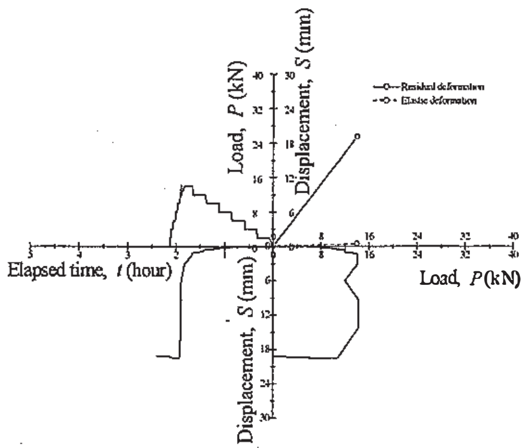

Figure 9. Comprehensive test results in S-MP pullout test

Shown in Figure 9 is the comprehensive test result in the S-MP pullout test with maximum applied load T_{max} = 14.3 kN and settlement S_{max} = 19.52 mm. Yielding load is identified as T_y = 10.0 kN, and the ultimate load is estimated as T_u = 14.3 kN.

4.2 *Single MP prestress test (FT-S-PSMP Prestress Test)*

FT-S-PSMP test includes two-phase prestress. In the 1st prestress test, the maximum prestress load was T_{max} = 7.5 kN. When T_{max} = 7.5 kN, ε_l = 49 μ; after the load was released, ε_l = 22 μ (T = 3.4 kN). The maximum displacement of footing was 0.48 mm, and the extension of the MP was 0.67 mm.

In the FT-S-PSMP 2nd prestress test, the maximum prestress load was T_{max} = 9.6 kN, with ε_l = 57 μ; after releasing the load, ε_l = 25 μ (T = 4.2 kN).

Then, the pullout test was conducted; the pullout load was increased by 2 kN a step, up to the maximum load T_{max} = 30 kN, the maximum displacement is S_{max} = 27.06 mm. The variation of load and displacement during the fill procedure of FT-S-PSMP prestress test is shown in Figure 10.

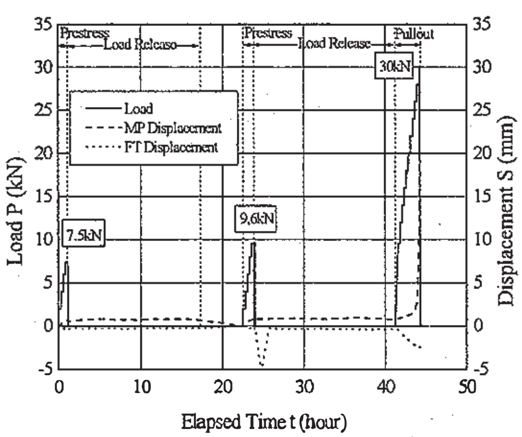

Figure 10. Full procedure of FT-S-PSMP prestress test

4.3 *MP group prestress test*

In the FT- PSMP group, there are two phase prestress, as in the FT-S-PSMP prestress test. In the 1st prestress test, the maximum prestress load was T_{max} = 7.5 kN, and T_{max} = 9.6 kN in the 2nd prestress test; the loads were applied to all the eight micropile begun with pile 1 and 5 simultaneously. The strain-time relationship at section 1 is shown in Figure 11. The top figure shows the MPs when they were subjected to the applied prestress.

4.4 *Horizontal loading test on the footings reinforced with MP group*

After the FT-PSMP prestress test, the horizontal loading test between the FT- PSMP group and FT-MP group (footing plus eight non-prestressed MPs) was conducted. The loading procedure was stopped when the horizontal movement of the FT- MP group reached 27.45 mm to minimized the damage to the footings. Shown in Figure 12 is the load-movement variation for FT-PSMP and FT-MP group, respectively.

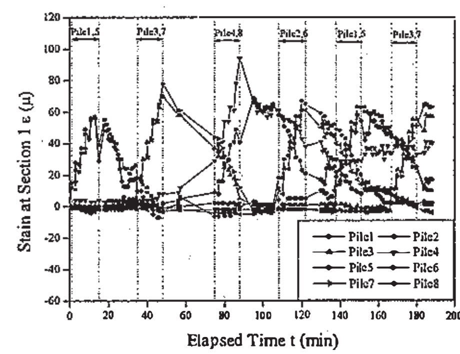

Figure 11. Strain variation at section 1 during the entire prestress in FT-PSMP 2nd prestress test

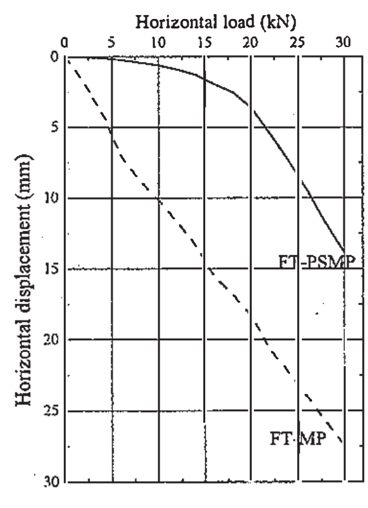

Figure 12. Movement of FT-PSMP and FT-MP groups under horizontal loading

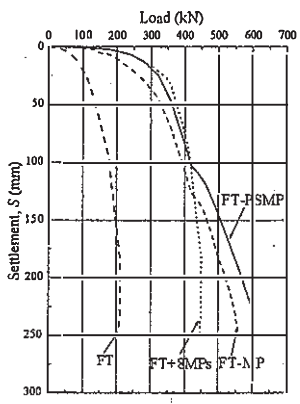

Figure 13. Load-settlement relations of FT, FT+8MPs, FT-MP, and FT-PSMP

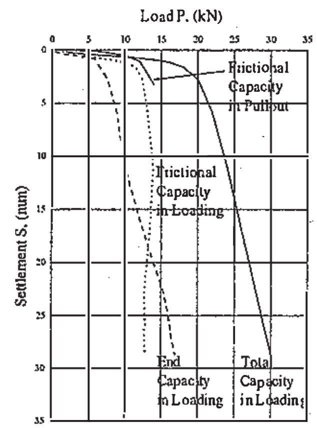

Figure 14. Comparison of the pullout load with the skin resistance in S-MP loading test

4.5 *Vertical loading tests the footings reinforced with MP group*

After the horizontal loading test, the vertical loading tests were conducted. The first applied load was 60 kN, the final applied load was up to 600 kN and 560 kN with the maximum settlement of 227.235 mm and 243.25 mm for FT-PSMP and FT-MP group, respectively (Fig. 13). Yielding load is judged as $P_y = 240$ kN, the ultimate load is estimated as $P_u = 600$ kN.

5 ANALYSIS AND DISCUSSION

5.1 *Mechanism of micropile in bearing load*

5.1.1 *Bearing mechanism of single MP*

From the Loading test on S-MP, the maximum applied load is 30 kN, among which point bearing capacity and the skin resistance are estimated 16.61 kN and 13.39 kN, respectively. From the S-MP pullout test, the ultimate bearing capacity is 14.3 kN, this result is well agreed with the skin resistance of 13.39 kN in the loading test, which testifies the accuracy and reliability of the strain gauges in the in-situ tests. Figure 14 shows the comparison of the pullout load in S-MP pullout test with the skin resistance in S-MP loading test. That the skin resistance is slightly higher in the S-MP pullout test than in the S-MP loading test may be due to the increased fitness between the MP and subsoils after the loading test.

5.1.2 *Bearing mechanism of MP group*

The maximum applied load of a single MP is 30 kN as stated in previous section, and the summation of the load carried by eight MPs can be estimated as 8 × 30 = 240 kN. To investigate the MP group effect, the load carried by FT and the load taken by eight MPs are summated, 210 + 240 = 450 kN. The load-settlement relationships of FT+8MPs, FT-MP and FT-PSMP are shown in Figure 13. From this figure, MP group effect is not clear at the early loading stage when the settlement is small; the curve of FT-MP group is even lower than that of FT+8MPs, which may be due to loose contact between FT and the ground surface at the early stage. But with the increase of the load, the load-settlement curve of FT+8MPs becomes lower, since the confinement of the FT and MPs in the MP group was induced with the increased stress in the MPs and subsoils. In this figure, the curve of the FT-PSMP group is always higher that of the FT-MP group, which strongly demonstrates the effect of prestress is positive on the improvement of veering capacity and reducing settlement.

5.1.3 *Effect of prestress on bearing capacity*

Effect of prestress on single MP: The maximum pullout load in S-MP pullout test was 14 kN, it was 30 kN as low as in FT-S-PSMP test. So the skin resistance of single PSMP can be more than twice the skin resistance of ordinary single MP. The difference in skin resistance between S-MP and FT-S-PSMP indicates the significant effect of prestress on increasing the confining stress of the subsoil around the MP and on increasing the frictional force between MP and the subsoils. After prestress, the stress in MP remains in tension side, which induced the upward stress onto the soil; however the base plate subsides, which applied downward stress onto the subsoil. So the subsoil beneath the FT was in confinement, and the stress hence increased. Meanwhile, due to the densification of the soil, the frictional angle may have increased. Therefore, the frictional resistance of MP was notably increased as observed in the test on FT-S-MP.

Effect of prestress on MP group: In the vertical loading tests, the maximum applied load in the FT-PSMP group is about 7% higher than that in the FT-MP test (Fig. 13), and both the load carried by FT and the load by MPs are generally higher in the FT-PSMP due to the increased confining pressure in the FT-PSMP group. But the improvement of bearing capacity by the prestress in MP group tests is lower than that in single MP tests, since there was a better confining effect in the center MP in the FT-S-PSMP test than in the peripheral MPs in the FT-PSMP test. The other reason lies in that the soft subsoils tend to move laterally under relatively large load so as to reduce the confining effect.

5.2 *Mechanism of micropile in movement control*

5.2.1 *Micropile in vertical settlement control*

One of the major features of MP is its excellent performance in settlement control. As shown in Figure 13, under the maximum applied load of 210 kN in FT test, the settlement of 250 mm in FT test is reduced to only 12 mm and 4 mm in FT-MP test and FT-PSMP test, respectively, under the same load.

5.2.2 *Effect of prestress on movement control*

Vertical Settlement: From Figure 13, the maximum settlement in FT-MP test is 243.25 mm with a maximum load of 560 kN, while it is only 227.23 mm in FT-PSMP test with a maximum load of 600 kN. In other word, the coefficient of subgrade reaction was $1.86\times10^4 kN/m^3$ and $3.97\times10^4 kN/m^3$ in the tests on FT-PSMP and FT-MP, respectively. This comparison means the settlement was suppressed at early stage offloading and become almost half due to the effect of prestress on MPs in the FT-PSMP group.

Horizontal Movement: The effect of prestress on horizontal movement control is remarkable compared with on vertical loading. The movement in the FT-MP group seems linearly increased with load as shown in Figure 12. The coefficient of subgrade reaction was $1.01\times10^3 kN/m^3$ and $17.1\times10^3 kN/m^3$ in the tests on FT-PSMP and FT-MP, respectively. This clearly showed the remarkable effect of prestress also in horizontal loading.

As shown in Figure 12, the failure pattern of FT-MP under horizontal load looks like punch-in, while the failure pattern of FT-PSMP is local failure. The difference in failure mode demonstrates that the subsoil composite was increased from soft soil of low strength to medium soil of medium strength due to the application of prestress on MPs.

6 CONCLUSIONS

The bearing capacity of the footing is greatly increased when it was reinforced with a group of micropiles, no matter prestressed or non-prestressed.

The effect of prestress on the improvement of bearing capacity was significant; the pullout resistance of S-PSMP was more than twice that of S-MP, and 7% vertical bearing capacity is increased in prestressed MP group (FT-PSMP) than in the non-prestressed MP group (FT-MP).

The effect of prestress in movement control was also remarkable in micropile group. The horizontal movement of prestressed micropile group (FT-PSMP) was less than tenth those of the non-prestress micropile group (FT-MP), compared in the coefficient of subgrade reaction. In vertical loading, the coefficient of subgrade reaction was twice in the prestressed micropile (FT-PSMP) compared with the non-prestress micropile group (FT-MP).

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