Bearing Capability for Mirco-Pile with Concrete-Filled Steel Tubular Reinforced Building Foundation

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Abstract. In general, the bearing capability is strength capability for mirco-pile. The stability bearing capability for mirco-pile with concrete-filled steel tubular becomes important in reinforced building foundation. The theory of buckling stability is applied to study the bearing capability of mirco-pile. According to the character of concrete filled steel tubular, the Euler force and the friction between pile and soil are combined for the buckling bearing capability of mirco-pile with concrete-filled steel tubular. The equation of mirco-pile with concrete-filled steel tubular is confirmed by some test data and numerical simulation. The slenderness ratio and material strength took great effects on the bearing capability of mirco-pile with concrete filled steel tubular. The equation on bearing capability mirco-pile with concrete filled steel tubular is applied for reinforce building foundation and referred to other application of concrete filled steel tubular.

Keywords. Concrete filled steel tubular, mirco-plie, stability bearing capability.

1. Introduction
Mirco-pile with concrete filled steel tubular was presented in 1950s and applied generally to huge seismic building in Japanese. Huqiu Tower, a famous heritage building in Suzhou, was reinforced by applying the technology of mirco-pile with concrete filled steel tubular in 1980. In recent years, mirco pile with concrete filled steel tubular has been applied to the building foundation reinforced and the side support in China, many research results of mirco pile with concrete filled steel tubular have presented [1]. However, few studies of foundation reinforced and pile base reinforce were focused on the applications of vertical loads in micropile with concrete filled steel tubular, great emphasis may be placed on the stability bearing capability.

For estimating the behavior of real-scale micropiles installed in higher density sand, a total of 36 tests were conducted on 3-m-long pipe micropiles, both while isolated and in 2 by 2 groups, with three different spacings [2]. A numerical study on an existing foundation underpinned was presented by micropiles using three dimensional (3D) finite-difference software. This study also revealed that the initial pressure ratio for underpinning and the length of micropiles had more effects on the behavior of the existing foundation underpinned by micropiles than the modulus of micropiles [3]. The model tests were carried out to understand the reinforcement effect induced. According to the experimental analyses, the reinforcement efficiency of micropiles by recommending the most effective pattern and design method for installing them were presented by the mechanical interaction between the micropile and soil [4]. The bearing behaviors of micropile cast-in-place pile with steel tuber under shaft load was studied by the number simulation method [5]. The buckling behaviors were analyzed for micropile steel pile and concrete filled was rarely considered [6]. Flexural Buckling Resistance of Micropiles was...
presented according to the Eurocodes, however the calculation result based on these codes of EC4, BS5400, AIJ, AISC-LRFD and GB50936 had great errors between code calculation and number simulation analyses [6-7].

2. Bearing Capability of Mirco-Pile with Concrete Filled Steel Tubular

2.1. Failure Mode of Mirco-Pile with Concrete Filled Steel Tubular

The bearing capability of pile was determined based on the limit failure mode of mirco-pile with concrete filled steel tubular under axial load. Three failure modes in limit condition were certified for mirco-pile with concrete filled steel tubular under axial load and were shown as follows:

- Failure for material strength of mico-pile. For the short-length of mirco-pile under strong bedrock, the section stress was more than material strength of pile.
- Failure for resistances between pile and soil. For moderate-length of mirco-pile under weak bedrock, the resistances between pile and soil were more than the soil strength of tension, shear or press.
- Failure for stability or buckling of mirco-pile under axial load. For long-length of mirco-pile, the bearing capability was more than the the buckling or stability bearing capability.

2.2. Method on Bearing Capability of Mirco-Pile

Number simulation analysis, analytical method and testing method have been applied to analyze the bearing capability of mirco-pile with concrete filled steel tubular. These research methods were verified each other and shown as follows:

- Finite element method of number simulation analysis. The softwares of FLAC, Aboqus or Anasys and so on were applied to analyze the bearing capability of mirco-pile, however these analysis modes might be modified for mirco-pile with concrete filled steel tubular.
- Equation analyse method of mathematical method. According to the failure modes, some analytical equations of mirco-pile with concrete filled steel tubular were presented in research literature, however some results from theoretical equations had more errors than some test data.
- Testing method. Few testing on mirco-plie with concrete filled steel tubular were conducted, however some expensive fees, prolonged process and many limit conditions were the shortcomings in these testing methods.

2.3. Equations for Bearing Capability of Mirco-Pile

2.3.1. Bearing Capability from Material Strength of Pile. According to the theory of steel & concrete pile cast in situ, the bearing capability of single pile was presented generally based on strength theory of concrete filled steel tubular under axial load. The material strength of pile with concrete filled steel tubular was shown as follow:

\[
N_u = \phi_1 \phi_2 A_c f_c \left(1 + \theta + \sqrt{\theta}\right)
\]  

In the equation, \(N_u\) was limit bearing capability, \(\phi_1\) and \(\phi_2\) were factors for slender ration and load eccentricity ratio, \(A_c\) was the section and \(f_c\) was the strength of concrete filled, \(\theta\) was confinement coefficient of concrete filled steel tubular and the bearing capability ratio between steel tubular \((f_s A_s)\) and concrete filled \((f_c A_c)\).

2.3.2. Bearing Capability from Resistance between Pile and Soil. Instead of bearing capability from pile of material strength, the frictional resistance between pile and soil might become the bearing capability in limit condition. The frictional resistance include the friction from pile-side and the resistance from pile-end. So the bearing capability of pile was shown as follow:
In the equation, the first section was friction from pile-side and the second section was resistance from pile-end. \( u \) was pile perimeter, \( q_{isik} \) was the friction of unit pile-length, \( l_i \) was the pile-length of soil layer, \( \lambda_p \) was the factor to soil plug effect of pile-tip and was 1 for close-section. \( q_{pk} \) was the standard value of penetration resistance from static penetration test. \( A_p \) was the section area of pile-end.

2.3.3. Bearing Capability from Buckling or Stability of Pile. In generally, the slender ratio of micro-pile with concrete filled steel tubular was larger for micro-diameter of steel tubular, so the micro-pile was long pile and the buckling stability might be the failure mode of micro-pile. The buckling bearing capability of micro-pile with concrete cast in situ was presented as a buckling factor \( (\varphi_0) \) and the strength bearing capability \( (\psi f_c + 0.9 f_y A_s') \). The bearing capability of buckling stability wasn’t presented for micro-pile with concrete filled steel tubular in current specification and normal of pile-base engineering, the equations for buckling capability of micro-pile with concrete filled steel tubular was presented based on Euler equation and shown as follows:

\[
N_u = \frac{\pi^2 EI}{(\mu d)^2} = \frac{EI}{E_s I_s + E_c I_c} \tag{3}
\]

So the stiffness of micro-pile \( (EI) \) was stiffness of steel tubular \( (E_s I_s) \) and 0.8 stiffness of concreted filled \( (0.8 E_c I_c) \). \( \mu \) was correlative length coefficient, \( l \) was the length of micro-pile.

The equation for stability bearing capability of buckling stability was presented based on stability coefficient of axial-press bar and shown as follow:

\[
N_u = \varphi_0 A_c f_c \left(1 + \theta + \sqrt{\theta}\right) \tag{4}
\]

\( \varphi_0 \) was the stability coefficient of axial-press bar and defined according to the stability coefficient from GB50936-2014 [8]. Other parameters were the same as equation (1).

3. Equation of Bearing Capability Combined Buckling and Friction

3.1. Four Assumptions of Micro-Pile with Concrete Filled Steel Tubular.

There were four assumptions of micro-pile with concrete filled steel tubular and shown as follows:

- Buckling of micro-pile was prior to the failure of pile-tip bedrock.
- Friction of micro-pile side wasn’t failure for buckling of micro-pile, little changes from micro-pile buckling were ignored in effect.
- Resistances on micro-pile buckling were ignored in effect from soil around pile.
- Micro-pile of concrete filled steel tubular was imbed completely in soil. The constrain of micro-pile tip was assumed as fixed end and the constrain of micro-pile top was assumed as hinge joint.

3.2. Equation Derivation.

In equation (3), the hoop effect was thoughtless for concrete filled steel tubular, moreover the stability bearing coefficient of axial-press bar was derivated from reinforce concrete in equation (4). These equations didn’t include of resistance between pile and soil. According to the assumption of buckling before bedrock failure and the force-balance, the bearing capability of micro-pile consisted of the buckling bearing capability of micro-pile and friction force from pile-side. So the equation was shown as follow:

\[
N_u = \frac{\pi^2 EI}{(\mu d)^2} + u \sum q_i l_i \tag{5}
\]
The parameters were same as equations (2-3), the stability coefficient of $\varphi_0$ was derivated from buckling stability of axial-press bar and Euler equation and shown as follows:

$$N_u = \frac{\pi^2 EI}{(\mu \ell)^2} = \varphi_0 A_c f_c \left(1 + \theta + \sqrt{\theta}\right) \quad (6)$$

$$\varphi_0 = \frac{\pi^2 EI}{(\mu \ell)^2 A_c f_c \left(1 + \theta + \sqrt{\theta}\right)} \quad (7)$$

According to the compare between equation (4) and equation (7), many different on stability coefficient of $\varphi_0$ were confirmed.

4. Verification Process on Equation of Bearing Capability
The analytical equations might be verified by number simulation method and test method. An example for micro-pile with concrete filled steel tubular were presented. The example on micro-pile with concrete filled steel tubular were referred to the studied from reference [7].

4.1. An Example for Mirco-Pile with Concrete Filled Steel Tubular.

4.1.1. Situation Condition. Three tests of micro-piles were located in LANZHOU city, the foundation soils included plain fill and sandstone. The soil distribution of foundation soil was shown as table 1:

| Depth      | Type      | Characters                    |
|------------|-----------|-------------------------------|
| 0.0-17.0 m | Plain fill| Average moisture content of 13.9% |
| 17.0-32.5 m| Plain fill| Plastic-soft-plastic Average moisture content of 22.8% |
| 32.5-33.5 m| Sandstone | Strong decomposed rock        |
| 33.5-40.0 m| Sandstone | Moderately weathered rock     |

4.1.2. Material. The lengths of micro-pile were 33 m, 24 m, 15 m and 6 m. The diameter was 168 mm, the thickness of steel tubular was 8mm. The strength of concrete was 50 Mpa. The strength of steel was 235 Mpa. The elastic module of steel was $2.06 \times 10^5$ MPa and the elastic module of concrete was $6.5 \times 10^4$.

4.2. Result Analysis of Bearing Capability. According to the parameters from 4.1, the bearing capability of micro-pile with concrete filled steel tubular were calculated by code method, equation in the paper and number simulation analysis of software FLAC. The results were shown as table 2.

| Pile length | Code     | Equation | Software |
|------------|----------|----------|----------|
| 6 m        | 788.77 kN| 2803.36 kN| 1000 kN  |
| 15 m       | 1607.68 kN| 1294.95 kN| 1375 kN  |
| 24 m       | 2401.47 kN| 1599.50 kN| 1750 kN  |
| 33 m       | 3094.78 kN| 2070.21 kN| 2250 kN  |

According to the standard of number simulation analysis, the calculation errors of equation were smaller than the error of code method except for micro-pile of 6 m. The reasons for large error of 6 m
micco-pile were that the failure mode wasn’t buckling failure and was resistance failure between pile and soil. So the formal in this paper was more accuracy than code method in buckling failure of micco-pile with concrete filled steel tubular.

5. Discussion

5.1. Influences Factors.
Pile length, resistance between pile and soil and material strength took some effects on bearing capability of micco-pile with concrete filled steel tubular. Three important factors of physic parameters of \( l/D, p_{ak} \) & \( p_{pk} \) and \( f \) were shows as these influences. Because these factors had great effects on the failure modes of micco-pile, the bearing capability might be referred for failure mode of micco-pile. With the increase of material strength, the bearing capability might be increased for short- pile with strong bedrock. With the increase of pile length and resistance between pile and soil, the bearing capability might be increased for friction pile with weak bedrock. However the micco-pile might become buckling as the increase of pile length the bearing capability might be decreased.

5.2. Optimal Pile Length.
The change of bearing capability was related to the failure modes and physical parameters of micco-pile with concrete filled steel tubular. The figure of bearing capability of micco-pile was shown as figure 1. In the figure, \( N \) was bearing capability, \( N_u \) was the bearing capability of short micco-pile in strong bedrock, \( N_0 \) was the resistance from pile-end. The line of (1) was the bearing capability from resistance failure between pile and soil, (2) was the bearing capability of short micco-pile in strong bedrock. (3) was the bearing capability of micco-pile buckling and friction from pile-side.

![Figure 1. Bearing capability of micco-pile with concrete filled steel tubular.](image)

In the II of figure, the limit bearing capability was \( N_{min} \) with the pile-length of \( l_2 \) and was derived from differential equation \( dN/dl = 0 \). Two pile-lengths were referred to a same bearing capability, so the short pile-length might be more economic than another long pile-length. With the change of friction from pile-side, the slope ratio of line (1) might change. With the change on pile length \( l_i \) the bearing capability from resistance between micco-pile and soil, might be the same as \( N_u \) of bearing capability from material strength and not be more than \( N_u \) of (2) and (3).

5.3. Deficiency Reflection

The accuracy of equations were refer to the results of number simulation analysis, however the deviation of equations were large from the test data. Some deficiencies of equations were induced for complicated mechanism and simplified mode. The resistances of pile-sile were nonlinearly distributed on the pile-length, however the resistances were simplified by linear calculation. The compression
force from soil around micro-pile was neglected. In addition, some mechanism of concrete filled steel tubular was indistinct and simplified in the equations.

6. Conclusion

6.1. Equation on Bearing Capability Combined Buckling and Friction
For simpleness and intuition, the analytic equations on bearing capability of micro-pile with concrete filled steel tubular might be more refer to the engineering design than other analysis tools. The equation of micro-pile with concrete filled steel tubular was studied for combined buckling and friction. The equation was accurate on the number simulation analysis.

6.2. Influences of Slender Ratio and Material Strength.
The slender ratio (L/D) , material strength and resistance between pile and soil were very important to the bearing capability of micro-pile with concrete filled steel tubular. With the increase of material strength and resistance between micro-pile and soil, the bearing capability might be increased for short micro-pile. The optimal length of micro-pile and the minimum of bearing capability was discussed for buckling and resistance between pile and soil.

6.3. Deficiency and Reflection
Some influences were simplified and neglected, the equations might induce some deficiencies and inaccuracy from test data. The equations were referenced to engineering design and analyzed to some characters. The range of slender ratio should be confirmed for the equation for buckling and friction. The calculation model of bearing capability might should be more accurate on micro-pile with concrete filled steel tubular.

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