Design and Calculation Method for Composite Foundation Using Large-diameter Rigid Piles in Pebble Bearing Soil

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Abstract: In the composite foundation using rigid piles, large pile-soil stress ratio often results in insufficient exploitation of bearing capacity of soil among piles. The rigid piles bear most of the vertical loads which makes the stress mechanism similar to that of pile foundation and fails to save cost. Based on the test and study of pile shaft resistance and tip resistance in the composite foundation using large-diameter rigid piles in pebble bearing soil and the stress monitoring of pile top and soil among piles, the pattern of variation in pile-soil stress ratio of composite foundation using large-diameter rigid piles was achieved. Furthermore, according to field test, use of cushion would lower the stress in rigid piles and exert bearing capacity of soil among piles which leaded to higher bearing capacity of composite foundation and smaller differential settlement. In contrast to “Technical Code for Ground Treatment of Buildings” (JGJ79-2012), a new design and calculation method for composite foundation using large-diameter rigid piles in pebble bearing soil was proposed based on the results from field test, numerical simulation and theoretical analysis. This improved and practical method has fully considered the potential bearing capacity of soil among piles and has been verified through practical engineering cases.

1. Introduction
Composite foundation, together with shallow foundation and pile foundation, has been commonly used in engineering. However, study on mechanism of composite foundation has a lot of catch-up works to execute compared to other two types of foundations. Composite foundation using large-diameter rigid piles mainly refers to the large diameter piles (D≥ 800 mm, use C15-C25 low-strength concrete), share upper loads together with surrounded soil. Its mechanism is to make full use of the bearing capacity of natural foundation soil, reduce settlement and save cost.

Composite foundation using large-diameter rigid piles was firstly applied in coastal soft soil areas of China and achieved good results¹[2]. With the increase of pile diameter, pile capacity has non-linear change sand pile-soil stress ratio will also be affected. The pattern of variation depends on interaction of pile shaft and tip resistance, pile length, layout, load conditions, cushion, and soil conditions, etc¹[3-6]. The research on the calculation methods regarding similar problems is still on-going. There are also great differences in different soil conditions and structural measures when using composite foundation. Further research and analysis need to be carried out in order to popularize and apply this method in pebble bearing soil.

The practical engineering cases of composite foundation using large-diameter rigid piles in pebble bearing soil indicate that use of cushion can boost the interaction between piles and soil and improve
load-sharing ratio between them by taking full advantages of the bearing capacity of soil among piles while meeting the requirements on bearing capacity and settlement[7] [8].

In the light of previous research on composite foundation cushion, this paper explored the pile-soil stress mechanism of composite foundation using large-diameter rigid piles in pebble bearing soil and the effect of reinforced cushion. The design and calculation method will be studied on the basis of field test, numerical simulation and theoretical analysis and verified by practical engineering cases.

2. Analysis on field test of composite foundation using large-diameter rigid piles

2.1. General Information

The geotechnical conditions of project site are given in following Table2-1 and fig.1:

| Soil                          | Bulk Density (kN/m³) | Compressive modulus E(MPa) | Cohesion c (kPa) | Angle of internal friction Φ (°) | Eigenvalue of bearing capacity fak (kPa) |
|-------------------------------|---------------------|-----------------------------|------------------|---------------------------------|----------------------------------------|
| Fill                          | 18.6                | 2.0                         | 7.0              | 8.0                             | /                                      |
| Clay (0≤Liquidity index<0.5)  | 20.1                | 9.0                         | 31.0             | 16.0                            | 210                                    |
| Pebble-bearing silty clay     | 19.4                | 8.0                         | 24.0             | 18.0                            | 200                                    |
| Fully weathered mudstone      | 19.6                | 6.0                         | 23.0             | 17.0                            | 160                                    |
| Strongly weathered mudstone   | 20.0                | 13.0                        | 45.0             | 28.0                            | 250                                    |
| Intermediary weathered mudstone | 21.0           | 250                         | /                | /                               | 700                                    |

The foundation type is raft foundation with composite foundation using large-diameter rigid piles below. The selected pile diameter is 1.0m and pile length is set as 16.0m. These piles, cast with C20 concrete, are equilateral triangular arranged by 2.30m center spacing.

A 0.3m-thick graded sand-gravel layer is paved and compacted (Compactness ≥0.90) on pile top as cushion to ensure piles and soil can work together to share the upper loads. The maximum particle size of cushion is less than 3 cm and the sand content is controlled around 20-30%. A polyethylene geogrid is added in the middle of cushion. The eigenvalue of bearing capacity f_{ak} of this composite foundation is not less than 600 kPa and the eigenvalue of bearing capacity of single pile is 2150 kN. The pile top is located in the pebble-bearing silty clay layer, 7-10m above the bedrock. And the intermediary weathered mudstone is used as bearing stratum which makes the piles rock-socketed. The geotechnical profile with rigid piles is shown in Fig1.
2.2. Stress results of pile shaft and soil among piles

The stress of rigid piles and soil among piles in composite foundation were monitored on site. Stress meters and strain meters were installed in the pile shaft to monitor axial strain under upper loads which can be utilized to deduce pile axial force. Earth pressure cells were embedded around piles (Fig.2) to monitor compressive stress of soil among piles.

![Figure 2. The layout of earth pressure cells](image)

![Figure 3. Variation of pile shaft axial force with upper loads at different depths of composite foundation.](image)

![Figure 4. Variation of earth pressure among piles with upper loads in composite foundation.](image)
2.3 Analysis of test results

The axial force of pile shaft increases gradually with the increasing of upper loads. The maximum pile axial force appears at 3m from the pile top. And the distribution patterns of the axial force along pile shaft remain the same under different upper loads.

The earth pressure among piles increases with the increasing upper loads. And the variation pattern stops fluctuating randomly after base pressure reaches 240kPa which marks the relative movement between soil and piles become stable.

The relatively stable pile-soil stress ratio will be achieved if base pressure reaches 240kPa, the main reason is that the cushion starts to kick in at this stage when settlement occurred on pile and then pile top pierced into cushion, that's the time that soil among piles can work together and share the upper loads with piles stably and notably.

According to the current code, the pile-soil stress ratio is 13.7 for composite foundation using large-diameter rigid piles (CFG pile composite foundation) while the monitored pile-soil stress ratio was around 8-10 from test results. It means that the code requirement on bearing capacity of single pile can be lowered further so that soil bearing capacity among piles can be brought into full play.

2.4 Mechanism of reinforced cushion

Practical engineering case in Chengdu pebble bearing soil proves reinforced cushion and its reinforcement plays a key role in the re-distribution of upper load sand exploitation of soil bearing capacity among piles in composite foundation using large-diameter rigid piles. And the settlement can be well controlled.

Besides, the cushion can adjust the vertical settlement of piles and soil among piles. The soil among piles would be squeezed horizontally because its vertical settlement is larger than piles. Such behaviour enhances pile shaft resistance, thus the pile bearing capacity.

3. Numerical simulation analysis

Midas GTS NX is adopted to simulate the pattern of variation of pile-soil stress ratio in composite foundation using large-diameter rigid piles. Contact surface between pile and soil is set to simulate the shear dislocation zone at pile-soil interface. The pile, using elastic model, diameter is 1.0m, length is 16.0m and these piles are equilateral triangular arranged by 2.30m center spacing with 0.3m thick cushion on top.

The soil is homogeneous using Mohr-Coulomb model and mechanical parameters can refer to Table 2-1.

Figure 5 and 6 show the results of pile stress and earth pressure indicating that the analysis results of pile-soil stress match the monitored results from practical engineering case which verifies the conclusion reached through filed test.
3.1. Pattern of Variation of pile axial force and earth pressure among piles
Figure 7 shows variation of pile axial force at 3m (where the max value appears) from pile top with upper loads for both FEA result and test result. The FEA result is larger in the high upper loads area, that may be the result of pile settlement.

Figure 8 shows variation of earth pressure with upper loads for both FEA result and test result. The value was extracted from soil located in centroid of triangular arranged piles. The FEA result is larger in the high upper loads area, the reason may be that numerical simulation failed to consider the dislocation of pebble particles which would disperse the stress and lead to smaller earth pressure. However, the pattern of variation of earth pressure for both FEA results and test results stay similar.

![Figure 7. Comparisons between FEA results and test result of pile shaft axial force.](image)

![Figure 8. Comparisons between FEA result and test result of earth pressure among piles.](image)

3.2. Pattern of variation of pile axial force and earth pressure among piles with spacing-diameter ratio
Fig.9-fig.11 shows the variation of pile axial force, earth pressure and pile-soil stress ratio with upper loads respectively considering different pile spacing while keeps the pile length, diameter, layout and stratum conditions fixed.

![Figure 9. FEA results of pile axial force under different pile spacing](image)

![Figure 10. FEA results of earth pressure among piles under different pile spacing](image)
Judging from the results in fig.9-fig.11, a conclusion can be drawn that the bearing capacity of soil among piles can hardly be exploited under the low distance-diameter ratio and in such case piles would bear most of the upper loads. However, by contrast, too large pile spacing can only lead to low bearing capacity due to low replacement rate, although the bearing capacity of soil would be fully exerted. Therefore, selecting a proper pile spacing and spacing-diameter ratio would be key in giving full play of both bearing capacity of soil and piles to satisfy requirement on cost, capacity and settlement to the greatest possible extent.

4. Design method of composite foundation using large-diameter rigid piles

The pile-soil stress ratio obtained from test result is much smaller than the code (JGJ79-2012) and numerical simulation result is even smaller. Therefore, the design method of bearing capacity of composite foundation stipulated in the code can be further optimized in the light of test results and numerical simulation results.

According to the stress mechanism of composite foundation:

\[ \sigma_{sp} = m \frac{N}{A_p} + (1 - m)\sigma_s \]  

(4-1)

In the equation, \( \sigma_{sp} \) is the equivalent uniform load due to upper loads, \( m \) is the displacement rate, \( N \) is the vertical load on the pile top, \( \sigma_s \) is the compressive stress of soil among piles, and \( A_p \) is the cross-section area of pile shaft.

And the equation calculating bearing capacity of CFG piles composite foundation stipulated in “Technical Code for Ground Treatment of Buildings” (JGJ79-2012) is:

\[ f_{spk} = \lambda m \frac{R_a}{A_p} + \beta(1 - m) f_{sk} \]  

(4-2)

In the equation, \( f_{spk} \) is the bearing capacity of composite foundation, \( \lambda \) is the exertion factor of single pile bearing capacity, \( R_a \) is the characteristic value of the vertical bearing capacity of single pile, \( \beta \) is the exertion factor of bearing capacity of soil among piles, \( f_{sk} \) is the bearing capacity of soil among piles.

Assuming composite foundation reaches its bearing capacity, equations (4-1) and (4-2) can be transformed:

\[ \sigma_s - \beta f_{sk} = m(\lambda R_a - N) / A_p(1 - m) \]  

(4-3)
And the equation can be further transformed considering different upper loads $q$:

$$
\beta(q) = \frac{\sigma_{s}(q) - m(\lambda R_{s} - N)}{f_{sk}(1 - m)A_{f}f_{sk}} \quad (4-4)
$$

Exertion factor of single pile bearing capacity can be assumed as 1.0 since large diameter rigid piles to be cast under the protection of steel casing and the pile strength and integrity can be guaranteed. Field test results under different upper loads are used to carry out fitting on equation 4-4 using same pile diameter, replacement rate and soil bearing capacity:

$$
\beta(q) = 3.765N / Ra - 2.729 \quad (4-5)
$$

In equation 4-5, if piles reach its capacity, the exertion factor of bearing capacity of soil among piles would be 1.03 which is larger than the code recommended value 0.8-1.0. In other words, soil among piles is capable of bearing higher pressure than its capacity obtained by load test. So equation applicable to composite foundation using large-diameter rigid piles in pebble bearing soil is proposed.

$$
f_{spk} = m \frac{R_{s}}{A_{f}} + \varepsilon(1 - m) f_{sk} \quad (4-6)
$$

$\varepsilon$ is the enhancing factor of bearing capacity of soil among piles.

According to the project monitoring results, the accumulated settlement of composite foundation is 12.2 mm, much less than the calculated value 39.59mm based on code. It means the settlement of composite foundation can be effectively controlled without plastic shear deformation of soil among piles while the soil among piles bears the pressure larger than its capacity.

Therefore, in the light of results achieved above, smaller pile diameter or larger pile spacing can be applied to speed up construction and save cost.

5. Conclusions and suggestions
Several conclusions and suggestions have been reached based on the field test and numerical analysis of composite foundation using large-diameter rigid piles in pebble bearing soil, focusing on variation of pile-soil stress ratio, spacing-diameter ratio with different upper loads.

(1) The pile-soil stress ratio fluctuated in low upper loads area and then reached stable value around 8-10 in high upper loads area which was lower than the code value. Such results verified cushion effect on adjusting pile-soil stress ratio to improve bearing capacity exertion of soil among piles.

(2) The variation of FEA results and test results regarding composite foundation main parameters can be well matched. The analysis on different spacing-diameter ratio showed pile-soil ratio reached its minimum value when spacing-diameter is 3.0, but the bearing capacity of composite foundation is comparatively low under such case due to limited bearing capacity of soil among piles which has been fully exploited.

(3) A modified equation was achieved regarding bearing capacity of composite foundation using large-diameter rigid piles in pebble bearing soil. This result can be applied to those projects on similar conditions.

(4) The mechanism of exertion of pile-soil bearing capacity with spacing-diameter ratio should be further improved and optimized through additional field tests and analysis.

References
[1] GONG Xiaonan. Theory of composite foundation and engineering application[M]. Beijing: China Architecture and Building Press, 2002: 45–67. (in Chinese)
[2] LIU Peng, YANG Guanghua. Designed calculation of rigid-pile composite foundation in soft soil ground considering deformation compatibility of pile and soil[J]. Chinese Journal of Rock Mechanics and Engineering, 2011, 30(Supp.2): 4039–4046. (in Chinese)
[3] ZHANG Jianxin, Wu Dongyun. Research on the interaction between resistance at pile and lateral resistance of pile[J]. Rock and Soil Mechanics, 2008, 39(2):541-544. (in Chinese)

[4] XIAO Yaoting, DANG Faning. Research on the design method of composite foundation cushion thickness[J]. Chinese Journal of Underground Space and Engineering. 2016, 12(5): 1331-1335. (in Chinese)

[5] HUANG Junjie, WANG Wei, SU Qian, et al. Deformation and failure modes of embankment soft ground reinforced by plain concrete piles[J]. Rock and Soil Mechanics. 2018, 39(5):1653-1661. (in Chinese)

[6] Yan Shuwang, LANG Ruiqing, SUN Liqiang, et al. Calculation of pile–soil stress ratio of rigid pile-net composite foundation based on plate theory[J]. Chinese Journal of Rock Mechanics and Engineering. 2017, 36(8): 2051-2060. (in Chinese)

[7] LU Qingyuan, LUO Qiang and JIANG Liangwei. Calculation of Pile-soil Stress Ratio of Rigid Pile Composite Foundation under Embankment [J]. Rock and Soil Mechanics. 2018,072:2473-2482. (in Chinese)

[8] HU Haiying,YANG Guanghua, ZHANG Yucheng, et al. Design method for rigid pile composite foundation based on settlement control and its application[J]. Chinese Journal of Rock Mechanics and Engineering. 2013, 32(10):2135–2146. (in Chinese)

[9] YAN Mingli, ZHANG Donggang. CFG pile composite foundation technology and engineering practice[M]. Beijing: China Water&Power Press, 2001:25-44. (in Chinese)