Design of composite foundation for high-rise buildings in complex red bed karst site

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Abstract. Ground collapse occurs frequently in deep foundation construction in the shallow overlying rock-karst area, constituting a major hidden danger to personal safety and engineering quality. This study reveals the structural characteristics of honeycomb heterogeneous anisotropic rock mass through the geological radar scanning and the foundation optimization design of a high-rise building (35 floors) in the red layer karst site. Meanwhile, the giant karst cave pipeline is filled and reinforced by karst grouting, and an artificial dam is constructed to block the groundwater transport channel. Based on the analysis results of the stability against the punching and cutting of the karst cave roof, the composite foundation of the plain concrete rigid pile with low-bearing capacity and high replacement rate is proposed. Regarding the extremely thin karst cave roof area, the steel pipe pile is used for underpinning and reinforcement, effectively avoiding the risk of local instability and construction collapse caused by the effective length of the pile and large stress at the pile end. After completing the building, it runs well. Meanwhile, the monitoring shows that the maximum settlement deformation of the high-rise building is only 9.63 mm.

Key Words: composite foundation, red bed karst, honeycomb structure, punching stability karst grouting

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1. Introduction
In the red bed karst area of Datansha, western Guangzhou and south of Datansha, rock masses differ in weathering and violent in dissolution because of embedded sedimentary of mudstone (sandstone) and limestone. Furthermore, karst and soil caves are large in scale and interconnected, most of which are non-filling or half-filling. Ground collapse induced by a deep foundation construction happens frequently, leading to severe problems, such as sliding, hanging, semi-hanging of piles, and collapsing of pile tip. According to statistics, the rate of broken piles has already been more than 30% in pipe pile construction, which is challenging to reduce.

It is challenging to design and construct the ground foundation of high-rise buildings in the karst area with low-risk and low-cost. Based on the optimization design of the foundation in Yicai New World Large Residential District, this study proposes a way of grouting reinforcement in the karst area. By blocking the groundwater migration channel and constructing a composite foundation with rigid piles of plain concrete with low-bearing capacity and high replacement rate, the problem above has been properly solved, and the design meets the foundation strength and deformation requirements of high-base stress.

2. The Original Design and Construction of Pile Foundation
The Yicai New World Large Residential District is located to the south of Shuangqiao Road in Guangzhou, covering an area of 210,000 m², with a total construction area of 756,000 m². In the first phase, eight high-rise buildings were divided into C1–C4 and C5–C8 clusters (Fig.1), each of which is a 33-story building with a height of 100 m above ground, 2-story basement, and 2-story skirt building. Moreover, the frame-shear wall structure is used for buildings, with a load of 3,900 kN–28,000 kN. The excavation depth of the foundation pit is 10 m, and the diaphragm wall and reinforced concrete inner supporting are used for soil retaining and water sealing.

The project is in the shallow cover areas of red bed karst with strong karst development and severe geological conditions. Consequently, the site is designed to use a punching board concrete pile foundation with a pile diameter of 1.0–2.4 m and a single pile-bearing capacity of 5,000–14,000 kN. The bearing stratum at the pile end is slightly weathering mudstone or limestone, and the effective pile length is evaluated to be 15.5–31.6 m by advanced drilling.

From May 2006 to January 2007, the construction of the pile foundation of the C1–C4 clusters and most of C5 and C8 were completed difficultly, and an entire collapse occurred frequently during the process (Fig. 2). Treatment measures, such as pouring and filling block stone mixed with yellow mud and lengthening the pile casing were adopted. However, slurry overflows became more serious, and
the range and depth of collapse were larger when closer to C6 and C7 buildings. The filling coefficient of the pile foundation reached 2.4–3.5. The construction company proposed using steel casing to protect the hole, which was 15–20 m long and passed through the sand layer to the strongly weathering rock surface. Four piles were constructed, costing 40,000–90,000 RMB per pile. However, it was challenging to weld, vibrate, and sink the steel casing, and the verticality control was also challenging. When the pile diameter was greater than 1.5 m, it failed to pass through the coarse gravel sand layer, and collapse occurred suddenly in a large range, endangering the safety of the laborers, and construction was forced to stop.

![Fig 2. Ground collapse of pile foundation construction](image)

**3. Development Characteristics and Causes of Karst Collapse**

3.1. **Rock and Soil Distribution**

A detailed survey and construction survey report shows that the rock and soil layers of the site from top to bottom are (1) miscellaneous fill, (2-1) silty sand with a thin layer of silt, (2-2) silty clay, (2-3) coarse and gravel sand, (3) residual silty clay and alternately distributed mudstone and limestone of the Cretaceous Dalangshan Formation. The mudstone contains soluble calcium blocks. The rock is intensively differentially weathered and severely dissolved. The surface of moderately and slightly weathered limestone and mudstone fluctuates violently, and the buried depth is 16.93–33.75 m. Some limestone surfaces are distributed with a thin layer of soft plastic cohesive soil. Table 1 shows the distribution characteristics of the rock and soil layers.
Table 1. Geotechnical distribution and recommended design parameters

| Number | Stratum lithology | State       | Depth of bedding (m) | Layer thickness (m) | N (Time s) | $f_r$ (MPa) | $q_{sia}$ (kPa) | $q_{lbs}$ (kPa) | $E_s/E_0$ (MPa) | $f_{ak}$ (kPa) |
|--------|-------------------|-------------|----------------------|---------------------|------------|-------------|----------------|----------------|----------------|----------------|
| (1)    | Miscellaneous fill| loose       | 0.00                 | 2.64–3.50           | 3–9        | 3.5         | 75             |                |                |                |
| (2-1)  | Silty sand with silt | loose       | 2.65–3.50           | 4.33–7.25           | 4–9        | 7.0         | 90             |                |                |                |
| (2-2)  | Silty clay        | Plastic     | 6.74–9.15           | 2.20–5.28           | 5–8        | 18          | 6.5            | 150            |                |                |
| (2-3)  | Coarse and gravel sands | Mainly medium dense | 9.86–12.35 | 4.16–8.24 | 17–38 | 30 | 26.0 | 250 |
| (3)    | Silty clay        | Mainly Plastic Strong weathering | 15.60–20.17 | 0.50–6.75 | 7–26 | 20 | 5.5 | 140 |
| (4-I)  | Mudstone          | Weathering Moderately | 15.90–25.64 | 0.50–6.27 | 46–68 | 0.4–1.2 | 50 | 700 | 60 | 400 |
| (4-M)  | Mudstone          | Weathering Moderately | 18.58–28.46 | 0.70–2.45 | 4.5–8.3 | 180 | 150 | 600 | 1500 |
| (4-S)  | Mudstone          | Weathering Moderately | 23.50–31.26 | 1.40–5.58 | 7.6–18.5 | 300 | 500 | 3000 | 4500 |
| (5-M)  | Limestone         | Weathering Moderately | 21.15–33.75 | 1.85–3.24 | 26.9–36.7 | 200 | 350 | 1000 | 3000 |
| (5-S)  | Limestone         | Weathering Moderately | 16.93–29.15 | 0.40–6.50 | 27.3–53.8 | 300 | 750 | 5000 | 7500 |

Note: The gravel sand is locally dense; $N$ is the actual blow number of SPT; $f_r$ is the natural uniaxial compressive strength of rock.

3.2. Karst Development Characteristics

Calcium clumps in the mudstone and limestone dissolve strongly. The mudstone has extremely low strength and weathering, and disintegrates easily, aggravating the development of karst. The karst forms include karst caves, karst grooves, karst troughs, karst gaps, karst holes, soil caves, and olecranon rock. The karst is strip-like, distributed northeast, and interspersed with mudstone. Large karst caves are mainly distributed in buildings C6 and C7. There are 214 advancing dills of the pile foundation and 165 holes drilled in the karst cave. The seepage rate is 77.1%, and the line karst rate is
28.6%. The height of the caves ranges from 0.30 m–10.60 m, and the average value is 3.93 m. Of the caves, 66.7% are higher than 2 m. Non-filling and half-filling caves account for 77.8%. Vertically, the karst caves are distributed in a beaded shape, and locally appear in 4 or 5 layers. The roof of the karst cave consists of slightly weathered limestone, 7.1% of which has a thickness less than 0.6 m, 24.3% between 0.6 m–1.0 m, and 16.9% between 1.0 m–2.0 m. The thin roof is the principal undesirable feature of the karst caves. Four earth holes are exposed with a height of 1.40 m–3.90 m. This area belongs to the extremely strong karst development area.

The groundwater is abundant, the quaternary pore water is mainly stored in the coarse gravel sand layer, and the depth of the water level ranges from 1.50 m to 2.00 m. The karst water is stored in the fissures of the karst cave, the depth of the water level ranges from 5.50 m to 6.50 m, and the amount of water inflow from a single hole is greater than 530 m³/d. The water level of the karst is approximately 4 m lower than that of pore water, which is closely related to the hydraulic power of the Pearl River. The karst and pore water are separated by residual cohesive soil, and it is speculated that the main recharge of groundwater comes from the nearby Pearl River. Taking building C6 and C7 as the center, 24 holes are arranged in a 12 × 15 m grid, and the hole depth is deeper than 3 m into the stable slightly weathering rock. The elastic wave method is adopted in a cross-hole geological radar scanning to study the cave distribution characteristics. Fig. 3 shows the three-dimensional (3D) geological typical profile. Between 20 m and 35 m below the surface, karst cave groups have formed interconnected and complex spatial piping systems. Rocks of different weathering degrees are mosaic-like distributed and present a heterogeneous anisotropic honeycomb structure.

Taking four groups of slightly weathering limestone for shear resistance tests, the result shows that c ranges from 2.8 MPa–4.3 MPa, of which the average value is 3.6 MPa, and φ ranges from 35°–41°, and the average value is 38°. Taking three groups of slightly weathering mudstone doing a shear resistance test, the result shows that c ranges from 1.1 MPa–1.8 MPa, of which the average value is 1.5 MPa, and φ ranges from 34°–39° and the average value is 36°. The strength of the rock is higher.

3.3. The Cause Analysis of Collapsing

The karst caves on the site are extremely developed and large in scale. Most caves are more than 2 m high and non-filling, excellent channels to transfer groundwater. The water stage of karst water is lower than the pore water, causing a difference in hydraulic pressure and a large density of mud. During the construction of the pile foundation, when the thin roof of the karst cave is broken by the impact of heavy hammer, the groundwater in the caves is squeezed at a high speed, and the mud is lost instantly. The pore water of the sand stratum flows into the pile hole quickly, and the entire wall
collapses unstably. The groundwater in the karst cave flows rapidly, forming a vacuum suction effect. Meanwhile, if the construction is affected in multiple spots and groundwater is squeezed repeatedly, the pipeline system between the karst cave and corrosion would be dredged. The constant disturbance of groundwater damages the relatively stable hard shell above the rock surface, which is composed of plastic-like viscous soil and medium-density sand stratum. The groundwater in the cave aggravates the surface collapse, leading to a sudden and complex collapse. Because of the large scale and irregular shape of the karst cave, filling block stones locally during the construction of the pile foundation cannot block the migration channels of groundwater effectively, causing surface collapse repeatedly and continuously.

4. The Research of Basic Optimization Design

4.1. Optimization of Pile Foundation Design
Considering this situation of pile foundation construction and requirements of the foundation of high-rise buildings, the C5 and C8 buildings still use the cast in the place pile foundation (Fig. 4). Moreover, large piles without construction are replaced by several 1.2 m diameter piles to reduce the bearing capacity of a single pile. The slightly weathering limestone with thickness more than 2 m is designed to be the principal bearing stratum of the pile end, reducing the risk from construction when crossing the multilayer karst cave. The karst cave grouting is adopted before the construction to block the migration channels of groundwater (Fig.8), meanwhile, using the steel casing to protect the hole, which could ensure the safety of the construction.

Fig 4. Zoning plan of foundation design
The central of C6 and C7 buildings are subordinate to the extremely karst developed area with high collapse risk. The base pressure ranges from 450 kPa–600 kPa, and the soil strata under the raft bottom are plastic clay and medium dense sand stratum. Its bearing capacity is 130 kPa–250 kPa. Consequently, a high strength rigid pile (plain concrete pile) composite foundation should be constructed. The podium building adopts the spread foundation and sets the anti-floating anchor.

4.2. The Difficulty of Composite Foundation Design
The principal technical difficulties of composite foundation design are ① The base pressure is high (450 kPa–600 kPa), but the characteristic value of the bearing capacity of the main soil strata in the basement is low (130 kPa–250 kPa). ② The rock mass is arbitrarily cut by the karst cave and grike to
form honeycomb heterogeneous rock mass. The karst caves with a roof thickness of less than 1 m account for 31.4%, which easily collapse under the pile tip load, leading to the instability of the foundation. ③ The basement is mainly composed of plasticized silty clay, medium dense coarse gravel sand, and residual soil, with a thickness of approximately 7 m–10 m. The rock mass is used as a bearing stratum of the pile end, which has been disturbed and with short effective pile length; hence, the bearing capacity of the single pile is low. ④ The excavation of the basement foundation pit is 10 m deep and the internal support is adopted. The plain concrete pile should construct on the ground and length of the empty pile reaches 10 m. As the connection of karst caves is highly developed, concrete pouring could grout runout so the quality of the pile is difficult to control. ⑤ Plastic cohesive soil is distributed on the surface of the limestone, affecting the effective contact between the pile and rock surface, and a weak interlayer could appear. ⑥ When a power shovel collides with the heads of the plain densely distributed concrete pile, there will be a different degree of cracks or broken piles in the upper section, which is challenging to reinforce. ⑦ If the pipe pile is adopted, it is challenging to pass through the serried sand stratum, and the rate of pile breaking and the risk of karst cave roof collapse are high.

4.3. Analysis and Evaluation of the Karst Cave Roof Punching Resistance

The central part of the karst cave roof bears pile tip stress, under the assumption that the rock mass of the karst cave roof is complete, relatively uniform, and the wall of the karst cave is stable. According to the method in 5.9.7 of the Technical code for building a pile foundation (JGJ94-2008), \( F_l \), which is the characteristic value of punching bearing capacity of karst cave roof with different thicknesses and lithology, can be calculated using

\[
F_l \leq \beta_h \beta_0 u_m f_t h_0, \quad (1)
\]

where \( F_l \) is the design value of the pile end punching shear force that is acting on the punching failure cone of the karst cave roof. It is also the limit value of the punching shear capacity of the karst cave roof (kN). \( f_t \) is the design value of the tensile strength of the rock mass with a value range 1/3–1/5 C, and C is the test value of rock cohesion (MPa), and the rest of the values refer to the specification requirements. Two pile diameters of 400 mm and 500 mm, and the punching shear capacity \( F_l \) (Table 2) of the karst cave roof with different thickness (0.8, 1.0, 1.2, 1.5, and 2.0 m) are calculated using formula (1). The greater the thickness, the higher the punching shear capacity. However, 31.4% of the karst cave roof is less than 1 m thick. Considering factors such as the shape of the karst cave, cracks, and pile group effects, the value of the punching shear capacity should be selected as 150 Kn–250 kN to minimize the risk of roof collapse.
Table 2. Punching shear capacity of different thickness of the karst cave roof

| Rock name                        | Thickness of karst cave roof (m) |
|----------------------------------|----------------------------------|
|                                  | 0.8   | 1.0   | 1.2   | 1.5   | 2.0   |
| Moderately weathering mudstone   | 158/197 | 197/247 | 236/296 | 295/370 | 394/494 |
| Slightly weathering mudstone     | 237/296 | 296/370 | 355/444 | 445/555 | 592/740 |
| Slightly weathering limestone    | 354/553 | 443/692 | 531/830 | 664/1038 | 886/1384 |

Note: 400 pile calculation value/500 pile calculation value

4.4. Conceptual Design of Composite Foundation

Based on the characteristics of karst development, the thickness and properties of the soil layer, especially the stability of the punching shear of the karst cave roof, a plain concrete pile composite foundation is adopted, combining the advantage of low single pile-bearing capacity with a high replacement rate. Grouting with the sleeve valve pipe and reinforcing the soil layer and karst cave filling within 3 m above and below the pile end, forms a mattress-type hard shell, which can spread the vertical stress of the short pile evenly to the rock surface to avoid the risk of local collapse of the karst cave roof.

5. Design of Composite Foundation of Plain Concrete Pile

5.1. Partition of Composite Foundation

C6 and C7 buildings are both 35 floors, including 33 floors above ground and 2 floors underground with a raft plane size of 61.7 m long, 33.6 m wide, and a total load of approximately 1010000 kN. According to the superstructure and load distribution, the composite foundation can be divided into five areas. The raft thickness in areas 1 to 3 is 1.8 m, and the base pressure is 450 kPa, 500 kPa, and 550 kPa, respectively. The thickness of the rafts in areas 4 and 5 is 2.2 m and the base reaction force is 550 kPa and 600 kPa. Considering the correction of the foundation burial depth and width, the characteristic values of the bearing capacity of the composite foundation in each area should not be less than 410 kPa, 460 kPa, 510 kPa, and 560 kPa, respectively.

5.2. Single Pile-bearing Capacity and Pile End Bearing Stratum

The Ф400 plain concrete pile is used as reinforcement. The bearing stratum of the pile end is mainly moderate-slightly weathering limestone and mudstone, of which part is strong weathering mudstone with a pile strength of C20. According to the recommended formula of the Guangdong Province Standard Technical Code for Ground Treatment of Buildings (DBJ 15-38-2005)

\[ R_a = Q_{sa} + Q_{pu} = \pi D \sum q_{st} l_i + q_{pu} A_p \]

and the survey report data, the characteristic value of bearing capacity of the pile in area 1 is calculated as 320 kN, area 2 is 340 kPa, area 3 and area 4 are 360 kN, area 5 is 400 kN. The pile length requirements are that the pile end in area 1 to 4 should enter the strongly weathering mudstone more than 2 m, and the pile end in area 5 should enter the strongly weathering rock no more than 3 m or reach the moderate weathering rock surface.

The construction adopts long spiral drilling to pump concrete, and the part of the empty pile is
backfilled with stone powder. The limestone surface of area 2, 3, and 4 is distributed with soft plastic clayey soil, and the bottom of the long spiral pile driver-drill pipe is approximately 100 mm away from the slurry outlet. However, the height difference between the bottom of the long auger drill pipe and the stock outlet is approximately 100 mm. When the concrete is pressed and poured, there could be a weak interlayer between the concrete at the pile end and the rock surface. Therefore, effective and full rigid contact cannot be ensured, and the bearing capacity of the pile end is affected. Consequently, when calculating the bearing capacity of a single pile, the value $q_{pa}$ of the moderate and slightly weathering rock is taken as 800 kPa, which is similar to the strong weathering mudstone. During construction, the drill pipe must reach the rock face, and the pumped concrete is lifted by 1 m before reverse insertion to expand the diameter of the pile end through an extrusion and the contact area between the pile end and rock surface, and eliminate the weak interlayer.

For boreholes with extremely thin overlying soil layer thickness and karst cave roof thickness less than 0.6 m, Φ108 steel pipe piles are adopted. During construction at the bottom of the pit, the holes are formed into 150 mm, entering the slightly weathering rock at 3 m. The design-bearing capacity of a single pile is 300 kN, the steel pipe wall thickness is 5 mm, and the bottom of the hole is filled with cement paste mixed with gourd stone. The strength grade is C20. Steel pipe piles are arranged according to 1.0 × 1.0 m, and more than 180 steel pipe piles are added in total.

5.3. Replacement Rate and Arrangement of Piles

Base on the characteristic value of the bearing capacity of the composite foundation and that of a single pile[2], the distance between plain concrete piles in areas 1 to 5 is taken as 1.0 m according to the recommended formula of the code, $m = (f_{spk} - \beta f_{sk}) \div (R_a/A_p - \beta f_{sk})$. Among them, the piles in area 1 are arranged in squares and the actual replacement ratio is 12.5%. The piles in areas 2–5 are arranged in triangles and the actual replacement ratio is 14.5%. In total, 2897 plain concrete piles exist, and Fig. 5 shows the arrangement of the piles.

The thickness of the cushion is 250 mm, and the cushion is made of gourd stone, medium-coarse sand, stone powder, and cement at a volume ratio of 1: 1: 1: 0.08. The cushion should be compacted statically, and the compacting factor not less than 0.95. By adding cement into the cushion, the cushion will harden when it meets water and its integrity will be improved. The deformation will be reduced. 50 mm thick C30 concrete cushion is laid on it, which is convenient for constructing the bottom plate.
For the 13 piles constructed, the top of the pile is removed by 250 mm, and the thickness of the cushion layer is set to 500 mm, which is used to reduce the differential settlement between the large-diameter rock-embedded pile and the plain concrete pile.

5.4. Settlement Calculation
The deformation of the composite foundation can be calculated according to the deformation of the pile (including the compression deformation cushion, pile, and rock/soil at the pile end) or the deformation of the composite soil layer.

(1) The compression deformation of the cushion layer $S_1$ can be calculated using formula 2:

$$ S_1 = \frac{R_{n} h_{co}}{A_{p} E_{pc}} $$

where $E_{pc}$ denotes the deformation modulus of the cushion (50 MPa is taken). The meanings of the other parameters could refer to the provincial standards (the same for below)\(^5\). According to the calculation, the deformation amount of the cushion in each area is approximately 12.7–15.9 mm.

(2) The compression deformation of the pile body and soil layer at the pile end $S_2$ can be calculated using formula 3:

$$ S_2 = \frac{1}{2} \left[ \frac{P_{pc} + q_{pa}}{E_r} + \frac{Dq_{pa}}{E_o} \right] $$

where $P_{pc}$ donates the load on the pile top (kPa) and $q_{pa}$ donates the resistance of the pile tip (kPa).

The compression deformation of the pile body and soil at the end of the pile, respectively, in each area is approximately 6.3–6.5 mm. The total settlement of the cushion layer, the pile body, and the soil at the end of the pile is 19.0–22.4 mm.

(3) The deformation $s$ of the compound soil layer
The compound soil layer includes the soil layers between the piles and layers at the pile tip, and the total settlement $s$ can be calculated from the layer-wise summation method.

$$ s = \varphi_s \sum_{i=1}^{n} \frac{P_0}{E_{si}} \left( z_i \alpha_i - z_{i-1} \alpha_{i-1} \right) $$

where $P_0$ donates the base additional stress, the value of which can be taken by 0.8–1.0 $(1 - m)$ fsk (kPa). The calculation depth $z_0$ of the foundation deformation is taken to the moderate weathering rock face\(^6\). If the soil layer at the pile tip is strong weathering mudstone, the depth should be increased by 2 m. Based on the results of the above two calculation methods, the total settlement of the foundation is estimated to be approximately 12.4–24.5 mm.

5.5. Split Treatment Between Different Basic Forms
Settlement joints are set between the raft foundations of buildings C6 and C7 and the pile foundations of buildings C5 and C8, and the thickness is 150 mm, which are U-shaped steel plate connections. The basement and outer wall located at the settlement joints are provided with back pouring tape. Between the raft foundation and natural foundation area of the north apron-building foundation, a post-cast strip
is set to adjust the vertical settlement. In the center of buildings C6 and C7, the base plate of the negative first floor and structure of the first floor will set the post-pouring belt of the settlement in the corresponding position.

6. Karst Grouting Reinforcement

6.1. Pretreatment of Large Karst Cave

First, for 8 karst caves such as 42, 43, and 59 (Fig. 6), with a cavern height of more than 4.0 m and non-filling or half-filling, Φ108 steel pipe is used for high-pressure grouting, with a grouting pressure of 6–10 MPa. Cement mortar (approximately 20 m$^3$) is infused to unblock the grouting passage, and then C20 concrete is grouted. Furthermore, 1–3 exhaust and drainage decompression holes are arranged. According to the sequence of the karst cave from big to small and from outside to inside, the space of the karst cave is filled with coarse granular material to form an artificial dam to block the groundwater migration in channel I.

The cement slurry is grouted into the decompression holes through a perforated pipe with a grouting pressure of 0.3 MPa–0.6 MPa to fill karst caves. Cement and sodium silicate double-liquid slurry is used for plugging when the amount of grouting is more than 30 m$^3$, and the solidification time is controlled at 30 s. Hole 71 is filled with 352 m$^3$ concrete at one time, 126 m$^3$ mortar, and 847 m$^3$ concrete. A row of inspection grouting holes were arranged at each end of the karst strip (Fig.6), with hole spacings of approximately 2 m, and the found karst caves are filled and plugged from bottom to top. Cement and sodium silicate double-liquid is grouted for filling and strengthening caves with a height of less than 2 m and non-filling or half-filling through the double-core pipe. Sleeve valve pipes are used to inject cement slurry into the filling carve, with a water-cement ratio of 0.5 and grouting pressure of 1.5–2.0 MPa, so that the property of cavern-filling material is improved and the contact of the karst underground inside and outside the composite foundation area is further blocked. The measure can also prevent the collapse of holes and grooves during the pile foundation or diaphragm wall construction. It will avoid the uneven settlement of the composite foundation caused by the revival of the karst cave and soil erosion caused by excavating dewatering and shifting sand in the surrounding deep foundation pit [7]. In total, 38.4 tons of cement and 9.7 tons of sodium silicate were used.

![Fig 6. Layout plan of karst grouting](image-url)
6.2. Sleeve Valve Reinforcement Grouting
For grouting areas I and II (Fig.6) with smaller overburden thicknesses and thinner karst cave roofs, grouting holes were arranged in a square or triangular shape with an interval of 2 × 2 m and entered 3 m below the surface of the medium and slightly weathering limestone. The sleeve valve pipe was used for grouting the reinforcement of sandy soil and clay within the range of 3 m above the rock surface (pile end) and the karst cave filler within the range of 3 m below the rock surface. The grouting pressure was 1.5–2.5 MPa. According to that filling condition of the karst cave, different processes were, respectively, selected. For the small karst cave with no filling or half-filling, cement and sodium silicate double-liquid slurry were grouted through a bored pipe at low pressure. Regarding fully-filled karst caves and karst fissures, sleeve valve tube compaction grouting was better adopted. In total, 874.5 tons of cement were used, which effectively improved the properties of karst cave filling, compacted the soil in the plane range of pile end, formed a relatively stable hard shell, transferred the stress of the pile body to the rock surface of the honeycomb rock mass uniformly, and reduced the concentrated force of the pile. The water-cement ratio is 0.5.

7. Composite Foundation Detection and Deformation Monitoring
7.1. Foundation Detection
Three large karst caves were inspected using the drilling and core-pulling method. The results show that there is no slurry leakage, the core sample collection rate is 88%–93%, there are cement slurry and mortar hardening material in the filling material, and the effect of grouting reinforcement is satisfied. The bearing capacity of the composite foundation with two piles, three piles, and four piles are evaluated using the static load test, and the settlement is only 5.5–10.9 mm. All results meet the design requirements. Approximately 24% of piles are detected by the low strain method and there are cracks in the upper 2 m range of pile bodies, which are affected by earthwork excavation, but the cracks do not affect the bearing capacity of the single pile [8].

Three short piles with thicknesses of karst cave roofs less than 0.6 m and a pile length of approximately 7–9 m were selected for the static load test. When the pile is loaded to 1.6–1.8 times of the design-bearing capacity, pile settlement is abruptly changed by 22–35 mm, and the pile integrity is good by the low strain method, showing that the roof of the karst cave has collapsed. Two short piles with the thickness of the karst cave roof approximately 0.8 m at the end of the pile are selected for the static load test, and the bearing capacity meets the design requirements with a settlement of only 6.7–8.6 mm. It shows that the thickness of the karst cave roof is the principal factor affecting the bearing capacity of the pile foundation and foundation stability [9].

7.2. Results of Settlement Monitoring
The construction was resumed in April 2010. Before the foundation was used, large-scale cavity-filling and grouting were conducted. In August 2011, the main structures of C5 and C8 buildings were completed. Meanwhile, the settlement of C5 and C8 were measured, ranging from 6.78 mm to 7.83 mm and 6.45 mm to 7.77 mm (Fig.7), with the differential settlement of 1.05 mm to 1.32 mm. In November 2011, the main structures of the C6 and C7 buildings were completed. The settlement of C6 and C7 was measured, ranging from 7.95 mm to 9.17 mm and 8.48 mm to 9.63 mm (Fig.8), with the
differential settlement of 1.15 mm to 1.22 mm. The maximum differential settlement was less than the allowable deformation value of 0.002 L specified in GB50007-2002.

The settlement of the composite foundation of the C6 and C7 buildings is consistent with that of the pile foundation of the C5 and C8 buildings, similar to the settlement value of the static load test, close to the calculated value of compression deformation of the soil layer around the pile body and tip, ranging from 6.3 mm to 6.5 mm. It shows the deformation characteristics of the pile foundation under stress. The reasons are as follow: ① The deformation observation was not conducted until the fourth floor above the ground was completed when most of the cushion-deformation was completed[10]. ② To effectively reduce the deformation, cement is added to the cushion, designing a concrete cushion. The cement slurry flowed into the gourd stone cushion to form a low-grade plain concrete layer. ③ The sleeve valve pipe grouting has an obvious reinforcement effect and reduces soil deformation. ④ The bearing stratum at the pile end is mainly moderate and slightly weathering limestone, and the construction of reverse insertion ensures the solid contact between the pile tip and rock surface. Hence, the short pile composite foundation shows the deformation characteristics of the pile foundation. So far, the construction has been put into use for about eight years, and the later deep underground engineering was completed and operated well.

Fig 7. Settlement monitoring of the C8 high-rise buildings

Fig 8. Settlement monitoring of the C7 high-rise buildings

8. Conclusions and Recommendation
(1) In the red bed karst area of western Guangzhou, the karst (soil) caves are large in scale, unfilled, and interconnected. The underground water level is low and fast-moving, which are the internal factors
of ground collapse induced by pile foundation construction. Additionally, groundwater is repeatedly impacted and squeezed by heavy hammers, destroying the soil structure, causing a vacuum suction effect, and thus, aggravating karst collapse.

(2) According to the development characteristics of karst caves, different grouting reinforcement techniques are used to construct artificial dams to block the groundwater migration channel, which can effectively prevent the collapse of the pile foundation construction, and eliminate the risk of karst cave revival and uneven settlement of composite foundation caused by soil and water loss.

(3) The thickness of the karst cave roof is the principal factor affecting the bearing capacity of the pile foundation in the shallow overburden karst area. Based on the analysis and evaluation of the punching stability of the karst cave roof and engineering properties of overburden, the composite foundation of plain concrete rigid piles with low-bearing capacity and high replacement rate fulfill the design requirements of high-base pressure and avoid the risk of local instability of the foundation caused by the insufficient effective pile length and large stress at the pile tip.

(4) Grouting reinforcement of the soil or karst cave around the pile tip using a sleeve valve pipe can effectively improve the engineering properties of soil and form a relatively stable hard shell. It can also transfer the stress of the pile body to the rock surface of the honeycomb rock evenly, and thus, reduce the concentrated force and deformation of the pile.

(5) The geological conditions of the karst area are complex. Different methods, such as drilling, geological radar, geotechnical tests, in-situ tests, and pumping tests, should be used to investigate the spatial distribution of karst caves, filling materials, the degree of filling, the thickness of roofs, engineering properties of the overlying soil layer, and groundwater distribution.

(6) Rigid pile composite foundation should not be adopted when the overburden layer with poor engineering properties and small thickness is used, whereas the foundation of a large diameter cast-in-place pile foundation can be designed under the condition that the groundwater migration channel has been blocked by karst grouting and hence, the risk of construction collapse has been reduced.

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