# The Application Research of Post-Grouting Technology at the Pile Base in Collapsible Loess Areas

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Keywords Bored Cast-in-Place Pile, Post-Grouting at Pile Base, Collapsible Loess, Pile Shaft Bearing Capacity, Engineering Application.

Abstract During the construction of bored cast-in-place piles, issues such as grout loss, grout overflow at the pile top, and the uplift of the reinforcement cage frequently occur, resulting in the pile's bearing capacity failing to meet the design requirements even after post-grouting. This study investigates the application of post-grouting technology for cast-in-place piles in collapsible loess formations and addresses its key technical challenges. It focuses on controlling the grout fluidity at the pile base, preventing the uplift of the reinforcement cage by installing a steel plate capsule at the pile base, and managing the bearing capacity of the pile after reducing its length. The composite post-grouting technology was successfully implemented in the realignment project of National Highway 108 (Xiangfen-Quwo-Houma section). This technology, utilizing three stages—open grouting, closed grouting, and re-opened grouting—effectively enhanced the bearing capacity of the pile foundation while controlling grout loss and reinforcement cage uplift. Experimental results indicate that the vertical compressive ultimate bearing capacity of single piles fully meets design specifications, significantly improving both the load-bearing performance and construction safety of the pile foundation. This technology not only reduces pile construction costs but also enhances engineering quality and economic efficiency, making it highly valuable and promising for broader engineering applications.



## 1 INTRODUCTION

With the rapid development of infrastructure construction in China, the use of pile foundation construction has increased significantly, and the post-grouting technique at the pile base has been widely adopted (Xu et al., 2017). However, issues such as grout loss, grout overflow at the pile top, and the uplift of the reinforcement cage still occur during construction, causing the bearing capacity of the pile to fall short of design requirements even after post-grouting (Zhou et al., 2021; Tan et al., 2017). Liu Zhonghua and colleagues, in their analysis of grout overflow and treatment measures in the Hangzhou Minghao Building project, pointed out that grout overflow occurs when the grout rises beyond the height of the pile (Gong et al., 2023).

During the construction of cast-in-place piles, grout overflow and reinforcement cage uplift are two critical issues with complex mechanisms influenced by the geometric properties of the pile (e.g., pile length, pile diameter), geological conditions, and grouting parameters (Li et al., 2019). Short pile designs tend to concentrate grouting pressure at the pile base, leading to rapid upward grout flow and increasing the risk of overflow. Enlarged pile diameters expand the grout flow channel, raising the upward grout height. Moreover, the thickness of the mud layer around the pile significantly impacts grout behavior; a thicker mud layer intensifies upward grout flow, especially in short piles, leading to grout rise beyond the pile length and resulting in overflow (Vakili et al., 2021). Therefore, optimizing pile design, conducting detailed geological investigations, and carefully adjusting grouting parameters are crucial to preventing grout overflow.

On the other hand, in the initial stage of cast-in-place pile construction, the concrete has not yet come into contact with the reinforcement cage, which mainly relies on the balance between the buoyant force of the slurry and its own weight. As concrete filling progresses, the concrete level rises to the base

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of the reinforcement cage, significantly increasing the risk of uplift due to the added buoyant force (Zhou et al., 2021). Eventually, as the conduit penetrates the reinforcement cage, the anchoring force at the base of the concrete increases, balancing the forces among the concrete, the slurry buoyancy, and the weight of the reinforcement cage, effectively preventing uplift. To address these challenges, optimizing the grouting process, enhancing construction monitoring, and timely adjusting construction parameters are necessary to ensure that the force states at each stage remain under control, thereby ensuring the quality and safety of the pile foundation construction.

Post-grouting technology for cast-in-place piles is a technique in which grout is injected into the base and sides of the pile through pre-installed ducts once the pile has reached the required strength. In the loess regions of Northwestern China, due to its unique geological conditions, cast-in-place piles are widely used because of their efficient utilization of soil bearing capacity and well-established construction techniques (Yu et al., 2017). Although post-grouting is highly effective in enhancing side friction resistance and strengthening the soil layer at the pile base, the technique's application in loess regions faces challenges due to the distinctive mechanical properties of these soils. Some believe its effectiveness in increasing side resistance in such areas is limited, which has hindered the widespread adoption of post-grouting technology at the pile base (Wan et al., 2019). Despite existing knowledge and practical achievements, there remain gaps in understanding its mechanisms, subjective biases, and deficiencies in analysis methods and precision in construction techniques. These issues require further in-depth analysis and study in conjunction with practical engineering applications.

Based on this background, this paper presents the developed post-grouting technology for pile bases and its application in the realignment project of National Highway 108 (Xiangfen-Quwo-Houma section). The successful implementation of this technology has significantly contributed to reducing project construction costs, minimizing the total cost over the full lifecycle, and saving overall investments. Furthermore, this technology can be directly promoted and applied in various pile foundation projects, generating considerable economic and social benefits, with broad application prospects and significant engineering value.

# 2 PROJECT OVERVIEW AND PROBLEMS

## 2.1 Project Overview

The project design begins near Zhujiageta in Xiangfen County, Shanxi Province, with a dual four-lane roadway and a design speed of 80 km/h. The starting and ending points are designated as K0+000 to K48+723.5, covering a total route length of 48.723 km. The proposed route corridor passes through Quwo County, an area located in the northern temperate and warm temperate semi-arid continental monsoon climate zone. This region experiences distinct seasons, with cold and dry winters, dry and windy springs, hot and rainy summers, and cool, clear autumns.

At the Xiyang Interchange bridge site, the surface layer consists of $Q_3$ silt and silty clay, with needle-like pores and visible large voids. According to the "Code for Building Construction in Collapsible Loess Areas," the bridge site is classified as a self-weight collapsible ground with a collapse grade of Level III (severe). The thickness of the collapsible soil at this location ranges from 14.5 to 15.0 meters.

## 2.2 Project Problem

Addressing the characteristics of collapsible loess, the key challenges for shortening the length of pile foundations in situ while ensuring the safety of existing bridges and enhancing the bearing capacity of the pile foundations include:

### 2.2.1 Control of Grout Fluidity in Post-Grouting at the Pile Base

During the post-grouting process at the pile base under high pressure, especially when using open split grouting methods, accurately controlling the flow direction of the grout poses challenges. The flow path can easily change with the natural fissures in sandy soil and gravel layers, increasing the risk of grout overflow to the surface and causing the grouting focus to be imprecisely concentrated in the pile base area. Additionally, adjusting grouting parameters is difficult, as precise control over pressure and volume becomes challenging, making it hard to fully comply with the predetermined design specifications. This not only increases the fluctuations in the bearing capacity of individual piles but also limits their potential for enhancement.

#### 2.2.2 Control of Reinforcement Cage Uplift After Installing Steel Plate Capsules at the Pile Base

In the construction of bored cast-in-place piles, the slurry within the hole poses challenges for the placement of the reinforcement cage equipped with steel plate capsules, similar to a piston effect that hinders slurry discharge and increases the difficulty of lowering the cage (Zhang et al., 2011). Once the reinforcement cage is in place, excess sediment tends to accumulate at the bottom of the hole, making secondary cleaning difficult. This requires precise control of slurry properties and optimization of reinforcement cage design in complex geological conditions such as collapsible loess to ensure smooth construction. Additionally, introducing efficient cleaning techniques to minimize the impact of sediment and ensure the quality and bearing capacity of the pile foundation is key to enhancing construction efficiency and engineering safety.

#### 2.2.3 Impact of Shortened Pile Length on Pile Shaft Bearing Capacity

In collapsible loess areas, once a pile foundation is subjected to water infiltration, not only is the original positive friction completely lost, but significant settlement caused by soil collapse can also induce negative friction, which results in additional loads ultimately borne by the soil at the pile tip (Zhang et al., 2006). If the length of the pile foundation is shortened at this point, it will further weaken the bearing capacity of the pile shaft, significantly impacting the overall stability of the bridge structure and increasing structural safety risks (Xi et al., 2022). Therefore, when designing pile foundations in collapsible loess regions, it is essential to fully consider the risks of water infiltration and the reasonableness of the pile length to ensure the stability and safety of the bridge.

## 3 TECHNICAL CONTENTS

### 3.1 Composite Post-Grouting Technology of Pile Bottom

Pile bottom composite post-grouting is divided into three stages: open pile bottom grouting, closed pile bottom grouting and open pile bottom re-grouting.

#### 3.1.1 Pile Bottom Open Grouting

Open grouting technology involves injecting the slurry directly into the soil through a non-blocking grouting pipe to ensure that the slurry is fully integrated with the soil, so as to achieve the desired engineering effect. The slurry is injected into the sediment and strata at the bottom of the pile, and the root cement slurry veins are formed at the bottom of the formation and the side wall of the pile. The simulation effect diagram of open grouting at the bottom of the pile is shown in Figure 1.

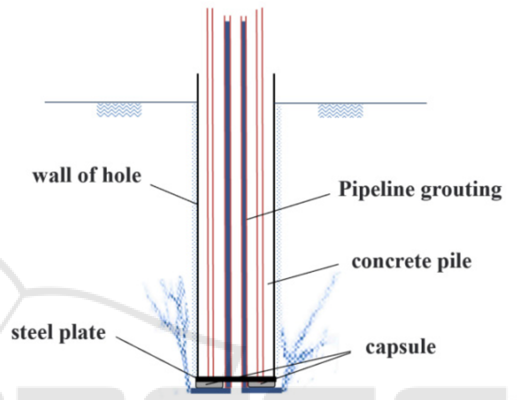


Figure 1: Simulated Effect of Open Grouting at Pile Bottom in Soil Layers.

In view of the high pressure required for grouting after pile bottom, split grouting is usually adopted for open pile bottom grouting, but it is difficult to control the grouting area under this method. Driven by high pressure, the slurry is easy to diffuse disordered along the natural cracks in sand, soil and gravel layer, resulting in the grouting focus may not be precisely concentrated in the pile bottom area. In addition, the precise control of the pressure and the amount of grouting becomes a big challenge in the process of grouting, and it is difficult to strictly follow the design standards, which affects the stability and consistency of the grouting effect. Such uncertainty not only intensifies the fluctuation range of the bearing capacity of a single pile, but also weakens the stability and reliability of its bearing capacity improvement (Zhu, 1998).

#### 3.1.2 Pile Bottom Closed Grouting

The remarkable feature of the closed post-compaction grouting technology at the bottom of the pile is that its process design cleverly ties the compression grouting pipe to the steel cage to ensure the construction of the grouting channel. Especially critical is the special steel plate capsule installed at the bottom of the reinforcement cage, which is not only structurally strong, but also carefully designed to seamlessly connect with the grouting pipe, realising a closed and efficient grouting process. This design enables the grouting operation to be precisely controlled, and the slurry enters the steel plate capsule through the grouting pipe under pressure, and then spreads effectively to the pile bottom and the surrounding soil layer to achieve the expected effect of foundation reinforcement, and the simulated effect of "closed" grouting at the bottom of the pile and the capsule are shown in Figure 2 and Figure 3.

During the construction process, slurry is injected into the pre-set capsule at the bottom of the pile through a precise slurry pipe system, which causes the capsule to expand uniformly and gradually form a solid stone enlarged head. This process not only strengthens the pile base structure, but also cleverly utilises the expansion force to extensively squeeze and spread the previously injected cement slurry around the pile base. This squeezing action prompts the cement paste to mix with the pile bottom slag in depth, and after the reaction, a denser cement soil layer is formed, which effectively improves the bearing capacity and overall stability of the pile foundation. The closed post-pressure grouting technique at the bottom of the pile can quickly and effectively squeeze and eliminate the slag layer at the bottom of the pile, and significantly improve the cleanliness and tightness of the pile bottom area (Teh et al., 2008; Orr, 2009; Wan et al., 2024). At the same time, this technique ensures that the injected slurry is accurately concentrated in the pile bottom, and the pile bottom and its surrounding strata are compacted and consolidated in depth by high-pressure action, which further enhances the stability of the foundation. In addition, the enlarged head formed during the grouting process significantly enlarges the support area of the pile bottom, and this structural optimisation greatly improves the ultimate bearing capacity of the pile foundation.

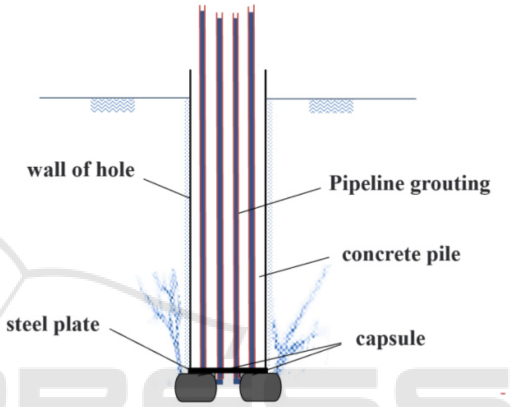


Figure 2: Simulation Diagram of Closed Pressure Grouting Effect at the Pile Base in Soil Layers.



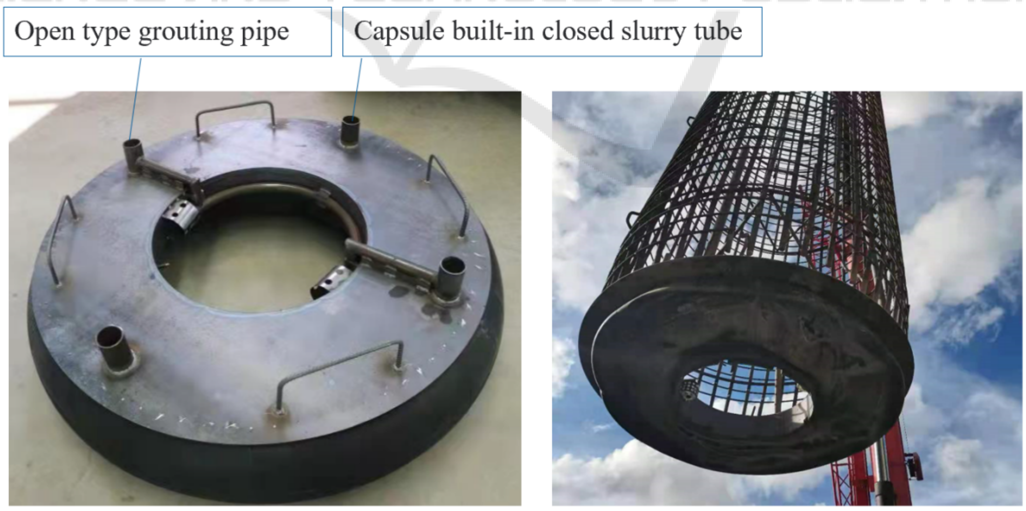


Figure 3: Plate capsule device picture.

### 3.1.3 Pile Bottom Open Grouting Again

The composite post-grouting technology at the pile base integrates both open and closed grouting techniques, retaining their respective advantages while overcoming their limitations. Its most notable feature is the combination of three grouting actions—fracturing, permeation, and compaction—focused at the pile base to work synergistically. The constraints provided by the ring-shaped capsule at the pile base effectively implement the "three-point" principle of grouting, which includes precise control of the grouting location, volume, and direction. The simulated effect of this composite post-grouting at the pile base is illustrated in Figure 4.

The design of the central-hole steel plate capsule skillfully incorporates multiple functions. Its key feature is the hole in the center, which plays a crucial role during the descent of the reinforcement cage. This design allows the slurry at the bottom of the pile to pass smoothly through the holes, reducing resistance to the descent of the reinforcement cage and ensuring that it reaches the bottom of the hole without obstruction. Furthermore, if excess sediment accumulates at the bottom of the hole after the reinforcement cage has reached its final position, these holes serve as a secondary sediment removal channel. Through the holes, the bottom of the pile can be effectively cleaned, removing any excess sediment and ensuring the quality and safety of the pile foundation construction.

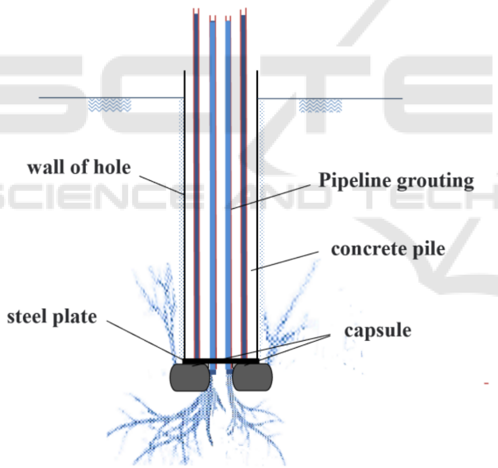


Figure 4: Simulation effect of open repressing grouting at pile bottom in soil layer.

An open grouting pipe is installed in the central holes to perform open grouting on the soil layers at the pile base, which can eliminate possible issues at the bottom of the pile, such as sediment, mud, voids, and gaps, thereby solidifying the soil layer. Due to the expansion of the closed grouting capsule, a large plug is formed at the pile base, preventing the upward return of the cement grout. The cement grout further fractures and permeates downward around the pile base, forming root-like grout veins that enhance the consolidation effect of the soil layers around the pile base, extending the reinforcement effect to greater depths.

## 3.2 Floating Control Technology of Steel Bar Cage

To prevent the uplift of the reinforcement cage after installing a steel plate capsule at the pile base, it is necessary to implement thorough preventive and control measures in three areas: the design of the reinforcement cage structure, the adjustment of concrete and slurry, and the concrete pouring strategy.

### 3.2.1 Steel Cage Structure Optimization

Strengthen the straightness of the main reinforcement: ensure that the main reinforcement of the steel cage is straight without bending, reduce unnecessary joints, so as to reduce the friction resistance and lateral adsorption force generated when the concrete is poured, and help the stability of the steel cage in the hole.

Initial anchoring strategy: place the reinforcing cage precisely on the bottom of the hole, and make full use of one of the first instant concreting anchoring effect, increase the reinforcing cage and initial connection strength of hole wall.

Stirrup spacing adjustment and the orifice fixed: appropriate increase the intensity of stirrup spacing in order to optimize the structure of reinforcing cage, at the same time in the orifice area add back pressure device, further reinforcing cage position, prevent to rise.

### 3.2.2 Concrete and Mud Performance Management

Reduce the density of the mixed liquid: According to the principle of buoyancy, the density of the mixed liquid between the mud and the concrete in the hole is reduced by precisely regulating the performance of the mud, thus reducing the buoyancy effect on the steel cage. Before perfusion, rock cuttings at the bottom of the hole should be completely removed to reduce the influence of impurities on the density of the mixed liquid.

Concrete performance optimization: strictly control the initial setting time of concrete, make sure it's in the process of infusion to keep good workability and liquidity, reduce the friction between the reinforcing cage and, at the same time guarantee the quality of concrete.

### 3.2.3 Fine Perfusion Speed Control

Initial low speed perfusion: When the concrete liquid surface first contacts the steel cage, the perfusion speed should be slowed down to reduce the direct impact force of concrete on the steel cage and avoid the buoyancy surge resulting in floating.
Speed in stages: reinforced concrete initial setting at the bottom of the cage, form a stable support, can be gradually to speed up the infusion speed, to improve construction efficiency, and ensure the safety of the infusion process under control.

## 3.3 Pile Bearing Capacity Control Technology

### 3.3.1 Selection of Grouting Mode

In the reinforcement of pile foundation, post-grouting technology becomes the key because of the high sensitivity of pile end to sediment (Guang-Yao et al., 2012). The technology not only strengthens the pile end sediment and produces bottom expanding effect, but also the reinforcement effect of the pile end sediment and soil is much stronger than that of the pile side mud. Therefore, pile end reinforcement should be taken as the primary consideration.

According to the Technical code for building pile foundations (JGJ94-2008), when a single pile end is grouting, the vertical reinforcement section is set to be 12 meters above the pile end, which is essentially focused pile end reinforcement. However, further analysis shows that if this range is extended to the pile side area 12 meters above the pile end, the overall reinforcement effect will be more significant by using the higher side friction resistance of deep soil. Therefore, the optimal strategy is to adopt the combination of pile end and pile side to maximize the bearing capacity and stability of pile foundation.

### 3.3.2 Strengthening Mechanism of Post-Grouting on Pile Side Resistance

In the construction technology of traditional bored pile, mud wall protection, as a key measure in the process of hole formation, effectively guarantees the stability of hole wall and construction safety. However, the mud crust formed by the gradual solidification of mud around the hole wall is difficult to be completely removed in the subsequent concrete pouring process, thus building a "barrier" between the pile and the soil. This layer of mud not only changes the physical properties of pile soil interface, but also profoundly affects the lateral resistance of pile. The moisture rich in the mud skin softens the structure of the adjacent soil under the action of infiltration, resulting in a significant reduction in the strength of the soil. At the same time, the mud skin itself has a lower friction coefficient than the undisturbed soil, which acts as a "lubricant" between the pile and the soil virtually, reducing the direct friction contact area between the pile and the soil, and thus weakening the generation of pile side friction resistance. In addition, with the gradual consolidation and hardening of pile concrete, the mud layer tends to shrink in volume to varying degrees, which further intensifies the separation tendency between pile and soil, forming new micro gaps, and further weakening pile side resistance (Jia et al., 2011).

At the top of the pile under load, the effect of pile side grouting can be analogy in around pile to form an enhanced concentric cylindrical "reinforcing tape". Through the infiltration and solidification of the grouting material, the reinforcement belt realizes the strengthening and integration of the soil on the side of the pile, and its influence scope extends roughly to 6 to 10 times the pile diameter. This expanding effect not only enhances the interaction of pile-soil interface, but also significantly changes the stress distribution in soil body. With the formation of the grouting reinforcement belt, the possible stress concentration in the soil is relieved, and the shear stress gradually dissipates and tends to be evenly distributed within the reinforcement belt. At the outer edge of the reinforced belt, the shear stress gradually decreases until it reaches a level close to zero.

# 4 TECHNOLOGY APPLICATION

In order to test the technical effect, NK0+371.5 Beidong Interworking bridge and LK0+465.3 Xiyang Interworking bridge of Xiangfen - Quwo - Houma transit transformation project of National Highway 108 were applied and verified, Figure 5. shows the installation and welding of the steel cage at the application site.. The projects are located in Quwo County, Linfen City, Shanxi Province. The pile body adopts bored pile. The pile length of Beidong Interconnecting bridge is 35m, the pile diameter is 1.5m, and the vertical compressive ultimate bearing capacity of single pile is 16376.04kN. The pile length of Xiyang interworking bridge is 35m, the pile diameter is 1.8m, and the designed ultimate bearing capacity is 13078.73kN.

(a) (b)

Figure 5: Installation (a) and welding (b) of steel cage.

Self balancing method to detect the pile bearing capacity, its core idea is to use special loading equipment on pile body in the load box, in the process of pile is based on the test objectives and the geological conditions of the default in reinforcing cage in specific depth, then closed pile, at the same time to ensure the loading box connecting line and other monitoring equipment smooth extends to the surface. After the pile body is fully cured, the device applies pressure to the load box through a ground-operated pressure system to simulate the stress situation at both ends of the pile body. In this process, the load box becomes a force transfer medium, applying both an upward reaction force ($Q_{uu}$) to the upper pile and a downward positive force ($Q_{ud}$) to the lower pile. Since the side friction resistance of the pile body and the surrounding rock and soil body balance each other, a self-reaction system is formed, and no external anchor pile or reaction device is required to achieve the loading effect equivalent to the traditional static load test (Cheng and Yu, X., 2013; Xing et al., 2019).

With the loading force increases gradually, the upper part of pile body in the reverse display its bearing capacity under load characteristics, through the monitoring equipment to record the corresponding parameters such as displacement, strain ($Q_{uu}$ series); At the same time, the lower pile reflects its bearing capacity under forward loading, and the corresponding response parameters are also recorded ($Q_{ud}$ series). Finally, through detailed data processing and analysis of the mechanical parameters obtained during the loading process, the bearing capacity of a single pile foundation can be calculated, as shown in formula (1) (Murali et al., 2024).

$$Q_u = \frac{Q_{uu} - W}{\gamma_1} + Q_{ud} \quad (1)$$

Where: Qu is the vertical compressive ultimate bearing capacity of single pile /kN; Quu is the measured ultimate bearing capacity of pile on the upper section of load box /kN; Measured ultimate bearing capacity of pile under Qud load box /kN; W is the dead weight of the pile in the upper section of the loading box; γ1 is the correction coefficient of pile side resistance in the upper section of load box, with a value of 0.9.

According to the results of self-balancing experiment, the bearing capacity indexes of single piles at two application points are statistically calculated as shown in Table 1. The test and analysis show that the vertical compressive ultimate bearing capacity of single pile at the two application points completely meet the design requirements.

Table 1: Single pile bearing capacity statistics table.

| sequence number | pile foundation | pile diameter (m) | pile length (m) | Load box buried position | Limit value of bearing capacity of pile (kN) | Design bearing capacity limit (kN) |
|---|---|---|---|---|---|---|
| 1 | Beidong Interconnecting bridge | 1.5 | 35 | Pile bottom up 14.8 meters | Not less than 16515 | 16376.04 |
| 2 | Xiyang Interconnecting bridge | 1.5 | 35 | The bottom of the pile is 7 meters up | Not less than 13316 | 13078.73 |

# 5 RESULT

This project has formed a complete set of technical achievements in the post-grouting construction of pile foundation in collapsible loess stratum, such as the flow control of post-grouting slurry, the floating control of steel cage after the pile bottom is installed with steel plate capsule, and the bearing capacity control of pile body after the length of pile foundation is shortened. The research results have been successfully applied in the support project of National Highway 108 Xiangfen - Quwo - Houma transit line change, and have played a demonstration role. As the key basis for pile foundation optimization in loess area, it is of great significance to improve the level of bridge construction in our country, and enhance the innovation ability and technical competitiveness of bridge construction in our country. The results of the project have a very positive role in reducing the construction cost and the total cost of the whole life cycle of the bridge, and saving the total investment. The results can be directly applied in the construction of various bridge projects, and can produce remarkable economic and social benefits, and has broad application prospects and important engineering significance.

# 6 DISCUSSION

In this study, we successfully applied post-grouting technology to address common issues in cast-in-place piles, such as grout loss and reinforcement cage uplift, in collapsible loess formations. By implementing a composite grouting method in three stages—open grouting, closed grouting, and re-opened grouting—we significantly improved the piles' bearing capacity and construction safety. The use of a steel plate capsule at the pile base effectively controlled grout fluidity and prevented reinforcement cage uplift. This approach not only enhanced the load-bearing performance but also reduced construction costs, demonstrating its potential for broader engineering applications.

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