Research on key technology of deep foundation pit support construction for bearing platform under complex geological conditions

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Abstract. The safety of excavation support structures during foundation pit excavation has long been a matter of concern in construction projects. This study focuses on a case study of a bridge foundation pit excavation project near the Yalong River. It investigates the key technical challenges faced under complex geological conditions, including thick rock formations. Various design options for support structures were compared and evaluated to choose the most effective construction measures. Subsequently, a three-dimensional model of the abutment support structure was created using midas finite element software to assess its bearing capacity and stability. The findings reveal that for deep foundation pits with complex geological conditions involving rock formations over 10m thick, employing interlocking bored piles with impact drilling is a more scientifically sound approach. This approach offers benefits such as minimal deformation, effective seepage control, structural safety, and cost-effectiveness. The calculated bearing capacity and stability both meet the required standards. Additionally, employing a mud and sand separator during the drilling pile construction process enhances efficiency and reduces cleaning time. Moreover, ensuring the integrity of the I sequence piles and thoroughly removing mud skin from the pile foundation during the construction process contribute to improved seepage control.

Keywords: Pit support, construction technique, interlocking sheet pile, complex geology

1 INTRODUCTION

In recent years, urbanization has rapidly advanced, leading to an increasingly significant role for deep excavation engineering in urban construction projects,

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particularly in the development of high-rise buildings, subways, and other large-scale infrastructure. However, the execution of deep excavation support works under complex geological conditions poses numerous technical challenges that impact not only engineering safety and cost control but also the surrounding environment. Therefore, to ensure safety and stability during the construction process, it is essential to adopt effective construction methods that minimize the impact of uncertainty factors.

Numerous scholars have extensively researched deep excavation engineering. Zheng[1] and colleagues stress the significance of selecting multiple support types based on diverse engineering geological conditions and support requirements when designing and constructing deep excavation support systems. They introduced a support group technology named "filling pile and internal support" and validated its effectiveness. Cui[2] introduced a demountable combination pre-stressed special-shaped steel plate reinforced core solidified soil foundation pit support technology, which exhibits strong permeability, rigidity, and economic characteristics, suitable for various foundation pit engineering projects. Zhang[3] summarized the importance of engineering foundation pit support in construction, highlighted the drawbacks of current traditional design and construction methods, and presented the application of ITASCAD technology in engineering foundation pit support, along with new ideas and innovations for the development of engineering foundation pit support technology. Han[4] conducted an in-depth investigation into the role of foundation pit support in the process of urbanization, identifying the limitations of current theoretical research on foundation pit pile anchor support systems and advocating the advantages of using 3D numerical simulation for predicting the foundation pit support process. Wan Yan[5] conducted real-time monitoring and prediction of foundation pit support structures, utilizing big data and deep foundation pit support technology, conducting a comparison of application scenarios, and employing mathematical analysis to validate the data, thereby offering a theoretical basis for foundation pit support and monitoring construction plans. Chen[6] performed model experiments by proposing and implementing a new type of deep foundation pit support system with adjustable support length and an intelligent adjustment method to coordinate the deformation of the deep foundation pit support system, demonstrating that adjusting the internal support length can enhance construction safety. Amir[7] undertook a thorough redesign of a foundation pit excavation project, considering the upgrade of the temporary support system to a permanent support system. Through diversified geological surveys and testing, the support system was reinforced, culminating in actual deformation being lower than predicted, validating the effectiveness of the design. Usama[8] devised and applied a multi-objective decision-making model to facilitate the selection from multiple deep foundation pit support systems, leveraging expert knowledge, cost calculations, and soil test results to effectively manage the complex construction projects. Li[9] simulated the impact of deep excavation on subway lines through the establishment of a three-dimensional numerical model and verified the model and input parameters by comparing model results with actual measured data. Yan[10] scrutinized various foundation pit support schemes, incorporating value engineering theory for optimization, illustrating that the application of value engineering theory can effectively reduce the construction cost of foundation pit engineering and improve economic benefits.

This paper centers on the critical technical issues related to raft deep excavation support in complex geological conditions. It explores a case study of a bridge foundation pit excavation project near the Yalong River and analyzes the primary technical challenges posed by the complex geological conditions at the site. Additionally, it conducts a comparative analysis of different support structure design schemes to determine the most suitable construction measures, followed by calculations of the bearing capacity and stability of the support structures. The findings of this study can offer valuable insights for similar engineering construction projects.

2 Geological conditions of the project

The river valley at the bridge site exhibits a broad, gently sloping "U" shape, with the slopes leaning towards the Yalong River on both sides, aligning with its flow. The left bank has a gradient of 20-35°, while the right bank is steeper at 30-40°.

As per the geological survey report, the 1# bridge pier is positioned near the river's center. In the dry season, the water depth averages around 5m, with turbulent flow. The riverbed terrain is relatively flat, with elevations ranging from 978.9 to 980.9m. There is a 10m thick construction platform made of artificial fill soil, composed of mixed crushed stone clay, exhibiting poor uniformity, slight density, and crushed stone particles of 2-8cm in diameter. The soil primarily consists of fine-grained clay with a minor presence of loam. The drilling extends to 8.0-10.0m, with previous stone throwing in some areas and single flash rock formations. The upper riverbed comprises gravel, floating stones, and fine sand, with a thickness of 4.2-7.2m, exhibiting mixed composition and moderate density, and gravel diameters of 5-12cm. The underlying bedrock consists of sandstone interbedded with shale from the Upper Triassic Bao Ding formation, characterized by varying layer thickness and moderate weathering. The fragmented rock mass has layers inclined to the northeast at an angle of approximately 45°. The geological map at pier 1# is shown in Figure 1.

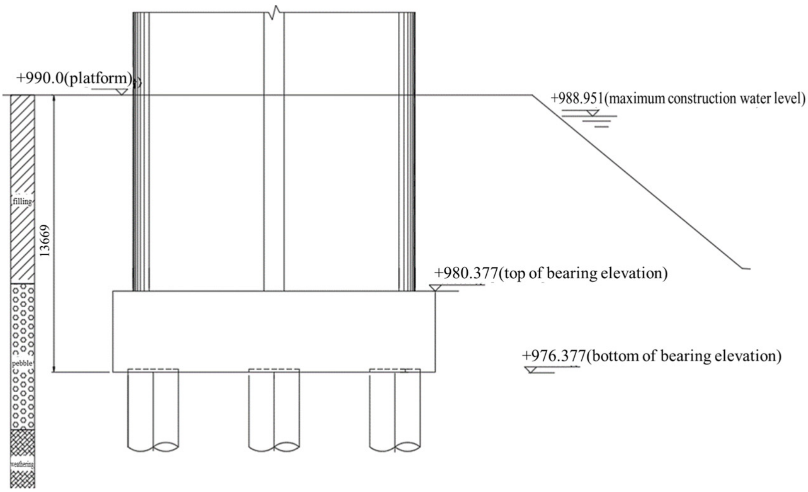


Fig. 1. Geological map at pier 1#.

3 Comparison of design options for bearing support structures

Through-water deep foundation pit construction technology encompasses various primary construction methods both domestically and internationally, including underground continuous walls, steel caissons, steel sheet piles, freezing technique, and pile driving. Considering the specific site conditions, a comparative analysis is conducted on the traditional approaches outlined below, presenting the advantages and disadvantages of each method in Table 1.

Table 1. Advantages and disadvantages of each method.

Serial number	Method name	Methodological advantages	Methodological disadvantages
1	Double-walled steel sleeve box	Precise positioning; small deformation; good water stopping effect	Uncontrollable efficacy; difficult to remove; higher cost
2	Steel sheet piles with guide holes	Controlled efficacy; easy removal; controlled cost	Easy to collapse; large deformation; more processes; poor water stopping effect
3	Sheet pile installation with high-pressure jet grouting water curtain	Controlled efficacy; good water stopping effect; small deformation	Poor water stopping effect; difficult to remove; high cost
4	Interlocking sheet piles	Controllable progress; good water stopping effect; small deformation	Difficult to remove

5	Combined steel sheet pile (vibratory)	Small deformation; easy to remove	Poor water stopping effect; uncontrollable quality
6	Steel sheet pile (static press-in)	Controlled efficacy; good water stopping effect; controlled cost	Large deformation; large site occupation

After conducting comparative research, it was decided to construct the support structure for foundation pit 1# using the interlocking sheet pile method. The construction process must address several primary technical challenges: 1) Coordinating the construction of support piles and structural piles, necessitating the strategic deployment of 7-8 impact drilling machines for simultaneous construction on the work platform and the implementation of dynamic control; 2) Implementing the construction of secondary reinforced concrete piles, which involves controlling the vertical deviation of the perforation and employing reliable methods to clear the mud skin on the borehole wall prior to concrete pouring; 3) Establishing safe and efficient measures for dismantling the support structure.

4 The key technology of interlocking bored pile construction

4.1 Analysis of key technical difficulties

Currently, the traditional construction method of concrete interlocking piles is categorized into soft and hard methods. In the soft method construction, guide walls are typically necessary. The concrete for the I sequence pile requires the addition of a retarding agent, while regular concrete is used for the II sequence pile. Soft cutting is commonly executed using a full casing drill rig. In hard method construction, ordinary concrete is utilized for both the I and II sequence piles. The conventional process involves employing a high-torque full casing rotary drilling rig or an ultra-high power rotary drilling rig to bore holes in the II sequence pile. These methodologies have drawbacks: the use of the soft method results in the retarding concrete's strength being significantly affected by environmental uncertainties, making quality control challenging. The location of guide walls becomes complicated due to the influence of core engineering pile construction facilities and spatial restrictions. When the hard method is used, the extensive space required for conventional large equipment and hard cutting limits the simultaneous operation of multiple machines. Depending on the geological conditions of the construction site, manual filling of broken stone soil layers, large block stone layers, and sandstone layers may be necessary. Consequently, using the aforementioned drilling rigs poses significant challenges in hole drilling, and verticality cannot be assured. From comparative analysis, it was determined that impact drilling is more advantageous for this project. As per the schedule, 52 interlocking piles must be completed within 35 days, indicating a tight schedule and challenging task. Synchronized construction of the interlocking piles with the structural piles is essential. To achieve this, 7-8 impact drill rigs must be strategically positioned for simultaneous construction within the limited space of the reclaimed area, representing a significant organizational challenge. During the construction of interlocking piles, there is a possibility of slag entrapment between the hard-cut joint surface of the I and II sequence reinforced concrete piles prior to the pouring of concrete for the II sequence pile. This can lead to poor water-stopping effectiveness of the pit support, resulting in water seepage following pit excavation. Hence, ensuring the water-stopping effectiveness of the pit support structure poses a major challenge for this project.

4.2 Support structure selection

The construction period for the lower bridge structure is constrained, necessitating simultaneous work on support and engineering piles, efficient piling, and the utilization of small equipment to expand the construction operational area, thereby reducing the construction duration through technological means. Additionally, Base Plate 1# is positioned at a depth of 4.5m to 6m beneath the riverbed, primarily composed of backfill soil (10m), and gravel/sandstone. Dry excavation and sealing the base are essential during foundation pit support construction, with pile penetration into the moderately weathered sandstone stratum required to be no less than 1.5m. In consideration of process and waterproofing requirements, a modified, large-diameter concrete interlocking pile support structure is suggested, comprising I sequence plain concrete piles (for waterproofing) and II sequence reinforced concrete piles (for structural load-bearing), reducing the number of support piles, enhancing anti-seepage stability, and utilizing a 1.5m pile diameter.

4.3 Support structure process analysis

Throughout the construction process, a comprehensive technical analysis of the foundation pit support for pier 1# was performed to determine the optimal construction methods, equipment, and tools for its support, as outlined in Table 2.

Table 2. Support structure process analysis.

Serial number	Process analysis	Process description
1	Process selection	The constrained space on the work platform makes it infeasible to employ the soft cutting method with retarding concrete and a full casing drill rig. As a result, the initial selection is to use the hard cutting method.
2	Equipment selection	Considering the construction schedule, the interlocking piles must be constructed concurrently with the engineering piles. In view of shared usage and efficiency, impact drilling is chosen to facilitate the setup of multiple work areas.
3	Guide wall setup	The confined working space precludes the installation of continuous concrete guide walls, and therefore, a detachable steel structure guide wall is utilized for positioning during construction.
4	Mudskin cleaning	A significant mudskin layer will develop at the interlocking surfaces. Employing a directional mudskin

		cleaning device to promptly remove the mudskin will improve the waterproofing.

4.4 Calculation of support structures

Based on the model design and calculations, 52 interlocking concrete bored piles, each with a diameter of 1.5m, spaced at 1.2m intervals and interlocking at 0.3m widths, were utilized. The piles were equipped with reinforced concrete cap beams and internal bracing at the top. The cap beam section, measuring 1.8m × 1.8m, formed a rectangular supporting structure, with dimensions of 19.10m in length and 12.30m in width. During the calculation process, three assumptions were made: ① conducting limit state designs for both the ultimate and serviceability limit states; ② the II sequence piles bore structural loads, while the I sequence piles functioned as water-stops without bearing any loads; and ③ the support piles were regarded as completely watertight structures. Water within the cofferdam was pumped out until the bottom concrete surface. The three-dimensional model was created using the midas software, as depicted in Figure 2.

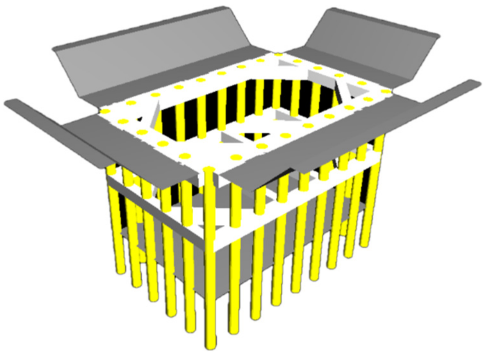
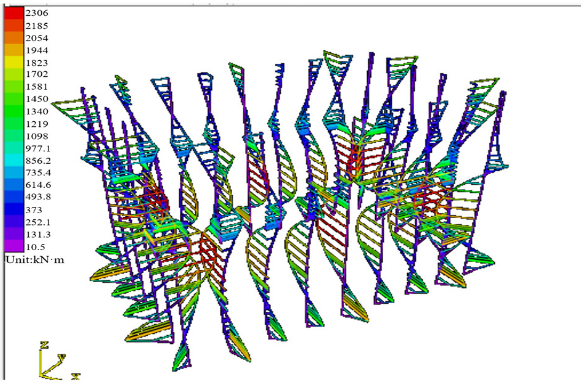


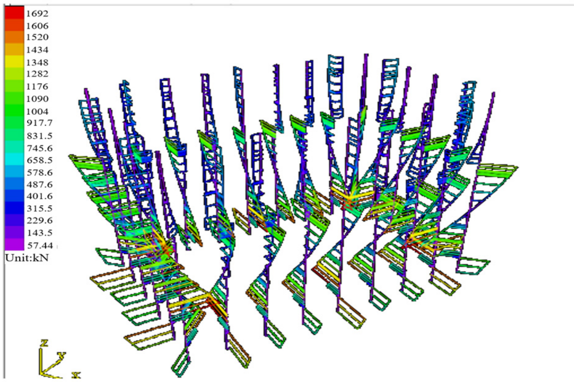
Fig. 2. 1# bearing platform foundation pit support structure Midas design model.

(1) Calculation results of bored piles

The internal force calculation result diagram for the bored pile is depicted in Figure 3, and a summary of the calculation results is presented in Table 3.



(a)



(b)

Fig. 3. Bored pile internal force diagram. (a): Bored pile bending moment diagram (kN·m). (b): Bored pile shear diagram (kN).

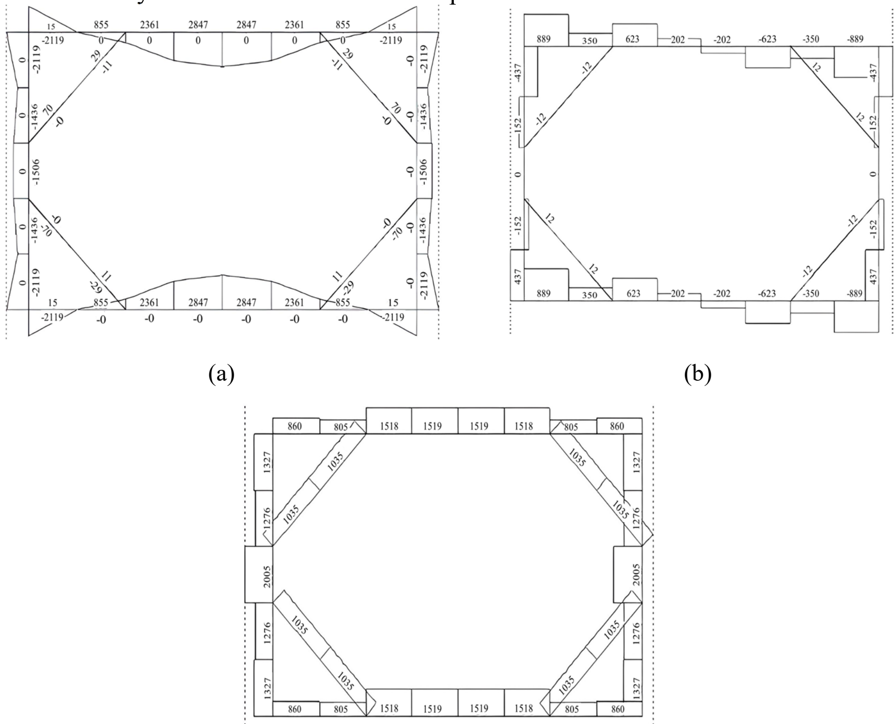
Table 3. Calculation results of bored piles.

Section number	**Type of internal force**	**Calculated value by the elastic method**	**Design value of internal force**
1	Maximum bending moment on the inside of the pit (kN·m)	2306	2883
2	Maximum shear (kN)	1692	2115

Based on the calculations, it was determined that a total of 22 steel bars with a diameter of 28mm were required; however, in practice, 25 steel bars were employed, which fulfills the specifications. The design standards from the "Code for Design of Concrete Structures for Water Transportation Projects" were consulted to assess the requirements for circular section reinforced concrete bending members, eccentrically compressed members, and tension members, as well as the limitations on the section and the criteria for the shear-bearing capacity of inclined sections. The calculations have verified that the shear resistance capacity of the inclined section of the bored pile, as well as the local shear resistance capacity of the interlocking pile, both satisfy the necessary criteria.

(2) Crown beam calculation results

The internal force calculation diagram for the crown beam is depicted in Figure 4, and a summary of the calculation results is provided in Table 4.



(a) (b)

(c)

Fig. 4. Crown beam calculation diagram. (a): Crown beam bending moment value (kN·m). (b): Crown beam shear value (kN). (c): Angle brace axial force value (kN).

Table 4. Calculation results of crown beam.

Section number	**Type of internal force**	**Calculated value**	**Design value of internal force**
1	Maximum bending moment on the inside of the pit (kN·m)	2847	3558
2	Maximum shear (kN)	889	1123
3	Maximum axial force of angle brace (kN)	1035	1294

Following the calculations, both the flexural and shear resistance capacities of the crown beam meet the specified requirements.

(3) Internal support calculation results

The results of the internal support calculations are displayed in Figure 5, and the compilation of the calculation results for the ring beam is provided in Table 5.

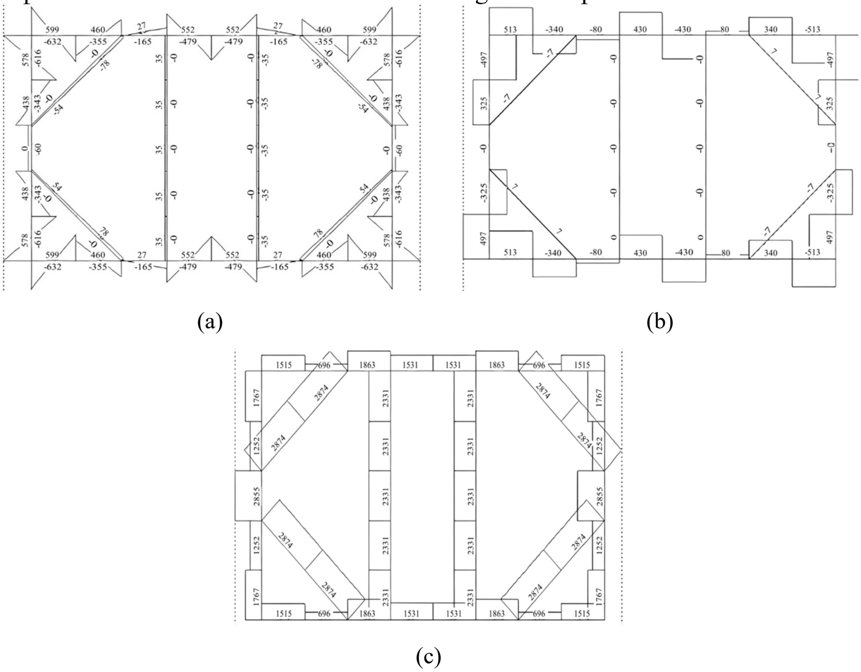


Fig. 5. Internal support calculation diagram. (a): Internal support bending moment value (kN·m). (b): Internal support shear value (kN). (c): Internal support axial force value (kN).

Table 5. Calculation results of ring beam.

Section number	Type of internal force	Calculated value	Design value of internal force
1	Maximum moment of ring beam (kN·m)	599	749
2	Maximum shear of ring beam (kN)	513	641
3	Maximum axial force of ring beam (kN)	2855	3568
4	Maximum axial force of internal support (kN)	2674	3343

The calculations indicate that the maximum combined stress for the ring beam and internal supports is 114.1MPa, with the maximum shear stress being 39.6MPa, meeting the specified requirements.

(4) Overall stability calculations

The Swedish strip method is used to check the overall stability, the width of the strip is 0.40m, the radius of the circle is 21.267m, the horizontal coordinate of the circle center is 1.407m, and the longitudinal coordinate of the circle center, Y, is 16.879m.

The overall stability safety coefficient of 40.840 is calculated to be more than 1.30, which meets the specification requirements.

(5) Uplift resistance calculation

The stability against uplift is calculated layer by layer, starting from the base of the support structure. The analysis results in a K_s value of 999.366, which exceeds the threshold of 1.600, thus demonstrating that the stability against uplift meets the specified criteria.

(6) Infiltration stability calculations

Figure 6 illustrates the seepage calculation model for the foundation pit's support structure.

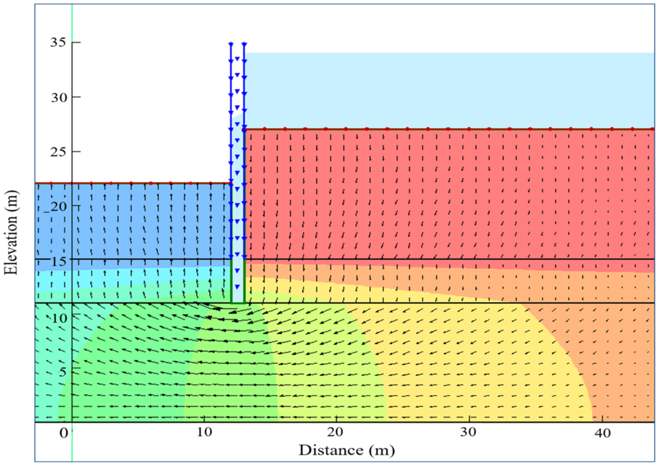


Fig. 6. Calculation model of seepage in foundation pit support structure of 1# bearing platform.

The safety factor for the stability of permeability can be determined using the following formula:

$$\frac{(2l_d+0.8D_1)\gamma}{\Delta h\gamma_w} \geq K_f \tag{1}$$

where K_f is the safety factor of soil stability; l_d is the insertion depth (m) of the cut-off curtain below the bottom of the pit; D_1 is the thickness of the soil layer from the groundwater level or confined water layer top to the bottom of the pit (m); γ is the unit weight of the soil (kN/m³); Δh is the difference in water head inside and outside the pit (m); γ_w is the specific weight of water (kN/m³).

The computed safety factor of 1.65 exceeds 1.60, classifying it as a first-level excavation.

The calculations for bending, shear resistance, overall stability, overturn stability, and uplift stability all comply with the regulatory standards.

4.5 Construction key process flow

The comprehensive construction procedure for the bearing platform is presented in Table 6.

Table 6. Steps in the overall construction of the bearing platform.

Steps	Instruction
1	In total, six impact drills were deployed. Specifically, three of the impact drills were used to execute the construction of three main engineering piles while the remaining three impact drills were employed for the construction of three I sequence piles and two II sequence piles respectively.
2	Six drilling rigs are being relocated. Specifically, three impact drills completed the remaining construction of three main engineering piles, while the other three impact drills each completed the construction of three I sequence piles and two II sequence piles.
3	Two drilling rigs were removed, and the remaining four rigs were relocated. The four impact drills completed the construction of the remaining support piles in four different directions.
4	Excavation is being conducted within the Chikushima Platform, involving a 3-meter reduction in the slope of the cut slope within the foundation pit area.
5	Excavation of the beam trench, casting of the beam and the first internal support, and installation of guardrails and drainage ditches are in progress.
6	The excavation process involves systematic de-watering and excavation, followed by the installation of a second layer of internal support and the pouring of concrete for the cushion layer.
7	The process involves securing the pedestal steel bars, installing the formwork, pouring the concrete, then removing the formwork and subsequently backfilling the coarse sand along the pedestal sides, reaching below the top surface by 0.5m, followed by pouring the pedestal ring beam.
8	Dismantle the second layer of internal support, build the bridge piers, and backfill to a depth of 1m below the top surface of the completed bridge piers.
9	Continue the construction of 2 to 3 sections of the pier columns, simultaneously backfilling to the level of the bridge girder, and further backfill the original soil to the top surface of the construction platform. The supporting structure is to be dismantled when the construction platform is removed.

4.6 Construction key technologies

The interlocking pile system consists of I sequence and II sequence piles, wherein the I sequence piles are composed of plain concrete and the II sequence piles are composed of reinforced concrete. Figure 7 illustrates the layout plan for the construction of the interlocking pile system.

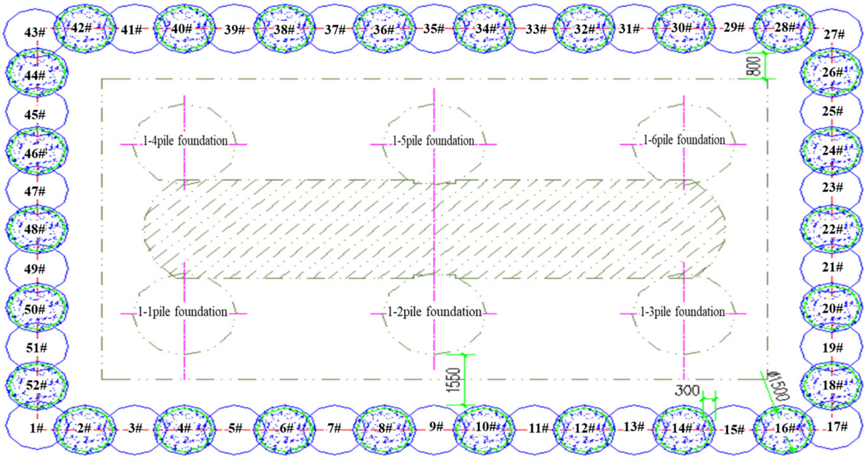


Fig. 7. Layout plan for the construction of interlocking piles.

(1) I sequence pile drilling hole formation

Preparation before commencing drilling involves applying for inspection prior to initiating drilling activities. Drilling can commence only after the drilling engineer inspects and approves the drill bit diameter, the alignment of the drilling machine, and completes the horizontal inspection.

Initial drilling procedure requires the addition of a suitable quantity of rock chips and clay, with a particle size not exceeding 5cm, inside the casing, followed by using a short stroke to crush them. After drilling to a depth of 0.5 to 1m, the space should be backfilled with clay or grout, with the grout initially injected vertically into the middle of the pile hole. Subsequently, the drilling should continue with a low stroke, repeating the process two or three times, and if necessary, more repetitions can be carried out.

For normal drilling, once the depth reaches 3 to 4m below the casing, regular impact operations can be conducted. The geological stratum can be determined based on the slag sample, with medium stroke being utilized for gravelly sandy soil, and high stroke for conglomerate and sandstone layers. During the drilling process, around the 8 to 11m position, the overall integrity is compromised due to the artificial disposal of stones, gravel, and fine sand layers, resulting in the hollowing out of the pile hole position. This leads to the inability of the retaining wall to maintain its integrity when subjected to external forces during pile hole construction, causing it to collapse into the pile hole. The sudden drop in the mud level within the pile hole due to mud leakage further leads to the abrupt loss of static pressure on the upper part of the pile hole wall, resulting in its collapse. As a countermeasure, the conventional method involves backfilling with clay and rocks with a higher colloid content and compacting them repeatedly. Given the complex geological layers of the project, in areas where collapse is severe, a mixture of clay blocks and small stones stirred with cement is used for backfilling in the pile hole. This is followed by repeated impacts to establish a solid wall before returning to normal drilling operations.

Slag Disposal: The slag is discharged through pump suction, with the central slag discharge pipe following the drilling process.

Mud Provision: Sufficient quantities of mud should be prepared prior to commencing the drilling operation. In the event of any loss or leakage of mud during drilling, it is crucial to replenish it promptly. Throughout the drilling process, it is important to constantly monitor the elevation of the mud surface to maintain optimal mud pressure within the borehole. The water level inside the borehole should be maintained at a minimum of 0.5m above the bottom of the casing or 1.5-2.0m above the groundwater level. Regular testing of the mud should be conducted during drilling, with attention given to any geological changes. Additionally, the mud density must be adjusted according to the geological conditions, and a sand separator must be utilized to ensure appropriate sand content in the mud.

Logging Drilling Operations: Throughout the drilling process, the vertical alignment should be verified, and comprehensive drilling records should be maintained at intervals of every 2-3 meters drilled. The records should encompass various parameters including the borehole position, elevation of the borehole entrance, commencement time of drilling, drilling speed, total drilling depth, mud density, and a detailed description of the geological conditions. During the construction phase of drilling, site technical personnel are responsible for meticulously documenting the drilling process, slag samples, and concrete pouring, and capturing image data for subsequent classification and organization by the quality inspection department, before timely archiving.

Hole Formation Inspection: It is essential to utilize a borehole inspection tool during the drilling process to thoroughly assess the borehole. The borehole inspection tool is constructed using a steel cage, with an outer diameter identical to the designated aperture and a length ranging from 4-6 times the designated aperture. It is imperative to conduct diameter assessments of the borehole at both intermediate and final stages, as per the specified guidelines. Suitable instruments should be employed to promptly evaluate the central position, diameter, depth, inclination, and additional parameters of the final borehole.

(2) II sequence pile drilling hole formation

After the completion of the I sequence pile driving process and meeting the design strength requirements, the drilling and holing process for the II sequence pile is initiated. For specific construction techniques, refer to the content "(1) I sequence pile drilling hole formation."

Following the completion of the drilling and holing for the II sequence pile, it is essential to remove the mudskin between the concrete surfaces of the adjacent I sequence piles, ensuring a secure connection between the fresh concrete of the II sequence pile and the existing concrete of the I sequence pile. To guarantee thorough removal of the mudskin, a "directional cleaning device for mudskin on pile holes" has been developed and studied.

The specific cleaning method is as follows: The mudskin cleaning device is fabricated in the workshop using existing reinforcement to create a framework reinforcement cage, with a diameter 20-30cm smaller than the interlocking pile diameter. High-pressure water spray nozzles are installed for diffusion and are mounted on multiple water pipes, which are equipped with water supply pipes and pumps. An 25-ton crane is lowered to the bottom of the hole and is kept suspended. The orientation of the mudskin cleaning device is adjusted according to the direction of the interlocking pile, aligning the high-pressure water spray nozzles with the side of the already installed I sequence piles. The position is secured using the limit plate at the top of the steel casing. The water pump is activated for high-pressure water spraying cleaning. The crane lifting mechanism is used to move up and down 3-4 times to ensure thorough mudskin cleaning, with a lifting speed of approximately 0.2m/s. Simultaneously, water is pumped out from the pile hole to maintain the water level 0.5m above the bottom of the casing or 1.5-2.0m above the groundwater level.

5 conclusions

Through research on the design and construction of the support structure for a 14-meter-deep foundation pit in the complex geological and hydrological conditions of a bridge, the following conclusions have been reached:

(1) In the presence of intricate geological conditions, particularly in deep excavation projects involving substantial rock layers, the utilization of impact drilling for hole formation in conjunction with an interlocking pile scheme proves advantageous in managing deformation, enhancing water-stopping effectiveness, ensuring structural safety, and controlling costs efficiently.

(2) Coordinating the construction of multiple drilling equipment within confined spaces necessitates meticulous pre-planning and real-time adjustments, a critical factor in enhancing construction efficiency.

(3) In geological contexts featuring sandstone layers, the application of mud sand separators represents a critical strategy for enhancing drilling efficiency and diminishing the time required for cleaning holes.

(4) In the construction phase, optimizing the sequence of pile driving and promptly cleaning the mud skin at the base of the piles is crucial to ensuring the stability of the support structure and the effectiveness of water-stopping measures.

While the general conclusions mentioned earlier have been validated in specific instances, the complexity and uncertainty of geological conditions necessitate further verification and enhancement of these conclusions in practical engineering projects. Subsequent research should emphasize the adaptability and optimization of these technical solutions in diverse environments and engineering conditions, while also exploring support structure design methods that are more environmentally friendly, cost-effective, and efficient.

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