Case Study on Advanced Hoisting, Positioning, and Control Techniques for Non-Standard Pier Construction in the Quanli-Dongfeng Viaduct Project

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Abstract. This study, reliant on practical projects, conducts an in-depth analysis of key technologies amid the construction of prefabricated viaducts. The primary focus is on the integrated hoisting, positioning, and control techniques for the bridge abutments and pier columns, culminating in a proposal of an innovative integrated and prefabricated construction approach. This approach optimizes the construction process and methods by factoring in the structural characteristics of different types of pier columns and addressing construction challenges. Simultaneously, it underscores the significance of material selection, prefabricated component design, and innovative construction techniques. The study also explores on-site management and quality control strategies to ensure the efficiency and safety of the construction process. The research indicates that this approach significantly improves construction efficiency, reduces safety risks, and solidly guarantees structural quality. These findings offer crucial theoretical and practical guidance for advancing the industrialization, modularization, and innovative development of construction techniques in bridge construction. They contribute to the continual optimization of technical innovation and engineering practices in the field of bridge construction.

1. Introduction

The accelerated pace of urbanization has heightened the demands for infrastructure development. Traditional cast-in-place construction struggles to meet the contemporary requirements for high quality, efficiency, low pollution, and minimal environmental impact. In this context, rapid prefabrication and assembly technologies have emerged as a satisfactory solution [1-3], gradually becoming a focal point of research.

Bridge construction stands as a crucial application scenario for prefabricated construction technology, offering significant advantages in reducing traffic disturbances, ensuring construction quality, and expediting construction speed [4]. Multitudinous scholars globally have undertaken research from various perspectives to maximize the advantages of prefabricated construction technology in bridge development. Addressing the substructure of prefabricated bridges, Billington et al. [5] detailed construction processes and employed a non-bonded prestressing method to connect segments. The findings revealed that this approach accelerates bridge construction and enhances durability. In a comparative study of design systems, Kim [6] examined the Korean highway bridge specifications and the load and resistance factor design, concluding that the latter can reduce construction costs by 9%. Several scholars have conducted research on the load-bearing capacity and seismic performance of pier columns. Wu et al. [7], using Ucfyber, investigated the mechanical performance of prefabricated bridge piers with a slot structure, discovering that the slot structure effectively transmits loads. Xin et al. [8] proposed a construction-friendly Ultra-High Performance Concrete (UHPC) pier perimeter connection for prefabricated bridge pier structures. Through a mechanical performance analysis, they found that this structure exhibits seismic performance similar to cast-in-place specimens but with added advantages in terms of ductility. Addressing operations such as hoisting and transporting prefabricated components, Zheng [9], based on the construction of the Shanghai Jiamin Viaduct, summarized the construction process of prefabricated column installation in prefabricated viaducts. Guo et al. [10] analyzed the advantages of precast installation technology for columns and piers, outlining key considerations in the construction process.

While there is currently a considerable amount of research on prefabricated construction technology, it tends to be oriented toward the construction process, with limited focus on the preparation and transportation assurance of prefabricated components. Moreover, research on pier columns often revolves around conventional forms, with less attention given to non-

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standard pier column reinforcement, which poses higher construction risks and warrants special consideration. In light of this, to mitigate safety risks associated with non-standard pier column reinforcement construction, reduce deviations in the on-site installation of steel frameworks, and minimize discrepancies in the spacing of main and stirrup reinforcements, this paper, in conjunction with a peripheral supporting infrastructure construction project, conducts research on the prefabricated construction of bridge piers from both the aspects of prefabricated design and construction technology. The aim is to enhance construction efficiency, minimize risks, and reduce costs.

2. Project Overview and Scheme Selection

2.1. Project overview

This research proceeds with the case study of a project that spans from the intersection of Quanli Second Road and Dongfeng Avenue in the north to the junction of Zhushanhu North and South Roads along the Quanli Third Road. The total length of the viaduct is 1678.5 m, comprising three main types of piers: portal piers (including crossbeams), slab piers, and column piers, totaling 112 in number. The pier shapes include curved sections, straight sections, and column-to-crossbeam configurations. The maximum pier height reaches 18.233 m, and the pier columns are characterized by significant elevation differences, predominantly featuring non-standard designs. Pier column construction primarily takes place in the center of the existing roadway, occupying a construction zone with a width of 14 m.

2.2. Scheme selection

The construction of bridge piers can follow different methods, each with distinct characteristics. Among them, the traditional method of bridge pier construction, characterized by on-site manual labor and conventional formwork, has stood the test of time and is renowned for its adaptability to variable on-site conditions. However, it is associated with a more extended construction period and higher labor intensity. Prefabricated assembly technology represents a modern construction approach, where major components are manufactured outside the site and assembled on-site. Due to its high efficiency, minimal environmental impact, and superior construction quality, this method has found frequent utilization in recent years. The advantages and disadvantages of the two schemes are outlined in Table 1.

Table 1. Comparison of the two schemes

Criterion	Traditional construction	Prefabricated assembly
Maturity	Long-standing history and wide applications	Emerging technology and progressive popularity in recent years
Applicability	Adaptability to diverse on-site conditions	Adaptability to most terrains and structural forms
Construction period	Longer (e.g., nine days)	Significantly shorter (e.g., three days)
Quality control	Affected by on-site conditions	Enhanced through factory-level precision
Labor intensity	Higher (requires significant manual labor)	Lower (reduces on-site work)
Safety risk	Higher (requires more on-site safety measures)	Lower (controllable under factory conditions)
Environmental impact	Increased (due to prolonged construction activity)	Reduced (minimized on-site disruptions)
Cost-effectiveness	Dependent on extended time	Higher (due to reduced construction time and labor)

Albeit with the immaturity of prefabricated assembly technology in the construction of bridge piers, its advantages in terms of efficiency, safety, and environmental impact are notable. Therefore, this project opts for prefabricated assembly technology.

3. Key Technologies

3.1. Prefabricated design

In the field of precast bridge construction, the quality of prefabricated design holds immense significance. It not only serves as the key to project success but also forms the cornerstone for efficiency, cost control, and structural integrity. Excellent prefabricated design ensures that the project is completed on time and within budget while guaranteeing construction quality and safety. Conversely, subpar design can lead to cost and time overruns, quality issues, and safety risks, thereby negatively impacting the entire project. Hence, thoughtful and meticulous assembly design is crucial for achieving efficient, economical, and safe construction. It necessitates interconnected aspects such as the prefabrication of the reinforcement cage for the pier cap, the framework design for the reinforcement cage of pier columns, the design of the hoisting-resistant framework, and formwork design and adjustment.

3.1.1. Prefabrication of reinforcement cage for the pier cap

The precise prefabrication and assembly of the reinforcement cage for the pier cap are crucial steps in ensuring the overall safety and stability of the structure. Firstly, during the binding process on the rear frame of the pier cap reinforcement cage, it is essential to adjust the spacing of the main reinforcement in the bottom appropriately. This adjustment ensures that the reinforcement can seamlessly coordinate with the pier head reinforcement during the hoisting process, avoiding structural weaknesses or the need for on-site adjustments due to improper reinforcement. Accurate reinforcement placement aligns with the load-bearing requirements of structural engineering, ensuring the stability and safety of the pier cap under load. Secondly, welding is applied to connect the bottom's main reinforcements in longitudinal and transverse directions, forming an integral structure that enhances stability in vibrating environments. Additional support is provided by reinforcing the lateral faces with two diameter-28 steel bars arranged in an X-shaped configuration, reinforcing the structure against lateral forces. Lastly, two H20 steel beams are placed at 1/4 of the width of the pier cap reinforcement cage on both sides, serving as bracing frameworks. These bracing frameworks are welded onto the bottom's main reinforcements of the pier cap, with hoisting points positioned at 1/4 of the width on either side of the H20 steel beams. Precise prefabrication and assembly of the reinforcement cage for the bearing platform reduce the need for on-site construction, thereby shortening overall construction time. Additionally, this method lowers the demand for on-site labor and reduces safety risks, enhancing work efficiency. Moreover, the method facilitates quality control, as achieving high standards of monitoring and maintenance is easier in a factory environment. It also significantly reduces rework and delays due to quality issues compared to on-site construction.

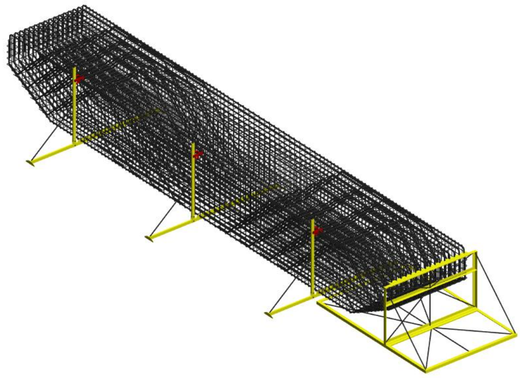
3.1.2. Prefabrication of the reinforcement cage framework for the pier column

The framework of the reinforcement cage for the pier column is depicted in Figure 1, and its precise construction is directly linked to the stability and safety of the structure. First and foremost, the assembly of the reinforcement cage framework must ensure that the pier column possesses sufficient load-bearing capacity and stability. In this phase, it is imperative to carefully select the appropriate types and quantities of steel reinforcement in strict accordance with design requirements and organize them into the designated structural framework.

During the precision construction process, specialized positioning and shaping formworks are strategically placed at the four corners of the reinforcement cage framework to ensure the accurate positioning of the steel reinforcement during construction. These formworks secure the main reinforcements, ensuring their precise alignment and orientation as per the design drawings, thereby effectively preventing deviations during construction.

Fixed braces are strategically placed at intervals of 1.5 meters to facilitate the stability of the structure. These braces primarily serve to prevent deformation of the reinforcement cage during the construction process, especially during the concrete pouring phase, caused by gravity or external forces. The design of the braces must consider the specific dimensions and weight of the steel reinforcement cage to provide ample support.

Finally, the shaping templates are secured to the fixed braces, marking a critical step in forming a stable steel reinforcement cage. The stability and accuracy of the reinforcement cage are ensured through meticulous operations throughout the construction process, laying a solid foundation for the subsequent concrete pouring work. This process not only significantly improves construction precision but also dramatically enhances the overall safety of the structure.



(a)Model diagram of the reinforcement cage of the pier column

(b)Schematic diagram of the reinforcement cage of the pier column

Figure 1. Framework for the reinforcement cage of the pier column

3.1.3. Design of hoisting-resistant framework and fixing devices

The rational and precise design of the reinforcement cage framework for the pier column ensures the structure's linear accuracy and forms the foundation for the overall design's accuracy and safety. Building upon the previous discussion, we delve into the design of the hoisting-resistant framework and fixing devices.

To commence with, a standard cross-sectional diagram of the reinforcement cage for the pier column is drafted on a leveled site before fabrication. This serves as a reliable reference for the hoisting-resistant framework, ensuring precise alignment and dimensional accuracy in subsequent tasks. By comparing with the diagram, technicians can verify the dimensions of the hoisting-resistant framework, guaranteeing that all details conform to the design requirements.

Upon confirmation of the dimensions, the 10-type square steel hoops are welded inside the main reinforcement of the reinforcement cage. Hoisting-resistant frameworks are strategically placed every 2 meters to enhance the stability of the structure, preventing deformations engendered by material weight or external forces during construction. The schematic diagram of the hoisting-resistant framework for the reinforcement cage is illustrated in Figure 2.

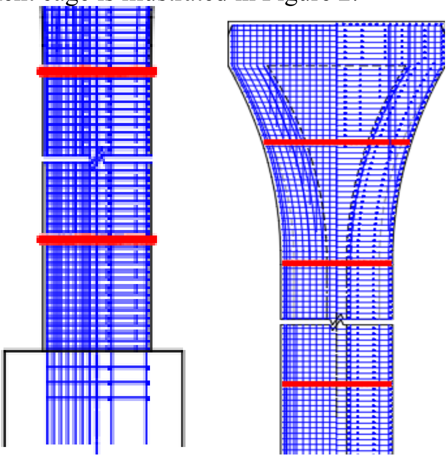


Figure 2. Schematic diagram of the hoisting-resistant framework for the reinforcement cage

In alignment with the principles of structural mechanics, the hoisting points in the reinforcement framework for the pier column are meticulously selected. These hoisting points are positioned at 1/6 to 1/5 of the length of the hoop reinforcement section and in the reinforced area of the framework. Steel rods with a diameter of 5 cm are installed at these critical locations, and four steel wires are utilized to ensure the stability and safety of the entire hoisting operation. To better disperse the load and reduce localized stress concentration during the hoisting process, the design specifies that the angle between the steel wires and the main steel reinforcement of the framework should exceed 60°. The specific details are illustrated in Figure 3.

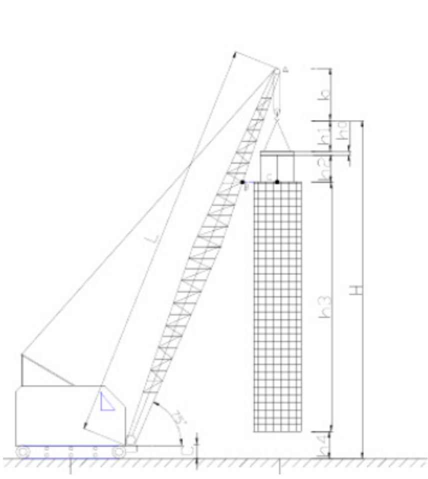


Figure 3. Schematic diagram of the hoisting operation for the reinforcement cage

Finally, support points are established by extending the main reinforcement to arrange the fixing devices for the reinforcement cage of the pier column. This decision factors in the load distribution and stability. C28 reinforcements are positioned at the bottom to provide both three-dimensional stability for the reinforcement cage and uniform, reliable support for the entire structure on the pier cap layer. The fixing device for the bottom support is illustrated in Figure 4.

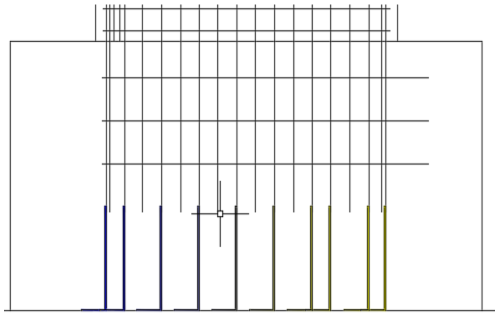


Figure 4. Fixing device for the bottom support of the reinforcement cage for the pier column

3.1.4. Formwork design and adjustment

In the construction of prefabricated bridge piers, the precision of formwork design and adjustment is crucial. This study adopts standardized large reinforcement formwork, known for its high strength and excellent wear resistance, capable of withstanding high pressure during concrete pouring. Simultaneously, its reusability provides the potential for reducing long-term costs. The back of the formwork is designed with flanges to enhance its stiffness, effectively preventing bending or deformation during the concrete pouring process. Moreover, the formwork is connected using M16 bolts and φ20 tie rods, ensuring the overall stability of the structure and allowing precise alignment of various components. This connection method proves reliable and facilitates ease of assembly and disassembly, meeting the requirements of construction efficiency and cost-effectiveness.

The primary purpose of formwork adjustment is to ensure the precise installation of the formwork, with a key focus on the application of geometric measurement principles. By employing principles from geometric measurement, the exact position and orientation of the formwork can be accurately determined. When measuring angles using a reflector prism, the angle (θ) between the formwork and the baseline can be calculated using the formula, $\theta = tan^{-1}(\frac{\text{opposite side length}}{\text{adjacent side length}})$. Additionally, the Pythagorean theorem ($(d = \sqrt{a^2 + b^2})$) is utilized to calculate the straight-line distance from the formwork vertex to the reference point. The application of geometric measurement guarantees the accuracy of formwork installation, reducing the likelihood of structural defects and enhancing the overall quality of the construction project.

Due to the elevated location and narrow construction space of the formwork, traditional measurement methods pose safety risks. Therefore, a novel dual 360° prism measurement device is introduced, as depicted in Figure 5. Prisms have the capability to reflect light or laser beams in any direction, enabling measurements from multiple angles without the need to physically move the prism. The prism is connected to the device's base through a measuring rod, allowing precise positioning of the prism. The measuring rod is equipped with scales or markings for additional assistance in measurements. The base of the device is embedded with a strong magnet, ensuring a secure attachment to steel structural formworks. This eliminates the need for drilling or welding, allowing for easy mobility and repositioning during construction as needed. A total station or similar measuring instrument sends a laser beam to the prism in practical operation. The prism accurately reflects the laser beam back to the instrument. This enables measurement personnel to determine the exact position of the formwork, facilitating adjustments to ensure strict alignment with the design specifications. The design of the strong magnet base ensures stability during measurements and provides flexibility for quick repositioning as construction progresses. This flexibility is crucial for ensuring construction quality and the accuracy of the bridge pier's structure.

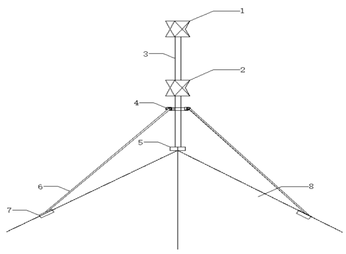


Figure 5. Schematic diagram of the measuring and positioning device for the bridge pier formwork

The quality of concrete structures can be ensured through precise formwork design and adjustment, mitigating subsequent quality issues and maintenance costs. Rational formwork design and an efficient adjustment process shorten the construction period, enhancing the overall construction efficiency of the project. Albeit with relatively high initial investment, the repeated use of formwork and the reduction in maintenance costs align with the principles of cost-benefit analysis in the long run, thereby improving the economic viability of the project.

3.2. Construction technology

A standardized process is crucial in the construction operations of prefabricated elevated bridges, as illustrated in Figure 6. Starting from the pre-processing stage, this process not only ensures project quality and construction safety but also effectively enhances construction efficiency and cost control. It represents a significant practice in modern engineering construction.

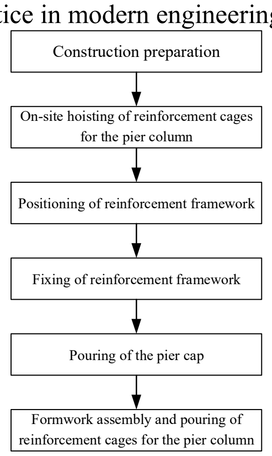
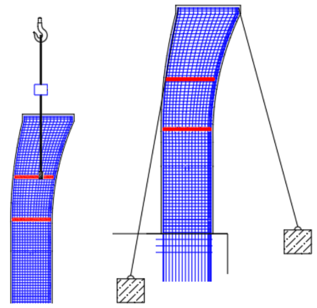


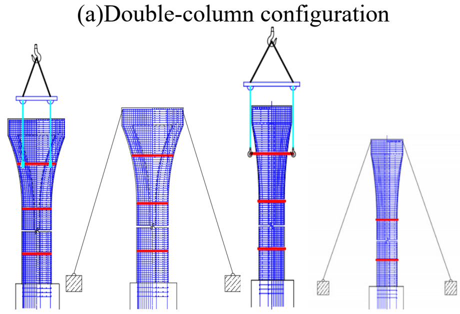
Figure 6. Construction process

During the construction preparation phase, the rear area undertakes the pre-processing work of the pier cap and pier column reinforcement to ensure material quality and processing precision. For on-site hoisting of the pier cap reinforcement, markings indicating the lifting positions for pier columns are pre-reserved on the top surface, ensuring accurate alignment in subsequent processes. Various anchor points are pre-set with cable wind ropes in place to enhance hoisting safety. The construction site has ample road access and water/electricity supply to support smooth construction operations. Design drawings undergo meticulous review, and the accurate identification of key embedded component locations ensures an efficient and precise construction process.

After completing the preparatory work, the hoisting operation, as a crucial aspect of the project, showcases the technical precision and efficiency of the construction process. Figure 7 illustrates a schematic diagram of the hoisting operation for the reinforcement cage. Upon the arrival of the reinforcement cage for the pier column at the site, it is positioned within the operating range of a mobile crane. The hoisting operation is carried out in a coordinated manner between the main and auxiliary hoists, enhancing the safety and controllability of the operation. Critical steps in the hoisting process include measurement and setting of hoisting points. Measurement personnel first verify the pier cap formwork and then mark the corner points of the reinforcement cage for the pier column on the surface of the pier cap reinforcement. Technicians precisely design the positioning of the stirrups based on the design drawings to ensure they accurately fit around the main reinforcement of the pier column. Construction workers then weld the positioned stirrups onto the surface of the pier cap reinforcement according to the layout markings. Regarding the setting of hoisting points, for a single square reinforcement cage for a pier column (weighing approximately 8.8 tons, with a pier height ≤10m), a 25-ton mobile crane is used for the overall hoisting. The double-point hoisting method is employed, providing better balance for the load and ensuring the stability and safety of the rebar cage during the hoisting process. This method, particularly effective when hoisting large or irregularly shaped objects, exemplifies the superiority of a well-coordinated and methodical approach in construction operations. By streamlining the hoisting process through meticulous planning and execution, this method not only enhances safety and precision but also significantly boosts the project's efficiency. It achieves this by reducing labor hours, minimizing the risk of errors, and ensuring a smoother and more consistent construction timeline, thereby embodying the ideal blend of technical excellence and operational efficiency.



(a)Double-column configuration



(b)Single-column configuration

Figure 7. Schematic diagram of the double-column reinforcement cage hoisting for the bridge pier

After installing the reinforcement framework, it undergoes strict adjustments until it is vertically aligned. Four steel cables fixed to the ground with stakes are employed to ensure that the alignment angle does not exceed 45° from the horizontal plane. A professional measurement team monitors the entire process, utilizing cross-direction measurements to ensure accuracy. Alignment is achieved through fine-tuning the crane and adjusting the tension of the cables. Verticality is initially corrected using the hanging plumb-bob method and then fine-tuned with a total station to ensure that the installation deviation of the pier column reinforcement is within the range of ±1 cm, contributing to the precision of subsequent construction stages.

After the accurate placement of the pier column reinforcement framework, a rigorous re-measurement of the planar position, verticality, and elevation is conducted to comply with design specifications. Once precision is ensured, support points are set in the reserved reinforcement section of the pier cap, maintaining a 1/3 ratio to the main reinforcement. Finally, the reinforcement framework is precisely welded to the pier cap to enhance the structural stability.

Before pouring the pier cap, a thorough inspection of the formwork reinforcement and the embedded pier column reinforcement is carried out to ensure the readiness of concrete pouring materials and mechanical equipment. The pier cap is cast in a single pour, proceeding during moments of lower temperatures to reduce temperature loads caused by hydration heat. Low to medium heat cement, fly ash, and water-reducing agents are incorporated into the concrete to optimize its performance.

During concrete pouring, a method of multi-point material distribution and horizontally layered casting is employed, with strict control to keep the layer thickness within 30 cm. When the thickness of the pier cap exceeds 2 m, tremie pipes are arranged at pouring points to limit the occurrence of segregation. Subsequently, deep compaction is performed using vibrating rods to ensure concrete density. Throughout the pouring process, continuous inspections proceed on the secure connection of formwork bolts to prevent shifting.

Elevation control points are set along the formwork edges, and elevation control reinforcements are arranged in a herringbone pattern at 3-meter intervals on the reinforcement framework. This facilitates leveling using the elevation points when constructing up to the concrete surface. Once the pier cap concrete reaches a strength of over 2.5 MPa, the formwork is dismantled. After removal, the surface concrete residue is cleaned, and manual bush hammering is performed within the pier body area.

The installation of the pier column formwork involves the assistance of a mobile crane. Prior to installation, the formwork is ground and coated with a demolding agent to ensure smooth demolding. A string line method is used for alignment during formwork assembly, and a plumb bob controls the verticality to ensure tight joints between adjacent formwork panels. Double-sided tape is used to prevent slurry leakage. The formwork is adjusted to the designed dimensions of the pier column, and after measurement and verification, reinforcing bolts and tie rods are tightened to ensure the stability of the formwork. Before concrete pouring, a comprehensive inspection of the supports, formwork, and reinforcement is carried out, with proper documentation, to ensure compliance with design requirements. Pouring can only proceed after a successful inspection. For pier columns exceeding 11 m in height, a two-stage pouring process is adopted, pouring half in the first stage and completing the second stage, ensuring that joints are bush-hammered and adequately watered to prevent standing water. The slump of the concrete is controlled at 160 to 180 mm, and pumping is employed. Concrete is discharged through chutes inside the steel forms to prevent segregation. Layered compaction is achieved using inserted vibrating rods to ensure concrete compaction. Throughout the concrete pouring process, special attention is paid to the connection of formwork bolts to prevent shifting.

4. Conclusion

This study demonstrates that the construction technology of viaducts offers significant advantages in enhancing construction efficiency and ensuring structural safety and quality. Notably, in the realm of overall hoisting, positioning, and control technology, optimization of construction schemes and processes not only accelerates construction progress but also reduces safety risks during construction. Moreover, this research provides valuable insights into new construction technologies for the field of bridge engineering, contributing to the advancement of bridge construction practices, especially in the application of industrialization and standardization. Future efforts to further explore and refine the construction technology of prefabricated viaducts will contribute to the advancement of industrialization in construction, fostering the sustainable development of

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the construction industry. However, this study still requires a deeper investigation into the specific operational details of implementing new technologies, such as their adaptability in various geographical and environmental conditions. Future research could focus on the application and efficacy of these technologies in diverse construction environments. Moreover, this study has not fully explored the long-term durability and maintenance requirements of these technologies, which is an important aspect for future research to further examine. Finally, considering the rapid development in the construction industry, exploring how to integrate these advanced technologies with emerging technologies like artificial intelligence and the Internet of Things will be a crucial direction for future research in bridge engineering technology.

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