Research on Construction Technology of 30m Precast T-Beam Assembly Line in Smart Girder Fabrication Yard

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Abstract. With the continuous development of bridge construction in the direction of rapid speed, high quality and environmental protection, prefabrication technology has become the mainstream trend of bridge engineering development. Based on the prefabricated T-beam construction of the smart girder fabrication yard of the Hangzhou-Shaoxing-Ningbo Expressway Project, it was proposed a "mobile pedestal + hydraulic formwork+ steam curing + two-stage tensioning" assembly line construction process. Advanced technologies such as intelligent mobile pedestal, fully-enclosed high-temperature steam curing and Building Information Modeling were utilized to achieve the intelligence of T-beam prefabrication production through smart equipment, standardized process and intelligent management. The result demonstrates that the new technology of prefabricated assembly line construction significantly reduces the production cycle and enhances the quality of prefabrication when compared to traditional construction methods.

Keywords: precast T-beam; smart girder fabrication yard; mobile pedestal; steam curing; assembly line construction.

1 Introduction

Bridge engineering is rapidly advancing towards high quality, efficiency, and standardization. Prefabrication, as an energy-saving and cost-effective construction technique, has gained increasing popularity. The rapid development of the new generation of information technology has further propelled prefabrication techniques into the era of intelligence [1-2]. Reinforcement and formwork construction, as crucial aspects of quality control in the prefabrication process [3-5], have attracted growing attention due to the importance of their precision, efficiency and convenience. Researchers[6-8] have conducted standardized design research on the reinforcement cage moulding frame and the formwork of prefabricated components, providing key precision control parameters and improving the accuracy of reinforcement and formwork construction. Wu[9] proposed a prefabricated T-beam with a self-propelled hydraulic formwork

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that allows flexible formwork installation and removal through walking wheels. Zhang[10] introduced a movable baseplate formwork, which offers easier installation and significantly increases construction speed compared to traditional fixed baseplate formwork. Wu[11] proposed a "1+N+1" intelligent beam yard system design framework for the smart management of prefabricated beam yards, which includes one beam yard information management platform, N beam yard intelligent subsystems, and one beam yard analysis and decision-making platform. Liu[12], taking the Shenzhen-Zhongshan Channel project as an example, introduced automated reinforcement processing, hydraulic integral movable formwork with fixed bottom formwork, intelligent concrete conveying center, and beam yard collaborative management platform, promoting the intelligent development of bridge prefabrication and assembly technology.

This paper is based on the construction of a 30m prefabricated T-beam assembly line at the intelligent beam yard on the Hangzhou-Shaoxing-Ningbo Expressway. It introduces a new "mobile baseplate + hydraulic formwork + steam curing + two-stage prestressing" assembly line prefabrication process by incorporating intelligent mechanical equipment, standardized construction processes, and mathematical production management, which has achieved significant economic and social benefits.

2 Project Overview

The Hangzhou-Shaoxing section of the Hangzhou-Shaoxing-Ningbo Expressway, starts near Nanyang Hongshan Village on the Hangzhou Ring Road (G104 National Highway) and ends at the junction of Shangyu and Yuyao. It has a total length of approximately 52.7 km. The main line consists mainly of elevated bridges, with a bridge length of 48.4 km, accounting for 96.4% of the total. Among them, the prefabrication yard is located in the Hangzhou Bay Industrial Park in Shangyu District, covering a total area of 700 acres. It is equipped with 33 intelligent production lines, with a total of over 17,000 prefabricated beams and slabs.

The intelligent beam yard of this project adopts a factory-like assembly line production mode. It applies advanced technologies such as intelligent mobile baseplates, hydraulic formwork control systems, and fully enclosed high-temperature steam curing. Production, monitoring, and management of prefabricated components are carried out through an information command center and a BIM-based digital management platform.

3 Smart Beam Yard Assembly Line for Prefabricated T-Beams

The intelligent beam yard achieves the automation of machinery and equipment, standardization of construction processes, and smartification of management decisions through the implementation of systems such as digital intelligent construction, material acceptance control, and intelligent monitoring.

4 Intelligent Construction Equipment for the Entire Process of Prefabricated Beams

(1)Intelligent Mobile Baseplate: It consists of a bottom mold formwork, longitudinal moving main beams, wheel sets, arch support blocks, anti-overturning braces, and others (Figure 1). The intelligent control system allows the longitudinal movement between functional zones on the production line, such as the concrete pouring area, curing area, prestressing and repair area, and lifting area. After lifting, the mobile baseplate returns to the beam production area by a gantry crane, enabling continuous production.

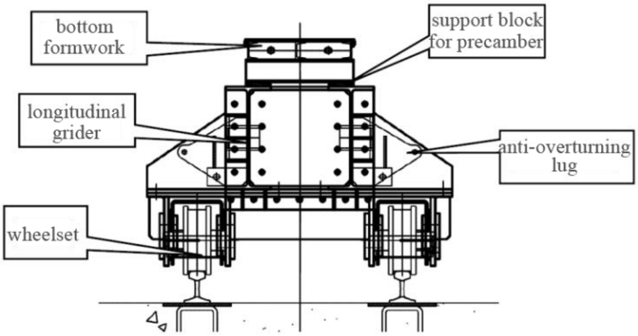


Fig. 1. Cross-section of the mobile baseplate for T-beams.

(2) Intelligent Formwork Control System: It consists of a central control system, side formwork sub-control system, hydraulic system, sensors, and wiring system, with a wireless human-machine interface. By precisely controlling the oil cylinders on both sides of the formwork, it automatically performs demolding, formwork closure, and separation of the beam mold. The system also has individual oil cylinder inching functions.

(3) Intelligent Reinforcement Processing System: This includes CNC steel straightening machines, CNC steel bending machines, CNC automatic steel truss production lines, and CNC steel mesh welding production lines, which achieve automatic production of reinforcement tasks, optimization of cutting schemes and lengths, and management of semi-finished and waste materials.

(4) Intelligent Steam Curing System: Based on automation control and wireless sensing technology, it effectively provides thermal insulation and moisture retention for prefabricated beams. The system uses real-time temperature and humidity data sensing and intelligent identification to control and improve the curing environment.

4.1 Standardized Process and Fixture Design for Prefabricated Beams

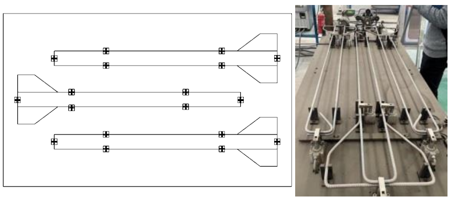
(1) Production of universal fixtures for prefabricated beams. Standardized designs and construction are applied to the reinforcement skeleton, formwork, and baseplate of the prefabricated T-beams (Figures 2 and 3). Uniform construction modules and basic standards are established, including module coordination, tolerances and fits, and connections.

(2) Standardized construction process for prefabricated beams. The template is controlled by a programmable logic controller (PLC). During the concrete pouring process, the hydraulic automatic control system and infrared temperature and distance measurement system enable automatic lateral and longitudinal movement of the external formwork and automatic support removal of the internal formwork. Based on experimental data analysis, control parameters for steam curing and two-stage prestressing of the beam and slab are established. Quality and safety control measures are implemented during the movement of the steel baseplate to ensure overall beam quality and operational safety.

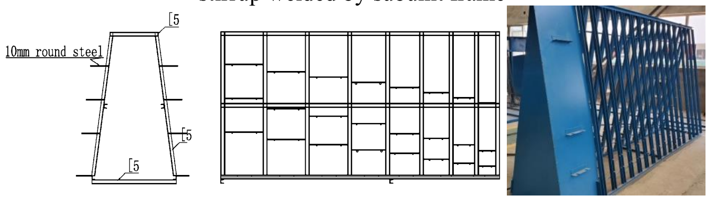
4.2 Intelligent Production Line Management for Prefabricated Beams

(1) Information Command Center: The production line of prefabricated components is visually displayed through the Internet, cloud computing, and information technology in the form of images, charts, and other forms. Real-time monitoring data of equipment is analyzed and correlated to identify various issues and unexpected situations on the production site. Data analysis charts support production line planning and output value statistics. Video surveillance records the implementation status on-site and allows for targeted instructions.

(2) Digital Management Platform: Utilizing BIM technology, the models of fixtures, equipment, and semi-finished components are accurately positioned and mapped to the physical structures of the actual prefabricated beam yard. Production data is connected and associated with baseplates, processes, and equipment models. Ultimately, a three-dimensional visualization of the prefabricated beam yard is achieved, enabling real-time viewing of on-site data. The collected and analyzed data is used for production management, linking and coordinating with construction progress, and providing visual supervision to dynamically monitor the progress of prefabricated beam production on-site.

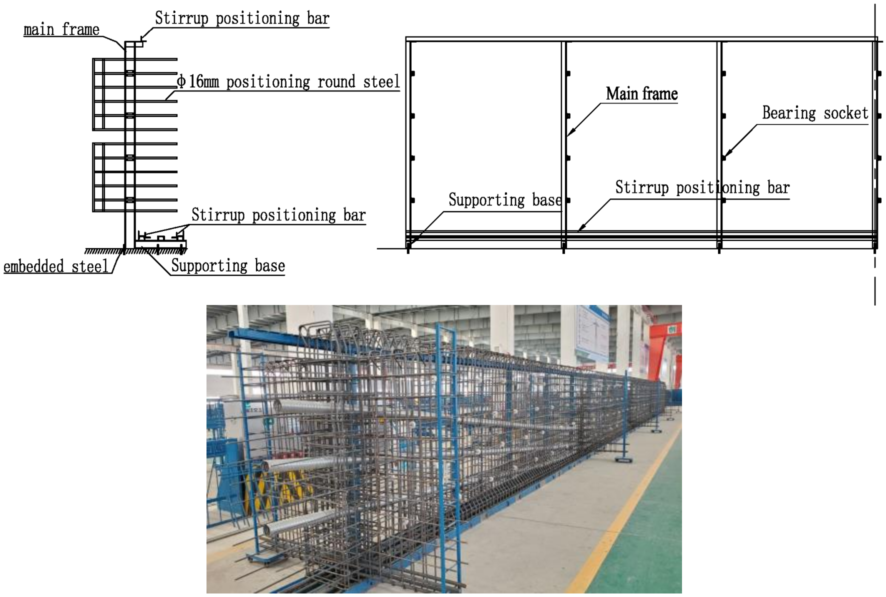


stirrup welded by subunit frame

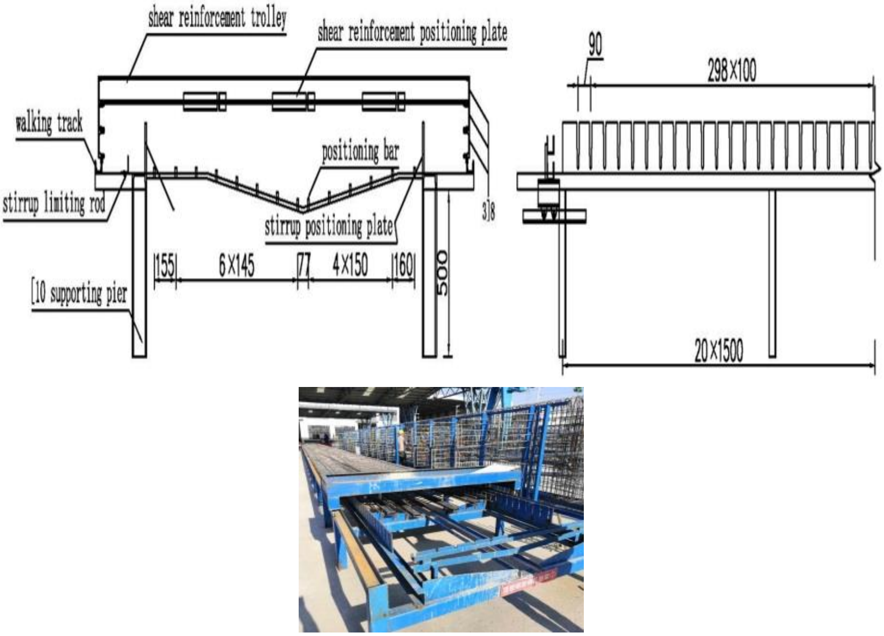


positioning steels for pre-stressed corrugated pipe welded by subunit frame

(*a*) subunit reinforcement moulding frames



T-beam web reinforcement skeleton tying by unit frame



T-beam top-flange reinforcement skeleton tying by unit frame

(*b*) unit reinforcement moulding frames

Fig. 2. Reinforcement moulding frame of the 30m prefabricated T-beam.

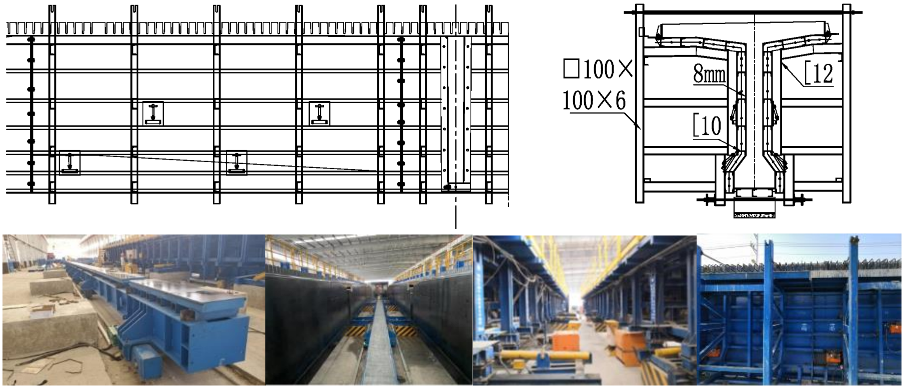


Fig. 3. Formwork of the 30m prefabricated T-beam.

5 Construction Process of the Prefabricated T-Beams

A new "mobile baseplate + hydraulic formwork + steam curing + two-stage prestressing" assembly line prefabrication process is employed for the production of T-beams. The production line consists of four main fixed operation areas: reinforcement binding, concrete pouring, steam curing, and initial prestressing. The main procedures include: using an intelligent control system to move the mobile baseplate to the pouring area, employing fixed hydraulic formwork for the side mold, conducting concrete pouring, and performing initial prestressing using an intelligent steam curing system after the concrete component reaches a strength of 70% or more of the design strength. This enables the T-beam to bear its own weight and impact loads during lifting and transportation. Afterward, the beam is transported to the beam storage area and undergoes full prestressing according to design specifications once the concrete strength, modulus, and age reach the required standards. Finally, grouting is performed in the ducts, and the ends are sealed.

5.1 Fine Production of Reinforcement Skeleton

The reinforcement skeleton is produced through modularization of the reinforcement cage, unitization of the reinforcement frame, and standardized design and fabrication. The reinforcement frame is divided into unit frames and subunit frames. Welding operations are conducted on the subunit frames, while reinforcement binding is performed on the unit frames. The frames are progressively installed and assembled to form the reinforcement skeleton.

(1) Reinforcement Welding by the Subunit Moulding Frames. The main plate reinforcement, stirrups, corrugated pipe positioning bars, and top plate reinforcement are manually or robotically welded on the subunit frames.

(2) Reinforcement Binding by the Unit Moulding Frames. Longitudinal reinforcement, stirrups, and vertical reinforcement for the main plate are placed using positioning slots on the unit frames for the main plate reinforcement. Horizontal partition plate reinforcement is placed on the unit frames for the transverse partition plate reinforcement. On the unit frames for the top plate reinforcement, top plate stirrups are placed along the two sides in transverse positioning slots, and top plate longitudinal reinforcement is placed along the front and rear vertical positioning slots of the frame. Shear reinforcement is arranged using embedded shear reinforcement bars. The reinforcement is bound to form the reinforcement skeleton.

5.2 Assembly of Mobile Baseplate and Bottom Mold

(1) Construction of baseplate track foundation. The excavation of the baseplate track foundation is carried out, and limit bolts are embedded. Then, the baseplate foundation is cast, and timely curing is done by covering and watering. After reaching the design strength, steel rails are laid, and the track surface is cast.

(2) Assembly of mobile baseplate and bottom formwork system. The baseplate wheel sets are placed in sections on the track, with the motorized wheel sets symmetrically arranged. The verticality between the control and the steel rail is controlled. The main beam of the baseplate is lifted, and the spacing between the wheel sets is adjusted during translation. The main beam's centerline is aligned and straight and the connecting bolts are tightened symmetrically and then welded for reinforcement. The bottom mold template is assembled on the main beam, and arch adjustment is carried out using pads.

5.3 Installation and Removal of Hydraulic Formwork

Installation of Side and End Formwork.

(1) Lateral installation of hydraulic side formwork. The main plate reinforcement skeleton is lifted above the bottom mold using a gantry crane. The bottom mold with the mobile baseplate is moved to the concrete pouring area. The hydraulic cylinders are used to fix the lateral movement of the side formwork, controlling the stroke of the cylinders, as shown in Figure 4(a). Careful attention is given to observe whether there is any sticking, until the de-molding process is complete.

(2) Longitudinal installation of end formwork. The H-beam of the end formwork is connected to the intermediate side formwork to form a whole and serves as the sliding track. Hydraulic jacks are bolted to the end formwork truss, and the end formwork is longitudinally slid using hydraulic cylinders, as shown in Figure 4(b). The top plate reinforcement skeleton is lifted as a whole and aligned. The template is measured and finely adjusted, connecting tie rods, and checking the joints between the template and the baseplate.

(*a*) lateral installation of hydraulic side formwork

(*b*) longitudinal installation of end formwork

Fig. 4. Installation and removal of hydraulic formwork.

Removal of End and Side Formwork.
After concrete pouring is completed, the top is immediately covered with tarpaulin, and the mold is thermally insulated and cured. Once the concrete strength reaches the design standard, the formwork can be removed. First, the tie rods are removed, and all connecting bolts are loosened. The exposed reinforcement at the end and top plate is inspected and cleaned, and the exposed reinforcement position at the end plate and side formwork is cleaned of grout leakage. Then, the end formwork is removed by longitudinal movement using hydraulic cylinders. Once the end formwork is in place, the side formwork is removed by lateral movement. The exposed reinforcement in the transverse partition plate is checked to ensure it is completely separated from the end formwork.

5.4 Steam Curing

After de-molding, the prefabricated T-beam is moved by the mobile baseplate to a fixed steam curing shed for steam curing. An intelligent steam curing system is used to set the curing environment parameters. Based on data collection and analysis, the command center issues instructions to start or stop the corresponding steam spraying system in the curing area. Alternatively, the steam curing can be remotely operated and scheduled using a steam cloud control app according to the curing requirements. When the steam curing reaches 70% of the concrete design strength, the component is moved out of the steam curing shed using the mobile baseplate and transported to the initial prestressing area.

5.5 Two-stage Prestressing

(1) First-stage prestressing. The first-stage prestressing is performed in the initial prestressing area to enable the T-beam to bear its self-weight and impact loads during lifting and transportation. The prestressing is carried out symmetrically from both ends, controlled by stress and elongation values. Intelligent prestressing system data is automatically collected using wireless transmission technology and the Internet of Things. The construction data is transmitted in real-time through wireless networks to the intelligent beam plant digital management platform, allowing automatic recording of prestressing construction information and real-time supervision of the construction process.

(2) Second-stage prestressing. The component is lifted off the prefabrication baseplate and transported to the beam storage area for curing. After the concrete strength, modulus, and age of the beam reach the design requirements, the second-stage prestressing is performed on the storage baseplate. After the final prestressing, grouting is performed in the ducts, and the ends are sealed. The mobile baseplate is lifted to the reinforcement binding area for the production of the next prefabricated T-beam.

6 Integrated Construction Efficiency Analysis

6.1 Comparative Analysis of Construction Techniques

The construction technique employed in this study, which involves the "mobile baseplate + fixed hydraulic formwork" assembly line method for prefabricated T-beams, has several advantages over traditional techniques such as "fixed baseplate + conventional formwork" and "fixed baseplate + mobile hydraulic formwork." The main advantages of this technique are as follows:

(1) The intelligent mobile baseplate enables streamlined operations, reduces the time required for process connections, and achieves standardized construction.

(2) The side formwork is fixed on both sides of each production line and only requires lateral movement. The hydraulic system is used for the overall assembly and disassembly of the formwork, eliminating the need for hammering and prying during removal. This ensures the preservation of the prefabricated beam products and avoids edge and corner damage.

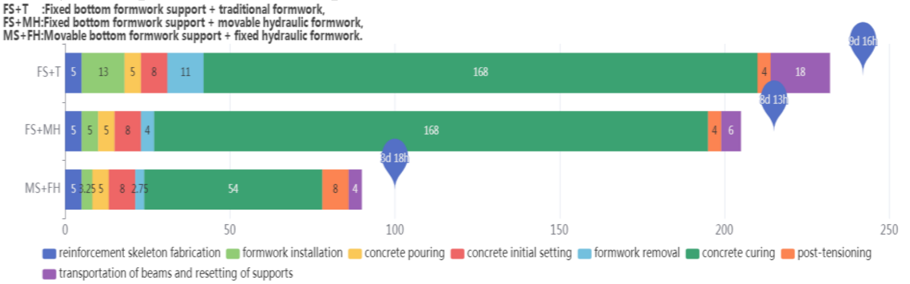
(3) The hydraulic end formwork can be vertically slid and assembled using the mobile baseplate, facilitating the construction process.

(4) The intelligent steam curing system ensures comprehensive curing without dead corners, effectively enhancing the concrete strength and elastic modulus within a short period. This accelerates the turnover speed of the mobile baseplate and greatly reduces the number of baseplates required. Additionally, there is minimal visible water during the curing period, resulting in a favorable construction appearance.

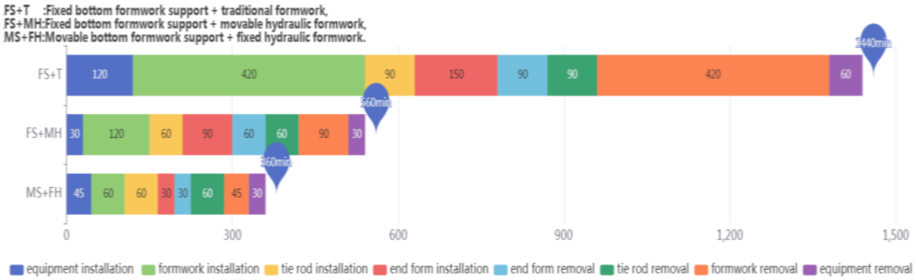
(5) The two-stage prestressing method allows for better control of the beam's camber value and reduces prestress losses. The prestressing area is relatively fixed, ensuring better safety.

6.2 Comparative Analysis of Construction Efficiency

From the perspective of construction efficiency, the production cycle of the 30m prefabricated T-beam is illustrated in Figure 5. The assembly line construction approach in this project has the shortest construction period, with a production cycle of each beam controlled within 4 days (Figure 5(a)). This is primarily due to the efficient removal of formwork, seamless process connections, and effective steam curing, which significantly shorten the prefabrication cycle. As an example, the removal of formwork (Figure 5(b)) is completed in just 6 hours, thanks to the utilization of mechanical equipment by the mobile baseplate. The rational arrangement of various prefabrication processes within the assembly line construction method ensures efficient operations in designated areas, thereby improving equipment utilization. Steam curing, characterized by high temperature, humidity, and early strength development, accelerates the turnover speed of the prefabricated baseplate and shortens the production cycle of prefabricated components.



(*a*) prefabricated construction duration (unit: hours)



(b) time required for formwork removal (unit: minutes)

Fig. 5. Comparison of construction efficiency for 30m prefabricated T-beam.

7 Conclusion

This paper has discussed a prefabricated construction technique for the Hangzhou-Shaoxing- Ningbo Expressway smart beam yard, which involves the use of "mobile baseplate + hydraulic formwork + steam curing + two-stage prestressing." The main conclusions are as follows:

(1) The smart beam yard adopts a factory-like assembly line production mode, utilizing digitalization and information processing of all production elements. This ena-

bles automatic data uploading and resource-efficient scheduling, achieving an intelligent production environment for the beam yard.

(2) The combination of mobile baseplate and hydraulic formwork facilitates a streamlined assembly line operation in different work areas according to the construction process. This improves the efficiency of formwork installation and removal cycles, reduces labor requirements, and enhances the quality of prefabricated components.

(3) Steam curing enhances the early performance of concrete, significantly reducing production time and lowering construction costs. The two-stage prestressing method minimizes prestress losses and improves the production efficiency of the baseplates.

(4) Compared to traditional formwork, the use of mobile baseplates and hydraulic formwork, along with mechanized equipment, increases construction efficiency. The production cycle is reduced from 10 days per beam to 4 days per beam, with the formwork removal time notably shortened from 24 hours to 6 hours.

(5) For bridge prefabrication construction with limited site space, short construction periods, heavy workloads, and complex construction environments, the combination of mobile baseplates and hydraulic formwork significantly shortens the construction period and reduces construction costs, yielding substantial economic benefits.

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