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Research and application of integrated pile-beam bridge construction technology

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Abstract: This paper, based on the construction of the Meilong Super Major Bridge within the Shenzhen-Shanwei Western Expressway Expansion Project, analyzes the construction challenges of this project, introduces the design concept and technical scheme for an integrated pile-beam bridge erecting machine, and discusses its detailed structure and key technologies. This integrated erecting machine addresses the limitation of conventional bridge erectors in pile foundation construction, enabling the simultaneous construction of pile foundations, cap beams, and T-beams. It provides benefits including minimal off-site space occupation and no requirement for temporary access roads, thereby significantly reducing environmental disruption.

Key words: fully prefabricated assembly; integrated construction; simultaneous construction; prefabricated bridge

1 Research background

Prefabrication and erection techniques are already commonly used worldwide for bridge superstructure elements like beams and cap beam piers. However, the construction of the bridge substructure and foundations still relies mainly on manual reinforcement binding and cast-in-place concrete, suffering from drawbacks such as messy and poor site conditions, significant traffic impact, environmental pollution of the surroundings, and serious material waste.

The mainline bridges of the Shenzhen-Shanwei Western Expressway Expansion Project adopt a "unilateral widening with new separate construction" expansion plan, upgrading the original four-lane expressway to an eight-lane configuration. The Meilong Super Major Bridge, situated within the project's channel area, features a water depth of approximately 6 meters, generally containing a thick layer of about 15m of silty soil, a 4-5m gravel layer, and 15m of completely weathered granite. One side of the Meilong Super Major Bridge is an existing operational line, and the other side adjoins existing farmland, requiring construction directly above the channel area within this constrained space. As shown in Figure 1, the superstructure consists of prefabricated prestressed concrete double-leg T-beams, the substructure uses prefabricated reinforced concrete cap beams, and the foundation structure comprises prefabricated pipe piles with lengths of 30m to 43.2m and a diameter of 1m. The prefabricated pipe piles and cap beams are connected into a whole using cast-in-place UHPC [1].

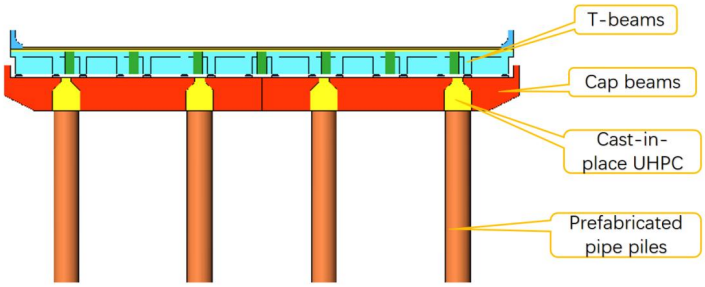


Figure 1. Schematic diagram of the transverse cross-section of the Meilong Super Major Bridge

Considering the project's surrounding environment and construction requirements, the construction of the Meilong Super Major Bridge faces the following challenges:

(1) Fully prefabricated assembly construction

Construction operations must not disrupt adjacent highway traffic, and the special environment in the surrounding area precludes methods such as backfilling or constructing temporary access roads or overpasses.

(2) Pile formation accuracy

The hammer impact and alternating loads during construction cause vibration at the cantilever end. How to perform high-precision pilot hole drilling and pile driving while controlling the vibration amplitude of the cantilever end is a key factor for the success of both the new construction method implementation and the new equipment development.

(3) Construction efficiency

Integrated prefabricated assembly operations require completing pilot hole drilling, pile driving, cap beam, and T-beam erection on a single set of equipment [2]. How to enable multi-process, multi-workface simultaneous construction while minimizing mutual interference is a key factor related to the overall project construction efficiency.

Therefore, it is imperative to develop equipment that enables fully aerial assembly of all bridge prefabricated components without requiring any space below or adjacent to the construction line. Based on the aforementioned background, this paper innovatively proposes a fully prefabricated assembled bridge construction technique with integrated pile-beam system and presents a corresponding erecting machine featuring integrated pile driving capability.

2 Overall design concept

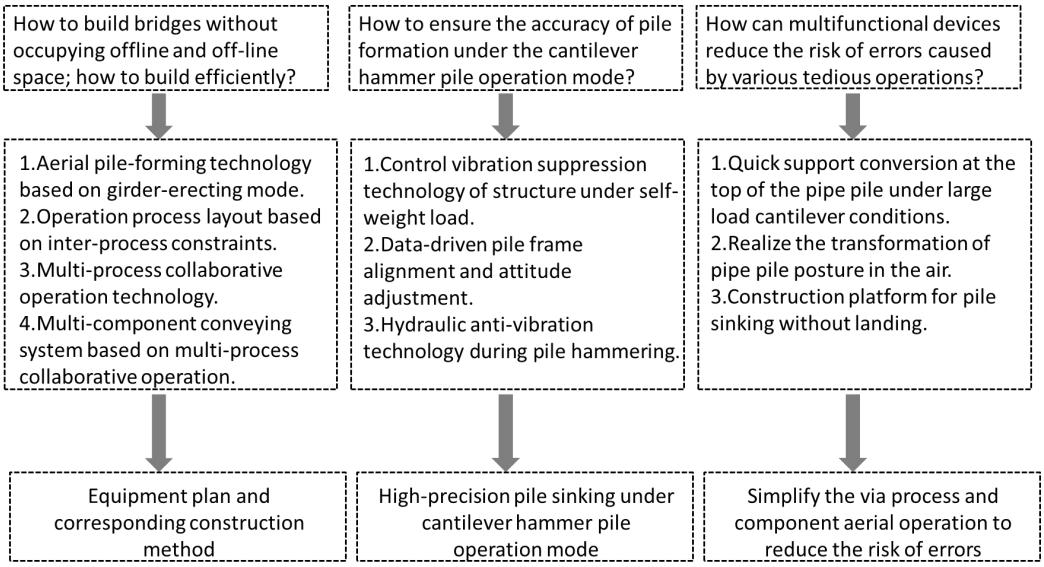


Figure 2. Design concept flowchart

3 Optimized design for synchronized aerial construction across multiple workfaces

Construction operations with the integrated pile-beam erecting machine require completing pilot hole drilling, pile driving, cap beam assembly, and T-beam erection on a single set of equipment. How to achieve simultaneous multi-process, multi-workface construction and reduce mutual interference is a key factor related to the overall project construction efficiency. After casting UHPC material on-site, a 24-hour waiting period for strength gain is required before other operations can be performed on it [3]. Balancing the UHPC curing time and strength gain with the improving construction efficiency is critical for promoting the adoption of new equipment and methods. Based on the above factors, the theoretical time for each process was determined.

The integrated pile-beam machine is designed as a five-and-a-half-span structure, as shown in Figure 3, mainly composed of the main girder, beam-launching trolley, pile-hoisting trolley, front auxiliary leg, front leg, middle leg, rear leg, pile driving device, etc.

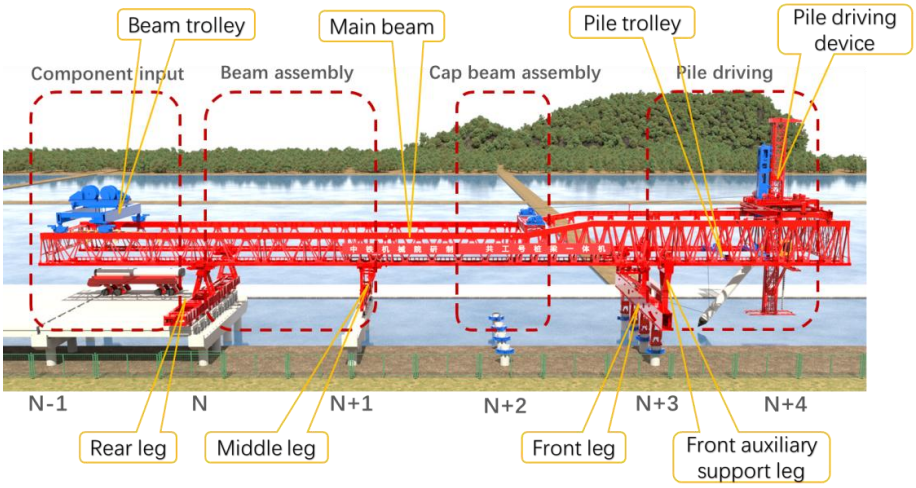


Figure 3. Schematic diagram of the overall structure of the integrated pile-beam machine

The front leg is supported on the pile top of the pipe piles in row N+3, the middle leg is supported on the front half of the cap beam in row N+1; the rear leg is supported on the T-beams in row N. To ensure proper time intervals for cap beam installation, beam launching, and support positioning on the cap beams, while meeting the requirements for wet joint concrete curing time, three workfaces are set up sequentially: pilot hole drilling and pile driving at pier N+4, cap beam erection at pier N+2, and T-beam erection workface between piers N and N+1. After the three workfaces complete their construction, the bridge erector proceeds with the span launching operation [4].

4 Working principle

Construction operations are divided into left and right deck erection. First, pilot hole drilling, pile driving, cap beam erection, and double-leg T-beam erection are carried out for a single deck construction. After completion, the machine transfers transversely to the position for the other deck and performs the same sequence of operations. After both decks are completed, the machine transfers transversely to the centerline of the route for the span launching operation.

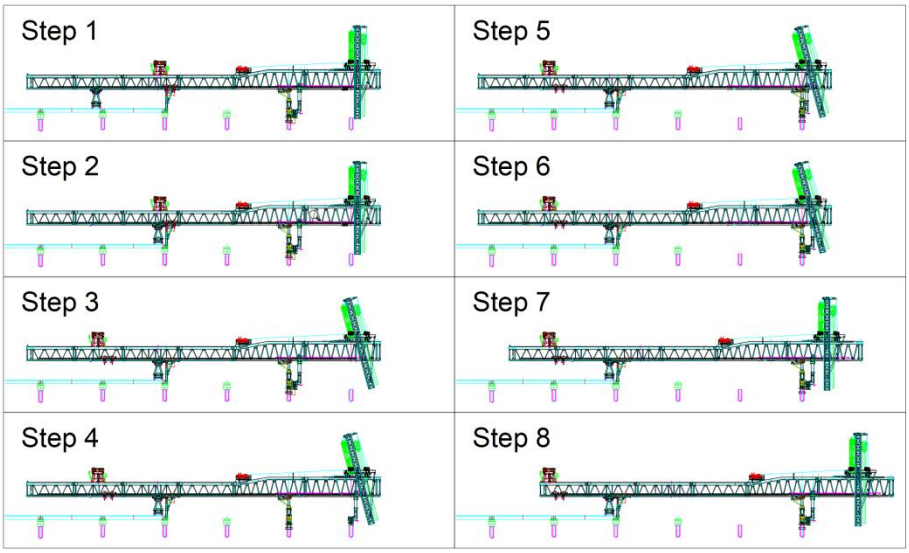


Figure 4. Flowchart of the integrated pile-beam machine span launching process

Pile Driving Operation: The pile driving device positions the drilling rig, which then drills to the preset depth by connecting and disassembling drill rod segments. Upon completion, the pile driving device moves forward, and the piling machine performs coarse positioning. Two pile-hoisting trolleys lift the prefabricated pipe pile from the rear of the erecting machine into position. Cooperating with the pile-holding winch, pile feeding and pile erection are achieved, setting the pipe pile into the power hammer's helmet. The pile frame's three-dimensional attitude is adjusted to the predetermined position and orientation, and pile driving commences, completing the single segment pile operation. Subsequent pile segments are hoisted into position, welded to the previous segment (splicing), and pile driving continues until the pile's penetration depth and elevation meet requirements, then driving stops. Finally, pile cutting completes the entire pile operation. The pile driving device position is adjusted, and the same method is used to complete the pilot hole drilling and pile driving for the other entire pile in the single deck.

Cap Beam Erection Operation: The beam-launching trolley lifts the cap beam from the beam surface at the rear of the erecting machine, travels to the target erection position, rotates the beam 90° via the spreader, and, after precise longitudinal, transverse, and angular adjustments, lowers and installs it onto the pile top after alignment. The pile-hoisting trolley carries UHPC material forward, positions it for casting, completing the cap beam erection for the single deck.

Double-Leg T-Beam Erection Operation: The beam-launching trolley lifts the double-leg T-beam from the beam surface at the rear of the erecting machine, travels to the target erection position, performs positional adjustments, and installs it. The same method is used to erect the other three double-leg T-beams for the single deck.

Span Launching Operation: The entire machine transfers transversely to the route centerline. The middle leg supports the rear end of the erector. The rear leg first performs its own span launching to position and provides support. The pile driving device rotates to clear space. The front auxiliary leg moves forward to position and provides support. The front leg retracts, moves forward, and provides support. The front leg and rear leg driving wheels propel the main girder forward. The span launching proceeds past the pile driving device, positioning it for the next pilot hole drilling, completing the span launching operation.

5 Multi-leg support switching technology for loaded cantilever span launching

According to the structural design of the Meilong Super Major Bridge, each row of the bridge foundation is supported by four pipe piles, which share the load equally. During support switching, the four pipe piles are divided into two groups to ensure comprehensive coverage: the two outer pipe piles form one group to provide footing for one leg; the two middle

pipe piles form the other group to support an adjacent leg. Therefore, a multi-legged support technology with spatially staggered movable supports is proposed. The design integrates an L-shaped front auxiliary leg, a position-adjustable front leg, and a rotatable/inclinable pile formation system. By leveraging spatial staggering and an innovative co-location strategy—where the front leg and front auxiliary leg share the same pile cap—the system effectively enables seamless multi-leg support switching on a single pile cap.

To achieve the above workflow and allow two legs to simultaneously step on the four pipe piles, special configurations were designed for the front leg and front auxiliary leg, realizing spatially staggered multi-leg positioning. The specific structures are:

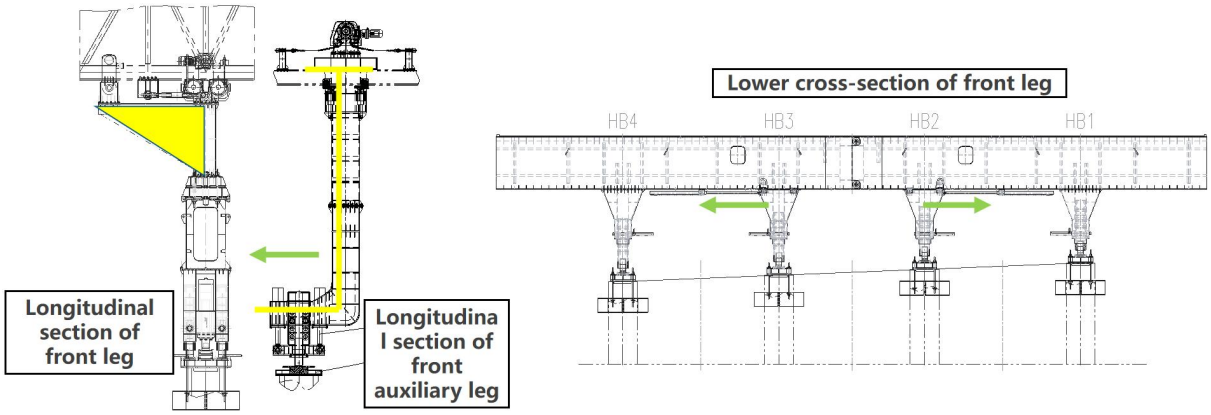


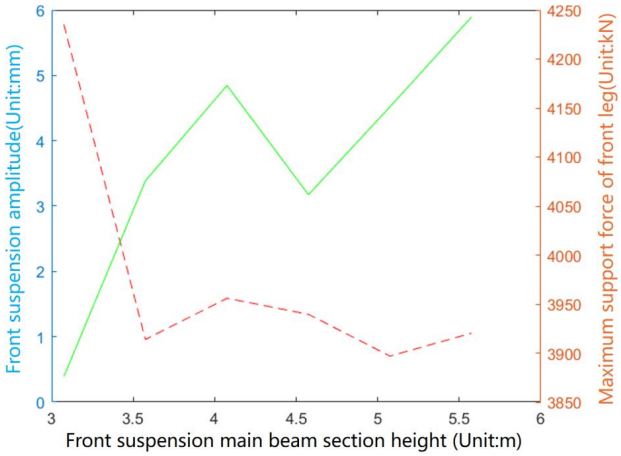
Figure 5. Schematic diagram of the special-shaped leg structure

The front leg serves as the main support leg. During pile driving operations and cap beam/T-beam erection of the integrated pile-beam machine, it acts as the front support leg for the erector and experiences eccentric loading conditions, making its stress conditions severe. During operation, the front leg steps on the tops of the four pipe piles. During span launching, it needs to vacate the space of the two middle pipe piles for the front auxiliary leg to position itself. Therefore, the lower structure of the front leg consists of a transverse moving rail beam, transverse moving cylinder, inner telescopic leg, outer telescopic leg, and pile-holding device. The two outer telescopic legs are fixedly connected to the transverse moving rail beam via flanges. The two inner telescopic legs are connected to the transverse moving rail beam with a reverse clip and can move left and right driven by the transverse moving cylinder. This ensures transverse staggered support when the front leg and front auxiliary leg are simultaneously supported on the same row of pipe piles.

6 High-precision pile formation technology

Pile formation is the most critical step in bridge construction. The accuracy of pile formation determines the success or failure of subsequent component assembly or affects its efficiency. Pile verticality and driving penetration are important data monitored during prefabricated pile construction. This project requires the plan position deviation of the pile axis from the design position not to exceed 15mm; pile verticality deviation not greater than 1‰; verticality deviation of the first pile segment not greater than 5‰. Traditional piling rigs and drilling rigs operate on the ground, transmitting vibration directly to the earth through the mast and chassis [5]. This project employs a non-ground-contact cantilever operation mode, integrating the piling machine and drilling rig onto the erecting machine. Vibration and alternating loads during construction can easily cause disturbance at the front end of the erector, leading to instability of the piling machine and drilling rig's base platform. How to perform high-precision pilot hole drilling and pile driving on an unstable construction base is a key factor for the success of the new method and equipment development.

1) Combining mechanical vibration suppression principles and techniques, the equipment vibration model was simplified. Qualitative and quantitative analysis of the cantilevered pilot hole drilling and pile driving structural model was conducted [6]. While setting reasonable anchor points for the entire machine, and under the dual constraints of dead load control and cantilever amplitude control, the structure and layout were optimized using a convergence algorithm. This achieved the control target of a minimum amplitude of 3mm for the cantilevered operation mechanism under stable vibration excitation, ensuring the foundational accuracy of the cantilevered operation mechanism.



Remarks: front suspension amplitude (red line); maximum support force of front leg (green line)

Figure 6. Calculation results diagram of cantilever amplitude and support loads

2) By leveraging precise control technology for the pile frame system's position and attitude adjustment mechanism, a target positioning data-driven pile frame self-traveling system and a dual-axis tilt sensor data-driven pile frame leveling system were developed [7]. Combined with an RTK technology-based pile frame positioning system, automatic positioning and attitude adjustment of the pile frame before cantilever operation were achieved, simultaneously improving the efficiency and accuracy of pile foundation construction.

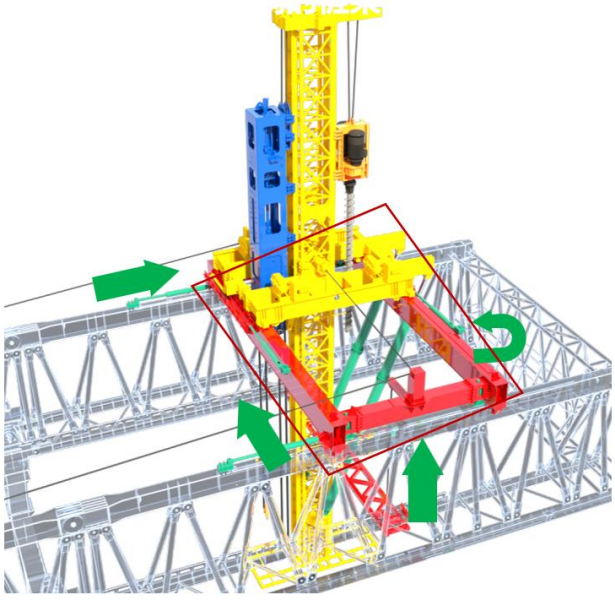


Figure 7. Data driven high-precision positioning of pile frame

3) Based on the excitation load data during pile hammer operation, a hydraulic locking and vibration-resistant design for the pile frame system was matched, ensuring the stability of the pile frame's attitude during the hammer-driven pipe pile process, and guaranteeing construction safety and pile formation quality.

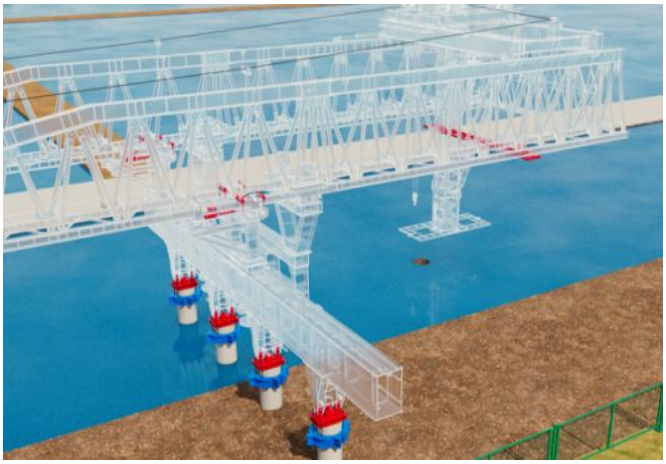


Figure 8. Schematic diagram of the hydraulic locking and vibration-resistant design of the pile frame system

7 Application status

The prototype was successfully applied to the construction of the TJ10 contract section of the Meilong Extra Large Bridge in the expansion project of the Shenzhen Shanwei Expressway. As of now, 188 spans of construction have been completed, including 752 guide hole drilling and pile driving for whole piles, as well as the installation of 376 cap beams and 1504 double leg T-beams. The application results of this device indicate that its various performance fully meets the design requirements.

Figure 9. Schematic diagram of the on-site application of the integrated pile-beam bridge erecting machine

The integrated pile-beam bridge erecting machine enables single-machine completion of all online assembly processes for bridge prefabricated components. Compared to ground-based equipment hoisting and assembly or conventional integrated pier-beam erector hoisting and assembly schemes, it shows significant advantages in the following aspects:

(1) Comprehensive Equipment Functions: This equipment covers the entire process of prefabricated bridge construction, integrating pilot hole drilling, pile formation, cap beam assembly, and T-beam erection functions [8]. Even the most advanced domestic integrated pier-beam erectors currently lack core functions like pilot hole drilling and pile

formation.

(2) High Operational Efficiency: The entire assembly construction meets the requirements for rapid bridge assembly with multi-deck segmented construction and multi-process parallel operations, while enabling the hoisting of multiple component types using multi-level arranged trolleys without interference. A single machine can achieve a rate of 1 span per 3 days, improving the construction schedule by more than three times compared to cast-in-place methods.

(3) Strong Environmental Performance: The equipment realizes full-process aerial operations for pilot hole drilling, pile formation, cap beam assembly, and T-beam erection, effectively reducing the amount of manual labor on-site, saving labor costs and land acquisition costs, lowering safety risks, and minimizing adverse impacts on the surrounding natural environment and traffic.

8 Conclusion

The integrated pile-beam bridge erection technology has overcome the challenges of non-ground-contact construction for piles and beams during bridge building, breaking through the conventional practice of cast-in-place bridge foundations. It has achieved a full set of "aerial" services including pilot hole drilling, pile driving, beam erection, and pier assembly. It addresses the current issue where bridge construction necessitates ground-level construction access roads and relies on ground-based auxiliary equipment, providing excellent protection for the ecological environment of the construction area. It is a first in the bridge construction industry and sets a good example for the subsequent development of assembled bridges.

Conflicts of interest

The author declares no conflicts of interest regarding the publication of this paper.

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