Scientific Research

Longitudinal Section Inspection and Quality Assessment of Grouting Sleeves in Precast Bridge Piers

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Abstract: This study investigates the construction quality and potential defects of grouted sleeve connections in a prefabricated bridge pier dismantled from a project in Shanghai using section-cutting inspection. Ten samples were examined with a focus on grout compactness, reinforcement anchorage length, and centering accuracy. The results show that the grout within the sleeves was highly compact, and all mechanical performance indices satisfied the relevant specifications and design requirements, indicating overall reliable construction quality. Minor deficiencies, including slightly insufficient anchorage length and deviations in reinforcement centering, were identified but are considered to have negligible effects on load-bearing and deformation capacities on the basis of existing research. The findings suggest that the current construction process generally meets quality requirements; however, improvements in grout mix proportion, construction procedures, and the addition of external threading on the sleeve surface are recommended to enhance bonding with surrounding concrete. This work provides experimental evidence from an actual engineering case to support the safety and durability assessment of grouted sleeve–connected piers and supplements nondestructive testing by revealing internal defects that are otherwise difficult to detect.

Keywords: prefabricated bridge; grouted sleeve; section-cutting inspection; construction quality; optimization

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1 Introduction

With the growing pace of urbanization, an increasing number of urban road and rail transit bridges are being constructed using fully prefabricated assembly techniques to achieve rapid construction [1]. The connections among prefabricated components are critical links in prefabricated bridges, as both structural integrity and safety must be ensured while maintaining a simple configuration and facilitating construction. Among them, dry joints between prefabricated segments represent key construction details, whose safety and reliability directly affect the overall structural performance of assembled bridges.

Grouted sleeve connections are widely used as an important method for connecting load-bearing reinforcements in prefabricated structures [2]. Such connections rely on the bonding action between materials—including chemical adhesion, mechanical interlocking, and friction—to achieve stress transfer between reinforcing bars, enabling the assembled components to achieve mechanical performance comparable to that of cast-in-place structures. Among the key indicators for assessing the reliability of grouted sleeve connections, grout compactness is the most critical. During construction, factors such as inadequate management, insufficient supervision, and variations in workers' technical skills may lead to insufficient grout compactness. Defects in sleeve grouting can prevent effective rebar splicing, directly compromising connection performance and structural integrity. Therefore, strict control of grouting quality is essential to ensure the safety and reliability of prefabricated concrete structures.

In recent years, many scholars have extensively researched methods for assessing the grout compactness of sleeves. Existing nondestructive testing (NDT) approaches generally involve evaluating construction quality without damaging the original structure by detecting variations in thermal, acoustic, optical, or electromagnetic responses caused by internal anomalies or defects in the material. These methods, which employ physical or chemical principles along with advanced technologies and equipment, allow indirect evaluation of the internal and surface structure, properties, conditions, and defect characteristics—such as the type, quantity, shape, location, size, distribution, and changes—of the tested object. However, for grouted sleeves deemed acceptable through NDT, the internal construction quality cannot be determined intuitively, and no NDT method can fully verify the actual conditions. Given the relatively recent adoption of grouted sleeves, no real-world engineering data are currently available from section-cutting inspections to reveal the true internal condition.

The mechanism of load-transfer between the reinforcement and grout in a grouted sleeve connection is similar to that between the reinforcement and concrete. A larger rebar diameter corresponds to longer anchorage length, resulting in greater stress being transferred to the grout at failure. The bond stress between the rebar and the grout is entirely transmitted to the sleeve, with the longitudinal strain of the sleeve wall increasing gradually from both ends toward the midspan, reaching its maximum at the center—identified as the most critical section of the grouted sleeve connection [3]. Factors influencing the mechanical performance of grouted sleeves include grout strength, grout compactness, rebar anchorage length, and rebar eccentricity. The combined effect of these parameters ultimately governs the tensile pull-out strength, deformation capacity, and seismic performance of the connection.

Su et al. [4] conducted uniaxial tensile tests on grouted sleeve samples with varying grout compactness and rebar eccentricity. Their results revealed that samples with high grout compactness ultimately failed by rebar fracture, with tensile strength, residual deformation, and total elongation at maximum load meeting the standard technical requirements. Rebar eccentricity had a minimal effect on connection performance. Conversely, samples with low grout compactness failed by rebar pullout, exhibiting reduced tensile strength, increased residual deformation, and decreased total elongation at maximum load. The lower the grout compactness and the greater the rebar eccentricity are, the more detrimental the effect on the connection performance of grouted sleeve samples. Li Xiangmin [5] investigated the influence of defect height as a primary variable on the performance of grouted sleeve connections, considering defect parameters such as height and fullness. Their study revealed that grout defects affected both the ultimate failure mode and load capacity in uniaxial tensile tests. When the defect height did not exceed 30% of the rebar anchorage length (eight times the rebar diameter), the joint performance still met the requirements.

Su [6] studied cast half-grouted sleeves and analyzed the effects of vertical and inclined rebar eccentricity within the sleeve on grouted connection performance and reported that such eccentricities had a limited influence on the ultimate bearing capacity but primarily affected deformation behavior. The peak strain of the sleeve surface was observed at the outlet section, which was identified as the most critical section of the sleeve. Feng et al. [7], through full-length grouted sleeve uniaxial pull-out tests, reported that the axial displacement of the rebar had a negligible effect on connection performance, provided that a sufficient contact area between the rebar and grout was ensured.

Xing et al. [8] examined the effect of grout defects on the performance of large-diameter grouted sleeve connections in prefabricated bridges. The results indicated that the ultimate tensile strength of the grouted sleeves decreased with increasing defect rate; however, when the defect rates were low, the impact on the ultimate tensile strength was minimal. For defect rates less than 15%, the influence was essentially negligible; within 30%, the ultimate tensile strength decreased with the increasing defect rates but still satisfied the code requirements. At defect rates exceeding 30%, failed to meet the standards. Wang et al. [9] investigated the impact of grouted sleeve connection defects on the seismic performance of prefabricated concrete columns. Their results revealed that when the size of connection defects did not exceed twice the rebar diameter (2d), the hysteresis curves of the prefabricated columns were full and exhibited good energy dissipation capacity. When the size of defects exceeded 2d, pinching effects in the hysteresis curves became more pronounced with increasing defect size. After yielding, connection defects significantly affected the load-bearing capacity of the prefabricated concrete columns.

Each currently used detection method has its own advantages and limitations and is applicable under different conditions. A summary of the characteristics of these methods is provided in Table 1. In accordance with Article 10.9.8 of the Shanghai Engineering Construction Code, “Technical standard for prefabricated bridges” (DG/TJ08-2160—2021) [10], grout quality inspection for grouted sleeves can be performed using endoscopic inspection, embedded steel wire pull-out tests, chip methods, pressure sensors, ultrasonic array imaging, and localized damage techniques.

Table 1 Summary of the characteristics of existing inspection methods

Inspection Method		**Damage**	**Applicable Stage**	**Advantages**	**Disadvantages**	**Application Status**
Preembedded Steel Wire Pull-out		Nondestructive	Preembedding, Postinspection	Simple operation, cost-effective	Limited inspection position, easily disturbed or damaged	Widely applied; adopted by Chinese national and local standards
Endoscopy		Destructive	Postinspection	Intuitive results, can be used to quantitatively assess defect size	Requires local damage, time-consuming and labor-intensive	Adopted by Chinese national standards
Ultrasonic Method	Ultrasonic Transducer	Nondestructive	Postinspection	Easy operation	Results not intuitive, ready interference from external factors	Mostly laboratory research stage; limited application
	Ultrasonic Phased Array	Nondestructive	Postinspection	Simple operation, intuitive results	Expensive equipment, high cost	Has engineering applications; adopted by Guangdong standards
Embedded Sensors	Piezoelectric Sensor	Nondestructive	Preembedding, Whole-process monitoring	Enables full-process monitoring of grout quality	Preembedding needed; sensor protection complex	Laboratory research stage
	Damping Vibration Sensor	Nondestructive	Preembedding, Whole-process monitoring	Simple operation, intuitive results, can be used to detect defects in a timely manner and allow for repair	Limited inspection position to grout outlet, cannot detect grout leakage	Adopted by Chinese national and Guangdong standards
Impact Echo Method		Nondestructive	Postinspection	Simple operation, single-face inspection	Results not intuitive, ready interference from other factors	Mostly laboratory research stage; limited application
X-ray		Nondestructive	Postinspection	Simple operation, intuitive results	Expensive equipment, harmful to human health	Included in Chinese national and Shanghai standards

This study, which is based on a project in Shanghai, presents the first section-cutting inspection of grouted sleeves from a dismantled prefabricated assembled bridge pier. The aim of the study is to analyze and assess potential construction quality issues and defects. As section cutting is a destructive method, it cannot be routinely applied in practical engineering inspections. Therefore, this destructive inspection method is used to reveal hidden problems that are difficult to detect via nondestructive testing, providing experimental data from a real engineering case to support the evaluation of the safety and durability of grouted sleeve-connected piers.

2 Project Background

Owing to adjustments in traffic planning, two existing ramp bridges in a project in Shanghai, both of which are currently in good operational condition, are scheduled for demolition. The ramp bridges were designed for an urban A-class load with a design service life of 100 years. The construction drawings were completed by the end of 2018, and the bridges were opened to traffic by the end of 2020, having been in operation for approximately 3.5 years at the time of demolition.

The superstructure of the bridge consists of prefabricated assembled box girders, whereas the substructure comprises prefabricated assembled cap beams and columns, cast-in-place pile caps, and bored cast-in-place piles. The prefabricated assembled columns are made of C40 high-performance concrete. The mortar bedding layer at the joint between the columns and cap beams is composed of high-strength, nonshrink mortar with a 28-day compressive strength of 60 MPa and an initial setting time exceeding 2 hours. The grouted connecting sleeves are manufactured from high-strength ductile cast iron, conforming to the material requirements of GB/T 1348—2019, with specific performance indicators meeting the provisions of “The Grouting Coupler for Rebars Splicing” (JG/T 398—2012). The high-strength, nonshrink cement grout used inside the sleeves is required to achieve a 28-day compressive strength greater than 100 MPa, and other technical parameters comply with those of the “Cementitious Grout for Coupler of Rebar Splicing” (JG/T 408—2013) and “Technical Specification for Prefabricated Bridge Piers” (DG/TJ 08-2160—2015). The sleeve connection strength meets the Level I joint performance requirements specified in the “Technical Specification for Mechanical Splicing of Steel Reinforcing Bars” (JGJ 107—2010).

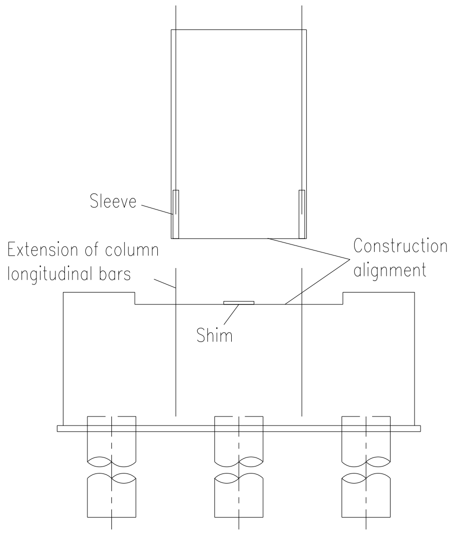

Figure 1 Schematic diagram of prefabricated assembled column construction

During construction, the pile caps were cast in situ with embedded reinforcement installed. A single row of 40 mm diameter HRB400 reinforcing bars was used for the columns. Steel formwork was employed at the interface between the top of the pile cap and the bottom of the columns to ensure proper alignment.

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Prefabricated columns were transported to the site and preliminarily assembled to verify that the main bars protruding from the pile cap aligned precisely with the sleeve connectors at the column base. The verticality deviation of the columns was required to be within H/3000, and the center position of the column top section was allowed a maximum deviation of 10 mm from the design location. The connection between the reserved reinforcing bar ends in the pile cap and the grouted sleeves in the prefabricated columns was achieved through grout injected via reserved grout holes at the sleeve base. Prior to grouting, the sleeves were inspected to ensure that the internal cavity was clear and free of debris. Grout was injected continuously until it emerged from the outlet port, at which point pressure grouting was stopped and the outlet was sealed with a grout stopper, completing the grouting process.

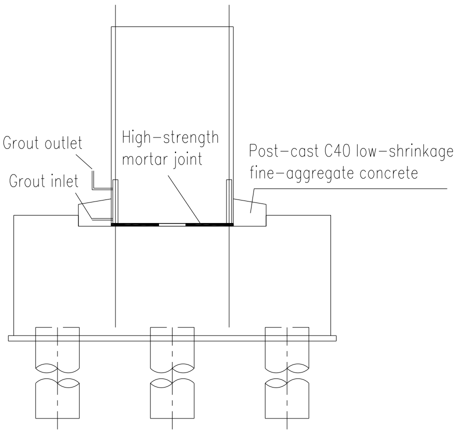


Figure 2 Schematic diagram of grouted sleeve joint construction

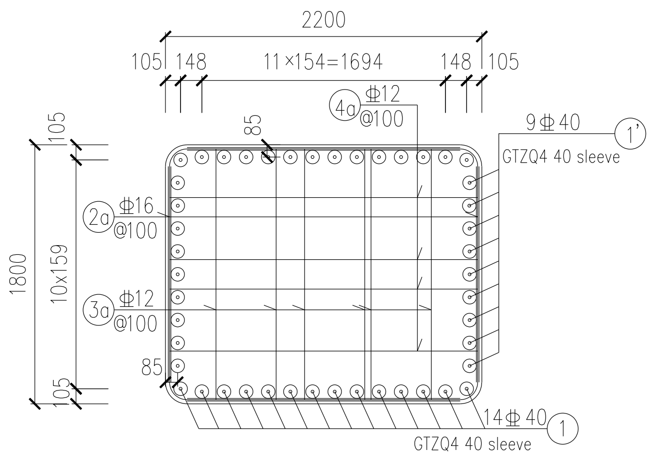


Figure 3 Reinforcement detail of the prefabricated column

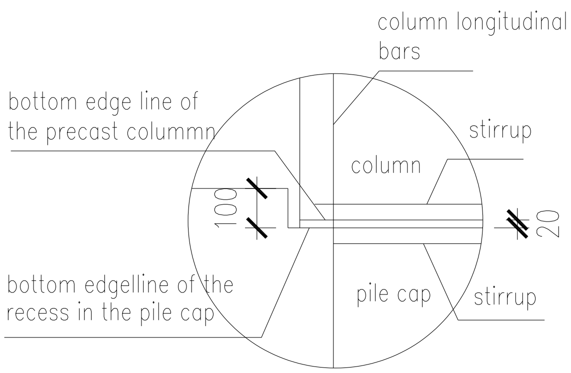


Figure 4 Prefabricated column and pile cap

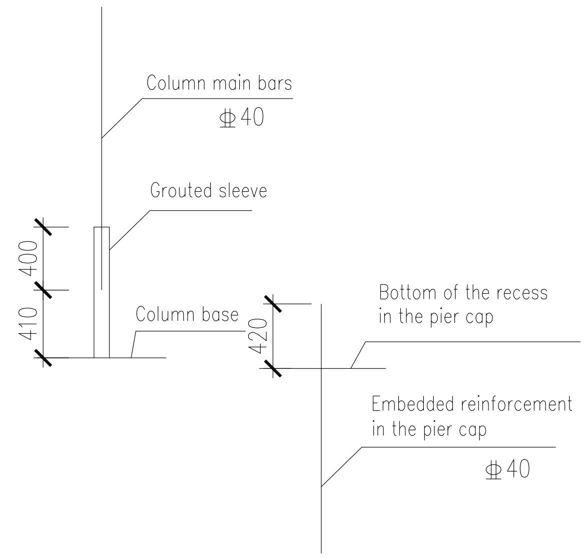


Figure 5 Reinforcement detail of grouted sleeve connections

3 Section-Cutting Inspection of Sleeves from Dismantled Bridge Piers

3.1 Inspection Objectives and Methods

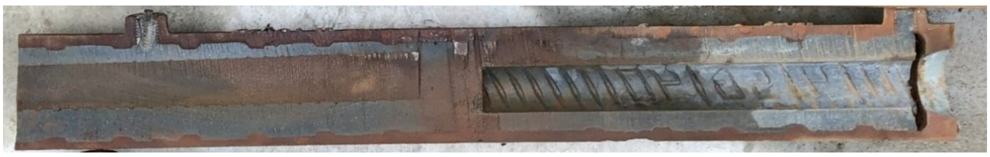
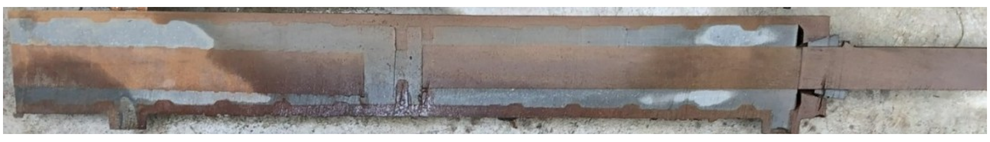
Grouted sleeve inspection by sectioning is a destructive procedure and cannot be routinely applied as a standard inspection method in practical engineering. The aim of this inspection is to overcome the limitations of nondestructive testing (NDT) by providing direct, destructive observations to reveal potential hidden issues during construction and to propose corresponding improvement measures.

After the bridge piers were dismantled, ten grouted sleeves connecting the columns and pile caps were randomly selected for longitudinal sectioning. The internal grout compactness, reinforcement anchorage length, rebar centering, and bond condition between the sleeve and the concrete were examined.

3.2 Inspection Results

Photographs taken after the ten grouted sleeve samples were sectioned are presented in Table 2, and the statistics of the construction quality defects are summarized in Table 3.

Table 2 Sectioned grouted sleeve samples

No.	Photograph of samples
No.1	
No.2	
No.3	

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No.	Photograph of samples
No.4	
No.5	
No.6	
No.7	
No.8	
No.9	
No.10	

Table 3 Statistics of construction quality defects in grouted sleeve samples.

Sample Number	Construction Defects			
	Void at top grout outlet /mm	Anchorage length deficiency of pile cap rebars /mm	Rebar eccentricity length /mm	Rebar eccentricity value /mm
No.1	9	26	176	12
No.2	11	27	317	10
No.3	5	28	279	10
No.4	6	30	244	11
No.5	6	52	0	20
No.6	8	56	222	6
No.7	8	51	129	1
No.8	10	60	392	4
No.9	8	57	383	6
No.10	7	50	303	7

4 Analysis and Discussion

Through observation and analysis of the data of the sectioned samples, the following main issues were identified.

4.1 Voids at the Top of the Sleeve Result in Insufficient Anchorage Length

(1) Defect manifestation (Figure 6): All ten samples exhibited voids ranging from 5 mm to 11 mm near the grout outlet at the top of the sleeve, resulting in slightly reduced rebar anchorage lengths. In addition, some rebars embedded in the pile cap were 26 mm to 60 mm shorter than the design requirements, with anchorage lengths approximately 1d shorter than the designed length (10d).

(2) Cause analysis: The voids at the top of the sleeve are attributed primarily to grout settlement or shrinkage after grouting completion. The insufficient anchorage length of the pile cap reinforcement may result from inaccuracies in rebar fabrication or embedding, as well as positioning deviations and deformations during construction.

(3) Safety implications: According to a study by Li et al. [5], when the grout defect height does not exceed 30% of the rebar anchorage length, the joint performance can still meet the requirements. The void heights (5–11 mm) and anchorage length deficiencies (26–60 mm) observed in this study are relatively small compared with the rebar anchorage length of 400 mm (10d, where d = 40 mm). Therefore, these defects have a negligible effect on the overall mechanical performance of the grouted sleeves. However, the voids at the top may adversely affect the durability of the reinforcement, although no corrosion or other durability issues were observed in the sectioned samples to date.

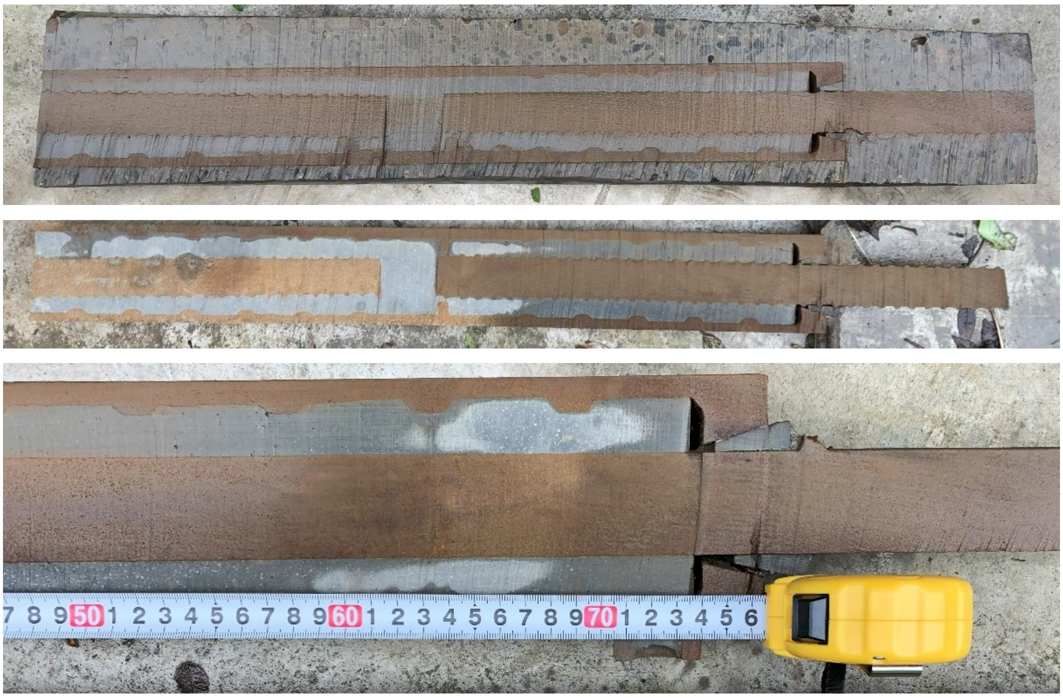

Figure 6 Example of a sectioned grouted sleeve—void near the grout outlet causing slightly reduced reinforcement anchorage length

4.2 Rebar Eccentricity

(1) Defect manifestation (Figure 7): The embedded rebars in the pile cap exhibited certain eccentricities within the sleeves, with eccentricity lengths ranging from approximately 176 mm to 392 mm and lateral displacement of approximately 9 mm.

(2) Cause analysis: Due to the large number of embedded rebars in the pile cap, deformation and positioning deviations during construction led to some rebars being eccentrically positioned within the sleeves during column installation.

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(3) Safety implications: According to studies by Su [6] and Feng [7], rebar eccentricity has a minor effect on the ultimate bearing capacity of joints but primarily affects deformation behavior. Therefore, the lateral displacement of 9 mm observed in this study can be considered negligible in terms of its impact on the load-bearing capacity of the components.

Figure 7 Example of a sectioned grouted sleeve—offset of embedded reinforcement bars in the pile cap

4.3 Delamination between the Sleeve Outer Wall and Concrete

(1) Defect manifestation (Figure 8): During the sectioning of the grouted sleeves, delamination was observed between the outer wall of the sleeve and the surrounding concrete, with the concrete surface appearing relatively smooth.

(2) Cause analysis: This indicates insufficient bond strength between the sleeve outer wall and the concrete, resulting in a lack of effective mechanical interlocking.

Figure 8 Example of a sectioned grouted sleeve—delamination between sleeve outer wall and concrete

4.4 Recommendations for Improvement

On the basis of the defects and issues identified through the current inspection, the following improvement recommendations are proposed.

(1) Construction management and process improvements

① Enhance construction management training to improve construction accuracy. Employ high-precision modules to fix the positions of the reinforcement and sleeves, addressing issues such as insufficient anchorage length and rebar eccentricity; and ② Improve the grouting process by installing check valves or double-bend pipes at the grout outlet to prevent backflow of the grout that causes voids at the top.

(2) Grout material optimization

① Optimize the grout mix proportion by using formulations with low shrinkage to reduce void formation caused by grout shrinkage; and ② Strictly control the grout volume to ensure adequate grout compactness through the use of a sufficient quantity of material.

(3) Sleeve structural optimization

The addition of threaded features to the outer surface of the grouted sleeve is recommended to increase bonding between the sleeve and the concrete, preventing delamination.

(4) Durability assurance

Regularly inspect and appropriately repair grout inlets and outlets to prevent exposed reinforcement from becoming corrosion paths, thereby improving the durability of joints.

5 Conclusions

Bridge assembly with prefabricated components offers advantages such as rapid construction, high quality, and labor savings, and this method is rapidly replacing traditional construction methods for bridges. With respect to the grouted sleeve connection method, a relatively complete theoretical system has been developed, with related standards established, and this method has been widely applied. However, owing to deviations in construction accuracy and insufficient onsite management, defects that are difficult to detect through nondestructive testing may exist.

In this study, a sectional analysis of ten grouted sleeve samples from dismantled prefabricated assembled bridge piers was conducted in a project in Shanghai. The results indicated that the construction quality met the design and code requirements, with good grout compactness. These findings suggest that the current construction processes and nondestructive testing methods can generally provide an objective reflection of construction quality.

The sectional inspection revealed specific defects, including voids of 5–11 mm near the grout outlet at the top of the sleeves, anchorage lengths of some embedded pile cap rebars that were 26–60 mm shorter than the design requirements, and lateral displacement of approximately 9 mm in certain embedded rebars. According to existing research, these defects have a negligible effect on the overall mechanical performance of grouted sleeves.

To further improve construction quality and component durability, specific recommendations are proposed, including enhancing construction management, optimizing grout mix proportions, improving construction procedures, and adding threaded features to the sleeve outer surface. These findings and suggestions provide valuable practical data to support construction quality control and technical improvements in future projects.

Conflict of interest: The author disclosed no relevant relationships.

Data availability statement: The data that support the findings of this study are available from the corresponding author, Wu, upon reasonable request.

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