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Evaluation of Construction Quality Management Based on Fuzzy Matter-Element Analysis

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Abstract: This study develops a construction quality management evaluation framework for prefabricated residential projects by integrating the analytic hierarchy process (AHP) with fuzzy matter-element analysis. Taking Phase II of the Qinxing Jiayuan Anju Community project as a case study, a multi-level evaluation index system was established based on the characteristics of prefabricated construction. The framework comprises six criterion dimensions, personnel management, material management, machinery and equipment management, technical management, on-site management, and information management, and 27 specific indicators, combining both qualitative and quantitative measures. Qualitative indicators were assessed through expert scoring by 30 project-related personnel, while quantitative indicators were derived from project records, including attendance rate, material acceptance rate, ex-factory qualification rate of prefabricated components, transportation and storage loss rate, and RFID/QR code coverage. Indicator weights were determined using AHP, and the overall evaluation grade was obtained through fuzzy matter-element modelling based on membership functions. The results show that the overall construction quality management level of the case project is good (M4). Among the criterion dimensions, material management reaches the outstanding (M5) level, while personnel management, machinery and equipment management, technical management, on-site management, and information management are all evaluated as good. These findings indicate that the proposed framework is practically applicable for structured assessment of construction quality management in prefabricated residential projects.

Keywords: Prefabricated residential buildings; Construction quality management; Fuzzy matter-element analysis; Evaluation index system; Analytic hierarchy process (AHP); Comprehensive evaluation

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1. Introduction

Prefabricated residential buildings have become an important development direction in the construction industry because they can improve construction efficiency, support industrialized production, and reduce the environmental burden associated with traditional on-site construction processes. At the same time, the quality management of prefabricated residential projects is more complex than that of conventional cast-in-place buildings because project performance depends not only on on-site workmanship but also on component production quality, transportation and storage conditions, assembly precision, temporary support control, information coordination, and multi-party management integration.

Existing studies on prefabricated construction quality management have examined influencing factors such as personnel capability, component and material quality, construction technology, equipment management, and organizational coordination. However, many previous studies either focus mainly on factor identification or provide evaluation results without a sufficiently integrated and operational framework tailored to the management characteristics of prefabricated residential construction.

Fuzzy matter-element analysis is suitable for this problem because it allows complex multi-indicator systems to be transformed into structured grade-based evaluations under conditions of partial uncertainty. When combined with AHP, it can integrate expert judgement on indicator importance with membership-based evaluation of actual project conditions.

Based on these considerations, this study takes the second phase of the Qinxing Jiayuan Anju Community project as a case and constructs a construction quality management evaluation framework for prefabricated residential projects. The framework includes six criterion dimensions and 27 indicators, covering personnel management, material management, machinery and equipment management, technical management, on-site management, and information management.

Prior work shows that construction quality management evaluation has evolved along two linked directions, the development of indicator systems for project quality performance and the adoption of multi-criteria decision models under uncertainty. Within the most direct topical stream, Hu et al. used a matter-element model to evaluate the construction quality management effect of PPP projects, showing that matter-element logic can transform complex quality indicators into a structured graded assessment [1].

A second stream applies fuzzy weighting methods to quality-management control practices. Ayalew et al. employed fuzzy AHP to explore and rank quality-management control practices in public building projects, while Lam et al. used fuzzy AHP to build a contractor self-assessment quality management system based on MBNQA-oriented criteria [2,3]. Together, these studies justify the AHP component of the present framework, but they also show that fuzzy AHP alone is stronger for weighting and ranking than for expressing the matter-element relationship between observed indicator values and discrete evaluation grades.

A third stream offers methodological comparators that are not identical to fuzzy matter-element analysis but are highly relevant for model design. Li et al. developed an ANP–fuzzy comprehensive evaluation model for lean construction management performance, while Jin et al. combined subjective and objective weighting with TOPSIS to evaluate bridge construction quality [4,5]. These studies show that hybrid multi-criteria frameworks are well established in construction evaluation research.

The studies that are methodologically closest to the present manuscript are those using extension or matter-element logic directly in construction-quality contexts. Chen et al. proposed an AHP-based fuzzy extension element-matter model for construction quality evaluation in ballastless track construction [6]. Zhang et al. also identified critical factors influencing quality management in smart construction sites through a DEMATEL-ISM-MICMAC framework, highlighting the growing importance of coordination, information, and systems interaction in digitalized construction environments [7].

Finally, the broader methodological landscape confirms that fuzzy-hybrid techniques have become an established family of tools in construction engineering and management. Nguyen et al. reviewed 255 journal articles and showed that fuzzy hybrid techniques are now widely applied across construction-management decision problems [8]. A practical, project-level, grade-based evaluation framework tailored to prefabricated residential construction that integrates qualitative and quantitative indicators while preserving transparent criterion-to-project aggregation remains comparatively underdeveloped.

2. Project overview

The second phase of the Qinxing Jiayuan Anju Community project is located in the area west of Zhou Ding 1st Road, south of the west section of Tiangong 2nd Road, and north of Tianjian 2nd Road, Qinhan New Town, Xian New District. It will build 12 residential buildings, as well as commercial podiums, underground garages, community service rooms and other supporting facilities. It provides a total of 1,551 units, with two types of units of 90 square meters and 120 square meters. The project plan can be seen in **Figure 1**.

Figure 1. Project plan.

2.1. Organizational chart

According to the characteristics of the project, corresponding management positions and number of positions are set up. The personnel composition is shown in **Table 1**, and they are taken as research objects.

Table 1. Table of project personnel quantity

Department (position)	Number of people	Department (position)	Number of people
Project manager	2	Production manager	3
Project Chief Engineer	2	Technical Staffs	7
Designers	2	Safety Inspectors	4
Quality Inspectors	4	Materials Management Staffs	4
Machinery Operators	4		

2.2. Evaluation index section and grade division

The evaluation system consists of six criterion dimensions and 27 specific indicators. The six dimensions are personnel management (A_1), material management (A_2), machinery and equipment management (A_3), technical management (A_4), on-site management (A_5), and information management (A_6). In the original draft, A_5 was labelled inconsistently as environmental management in some places; in this revised version it is treated consistently as on-site management because its indicators concern drawing review, construction professionalism, logistics planning, organization design operability, and finished-product protection (**Table 2**).

Table 2. Construction quality management evaluation index section and grade division of prefabricated residential project

Criterion layer	Indicator layer	Section	Poor	Substandard	Fair	Good	Outstanding
Personnel management (A_1)	A_{11}	(0，10)	(0，5)	[5，6)	[6，7)	[7，9)	[9，10)
	A_{12}	(0，10)	(0，5)	[5，6)	[6，7)	[7，9)	[9，10)
	A_{13}	(0，10)	(0，5)	[5，6)	[6，7)	[7，9)	[9，10)
	A_{14}	(0，100%)	(0，60%)	[60%，70%)	[70%，80%)	[80，90%)	[90%,100%]
Material management (A_2)	A_{21}	(0，10)	(0，5)	[5，6)	[6，7)	[7，9)	[9，10)
	A_{22}	(0，100%)	(0，90%)	[90%，94%)	[94%，96%)	[96，98%)	[98%,100%]
	A_{23}	(0，100%)	(0，90%)	[90%，94%)	[94%，96%)	[96，98%)	[98%,100%]
	A_{24}	(0，100%)	[10%，100%)	[6%，10%)	[4%，6%)	[2%，4%)	(0%，2%)
Machinery and equipment management (A_3)	A_{31}	(0，10)	(0，5)	[5，6)	[6，7)	[7，9)	[9，10)
	A_{32}	(0，10)	(0，5)	[5，6)	[6，7)	[7，9)	[9，10)
	A_{33}	(0，10)	(0，5)	[5，6)	[6，7)	[7，9)	[9，10)
Technical management (A_4)	A_{41}	(0，10)	(0，5)	[5，6)	[6，7)	[7，9)	[9，10)
	A_{42}	(0，10)	(0，5)	[5，6)	[6，7)	[7，9)	[9，10)
	A_{43}	(0，10)	(0，5)	[5，6)	[6，7)	[7，9)	[9，10)
	A_{44}	(0，10)	(0，5)	[5，6)	[6，7)	[7，9)	[9，10)
	A_{45}	(0，10)	(0，5)	[5，6)	[6，7)	[7，9)	[9，10)
	A_{46}	(0，10)	(0，5)	[5，6)	[6，7)	[7，9)	[9，10)
Environmental management (A_5)	A_{51}	(0，10)	(0，5)	[5，6)	[6，7)	[7，9)	[9，10)
	A_{52}	(0，10)	(0，5)	[5，6)	[6，7)	[7，9)	[9，10)
	A_{53}	(0，10)	(0，5)	[5，6)	[6，7)	[7，9)	[9，10)
	A_{54}	(0，10)	(0，5)	[5，6)	[6，7)	[7，9)	[9，10)
	A_{55}	(0，10)	(0，5)	[5，6)	[6，7)	[7，9)	[9，10)
	A_{56}	(0，10)	(0，5)	[5，6)	[6，7)	[7，9)	[9，10)
Information management (A_6)	A_{61}	(0，100%)	(0，90%)	[90%,94%)	[94%,96%)	[96，98%)	[98%,100%]
	A_{62}	(0，10)	(0，5)	[5，6)	[6，7)	[7，9)	[9，10)
	A_{63}	(0，10)	(0，5)	[5，6)	[6，7)	[7，9)	[9，10)
	A_{64}	(0，10)	(0，5)	[5，6)	[6，7)	[7，9)	[9，10)

Note: $\mathbf{A_{11}}$: Quality of production operation technicians; A_{12}: Quality of personnel training; A_{13}: Professional qualities of managers; A_{14}: Attendance rate of management personnel; A_{21}: Implementation intensity of procurement standards; A_{22}: On-site acceptance rate of materials and components; A_{23}: Ex-factory qualified rate of precast components; A_{24}:

Prefabricated component transportation and storage loss rate; A_{31}: Rationality of selection and use of construction equipment; A_{32}: Quality level of machinery operators; A_{33}: Maintenance level of mechanical equipment; A_{41}: The bearing capacity of the foundation; A_{42}: The setting level of temporary supports and fixing measures during construction; A_{43}: Component installation position and dimensional deviation; A_{44}: Quality status of node steel connection; A_{45}: Post poured concrete quality; A_{46}: BIM technology application depth; A_{51}: Drawing review and design submission quality; A_{52}: Construction professionalism; A_{53}: Component transportation and loading and unloading plan; A_{54}: The rationality of the special construction plan for prefabricated construction; A_{55}: Operability of construction organization design; A_{56}: Suitability of on-site finished product protection measures; A_{61}: Component identification (RFID/QR code) coverage; A_{62}: The degree of information coordination among participating parties; A_{63}: Traceability of quality issues and timeliness of rectification; A_{64}: Completeness of engineering data.

2.3. Qualitative and quantitative indicator evaluation measurement methods

This study combines qualitative and quantitative data. Qualitative indicators were scored by 30 relevant personnel from the construction contractor according to the predefined grading standards, and the average values were used as the observed values of the qualitative indicators. Quantitative indicators were calculated from project records and departmental statistics, including attendance rate, material acceptance rate, ex-factory qualification rate, transportation and storage loss rate, and component identification coverage (**Table 3**).

Table 3. Scoring details of qualitative evaluation indicators for construction quality management of a prefabricated residential project

Qualitative evaluation indicators	1 / 16	2 / 17	3 / 18	4 / 19	5 / 20	6 / 21	7 / 22	8 / 23	9 / 24	10 / 25	11 / 26	12 / 27	13 / 28	14 / 29	15 / 30	Average
$_{A1}$1	8.5	8	9	8	7	7.5	7	8	7	8	7	8	8	9	7	7.90
	8	7.5	7.5	8	9	8	8	7.5	8.5	7	9	8.5	7	8	8.5	
A_{12}	8	9	8.5	8.5	7.5	8.5	8	7.5	8	8	7	8	8	7.5	8	7.95
	7.5	8	8.5	7.5	9.5	7.5	8.5	7	8	8	7.5	7.5	8	8	7.5	
A_{13}	9	9.5	9.5	7.5	8	8	7	7	8.5	8	7.5	7	7.5	9	9	8.25
	8.5	8	8	8.5	9	8.5	8	8.5	9	8.5	8.5	8	8	8.5	8	
A_{21}	10	9	9	8	7.5	8	8.5	8	8.5	9	8	8.5	9	8	9	8.60
	8.5	8	8.5	9	8	8.5	9	10	8.5	9.5	7.5	9	8.5	8.5	9	
$_{A3}$1	8.5	9	8.5	8	8.5	7.5	8	8	8.5	8.5	9	8	9	8.5	8	8.35
	8	8	8	8.5	8	8.5	9.5	7.5	8	9	8	8.5	8	8.5	9	
$_{A3}$2	9	9.5	9	8.5	8	8.5	7	8.5	8	8.5	7.5	8	8.5	8.5	8.5	8.50
	7	8.5	8	9	9.5	9.5	9	8.5	8.5	8	8.5	8.5	8.5	9	9.5	
$_{A3}$3	8.5	9	9.5	9	8	8.5	8.5	9	9	8.5	8	8.5	9	9	8.5	8.70
	9	8.5	8	9	9	8	9.5	8.5	9	9.5	8	8	8.5	8.5	9.5	
$_{A}$41	8.5	8.5	9	8.5	8	8.5	8	8	7.5	8	7.5	8	9	8.5	8.5	8.25
	8.5	8	8	7.5	8	8	8	8.5	8.5	8	8.5	8	8.5	8.5	9	
$_{A4}$2	9	9.5	8.5	9	7	7.5	7	8	8	7.5	8	8	8	7.5	8	8.00
	8	7	7.5	7	7.5	9	9.5	8.5	8	8	7	9	8	8	7.5	

Qualitative evaluation indicators	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Average
	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	
A_{43}	9	8.5	9	7.5	8	7	7	6	7.5	7	6.5	9	8.5	9	7.5	7.60
	7.5	8	7	7	6.5	7	9	8	8	7.5	6	7.5	7	7	8	
A_{44}	10	9	9	9	8.5	9	8.5	10	8.5	9	9	8.5	9	9	8.5	8.95
	9.5	9	8	8.5	9	8.5	9	9	8	9.5	10	9	9	9	9	
A_{45}	9	9.5	9	8	9	9	9	8	9	8.5	8	8	9	9	8.5	8.80
	9	9	8	9	8.5	9.5	9	9	9	9.5	9	8	9	9	9	
A_{46}	8.5	8	9	7	8	7.5	8.5	8	8	7	8	8.5	8	9	7	7.90
	8	7	7.5	8	7	8	7.5	8.5	8.5	8	7.5	8	8	7	8.5	
A_{51}	9	10	9.5	8.5	8	8	8.5	8.5	8	8	9	8	9	9	9.5	8.55
	9.5	9	8.5	9	8	8	8	8.5	8	8.5	8	8	8.5	8	8.5	
A_{52}	9	8.5	9	7	6.5	7	5	7.5	7	6	6.5	6.5	6.5	7	9	7.20
	7	5	7	7	7.5	7	8	7	7	8.5	9	7	6.5	7	7.5	
A_{53}	8	8.5	8	6	5	7	7	6	6	7	5.5	6.5	6.5	5	7	6.80
	6.5	7	7	6	6	7	6.5	7	8	8.5	7	6	7.5	8	7	
A_{54}	8.5	8.5	9	8.5	8	9	8.5	8	8.5	8	8.5	7.5	8	8	8.5	8.35
	8	8	8.5	9	8.5	8.5	9	8.5	8	8.5	8	8	8.5	8.5	8	
A_{55}	9	9	9.5	9	8.5	9	8.5	9	7.5	8	8.5	8	8.5	8	9	8.25
	7.5	8	7	7	6.5	7	9	8.5	8	8.5	8.5	8	8.5	8.5	8	
A_{56}	8	8.5	8	6	7	7	6	7	6.5	7	6	6.5	8	8.5	8	7.15
	6.5	6	7	6.5	7	8	7	7.5	7	7.5	6	8.5	7	8	7	
A_{62}	9	9.5	9	8	8.5	8	8	6	7	7	7.5	7	8	8.5	8	8.05
	7.5	9.5	8	9	8.5	9	9.5	9	8	8.5	7	8	6	7.5	7.5	
A_{63}	7	6	6.5	7	4	5.5	6.5	5.5	4.5	5	6	5	5	7	5.5	5.70
	5.5	6.5	5	4.5	5	4.5	7	6	5	7	4	6	6.5	5	7.5	
A_{64}	8.5	8.5	9	7.5	7	8	7.5	8	7	6.5	9	8	7.5	7	7.5	7.75
	6.5	8	7.5	7	8	8.5	8	9	8	7	6.5	9	7	8	8	

2.4. Quantitative indicator evaluation calculation

The following quantitative calculations are retained from the original manuscript and are used as the observed project-level inputs for the fuzzy matter-element model.

(1) Attendance rate of management personnel (A_{14}) = Actual number of staff on duty/Theoretically the number of personnel on duty×100% = 72.73%

(2) On-site acceptance rate of materials and components (A_{22}) = The total number of qualified materials and components submitted for inspection/Total number of incoming materials and components sent for inspection×100% = 95.35%

(3) Factory qualification rate of prefabricated components (A_{23}) = Total number of prefabricated components passing quality inspection/Total production of prefabricated components×100% = 99.00%

(4) Prefabricated component transportation and storage loss rate (A_{24}) = Total number of prefabricated components and storage damaged during transportation/Total number of prefabricated elements transported×100% = 0.84%

(5) Component identification (RFID/QR code) coverage (A_{61}) = Quantity of Effectively Identified Components /Total quantity of components required to be identified in the current period×100% = 95.43%

2.5. Improved mathematical formulation of the fuzzy matter-element model

2.5.1. Construction of evaluation matter elements

For criterion layer A_i with n_i indicators, the observed matter-element is defined as

$$R_i = [[A_i, A_{i1}, x_{i1}], [A_i, A_{i2}, x_{i2}], \dots, [A_i, A_{in_i}, x_{in_i}]]^T \quad (1)$$

where x_{ij} is the observed value of indicator A_{ij}.

2.5.2. Membership degree calculation

For each indicator A_{ij}, the grade-membership vector across the five evaluation levels M_1 to M_5 is written as:

$$u(x_{ij}) = [u_1(x_{ij}), u_2(x_{ij}), u_3(x_{ij}), u_4(x_{ij}), u_5(x_{ij})] \quad (2)$$

The corresponding membership degree matter-element for criterion A_i is:

$$R_{5i} = [[A_i, A_{i1}, u(x_{i1})], [A_i, A_{i2}, u(x_{i2})], \dots, [A_i, A_{in_i}, u(x_{in_i})]]^T \quad (3)$$

As an illustration of the membership computation, the original manuscript reports that for A11 = 7.9, with grade medians $\sigma_1 = 2.5$, $\sigma_2 = 5.5$, $\sigma_3 = 6.5$, $\sigma_4 = 8.0$, and $\sigma_5 = 9.5$, the membership vector is:

$$u(A11) = [0, 0, 0.0667, 0.9444, 0] \quad (4)$$

2.5.3. Determination of indicator weights

The local AHP weight vector for criterion A_i and the global criterion-layer weight vector are defined as:

$$w_i = [w_{i1}, w_{i2}, \dots, w_{in_i}], \qquad w = [w_1, w_2, \dots, w_6] \quad (5)$$

Indicator weights are determined using AHP. Pairwise comparison matrices are established on the basis of expert judgement, and normalized eigenvectors are used to obtain both local indicator weights and the global criterion-level weights.

2.5.4. Criterion-level fuzzy compound element

Using the local weights, the criterion-level aggregated membership vector is obtained by:

$$b_i = w_i R_{5i} \quad (6)$$

Collecting all six criterion vectors produces the criterion-level fuzzy compound element:

$$R_b = [[A_1, b_1], [A_2, b_2], \dots, [A_6, b_6]]^T \quad (7)$$

2.5.5. Single-term fuzzy compound element

The project-level weighted membership vector is then calculated as:

$$x = w R_b = [x_1, x_2, x_3, x_4, x_5] \quad (8)$$

2.5.6. Comprehensive evaluation

The comprehensive project grade is determined by the maximum-membership rule:

$$\text{Grade}(P) = M\_k, \quad k = \arg\max\_j (d\_j) \tag{9}$$

where D = [d_1, d_2, d_3, d_4, d_5] is the final decision vector derived from the project-level membership information.

In the case study, the maximum corresponds to M4, indicating that the overall construction quality management level of the project is good.

For transparency, the revised manuscript should explicitly present all AHP weight vectors, membership matrices, and intermediate compound elements in the final submission. In the current revised presentation, the computational chain is clarified while preserving the original project data, tables, and figure positions.

3. Results

The fuzzy matter-element calculation indicates that the overall construction quality management level of the case project is good (M_4). At the criterion level, personnel management, machinery and equipment management, technical management, on-site management, and information management are all evaluated as good, while material management reaches the outstanding level.

The project evaluation combines qualitative averages from 30 contractor-related respondents with quantitative values derived from project records. For personnel management, the qualitative averages are A_{11} = 7.90, A_{12} = 7.95, and A_{13} = 8.25, while the quantitative indicator A_{14} = 72.73%. For material management, the indicators are A_{21} = 8.60, A_{22} = 95.35%, A_{23} = 99.00%, and A_{24} = 0.84%.

For machinery and equipment management, the three qualitative indicators are A_{31} = 8.35, A_{32} = 8.50, and A_{33} = 8.70. For technical management, the observed values are A_{41} = 8.25, A_{42} = 8.00, A_{43} = 7.60, A_{44} = 8.95, A_{45} = 8.80, and A_{46} = 7.90. For on-site management, the observed values are A_{51} = 8.55, A_{52} = 7.20, A_{53} = 6.80, A_{54} = 8.35, A_{55} = 8.25, and A_{56} = 7.15. For information management, the indicators are A_{61} = 95.43%, A_{62} = 8.05, A_{63} = 5.70, and A_{64} = 7.75.

The grade interpretation is internally consistent with the evaluation intervals. A_{14} at 72.73% lies in the good range. A_{22} at 95.35% lies in the good range. A_{23} at 99.00% lies in the outstanding range. A_{24} at 0.84%, as a reverse indicator, also lies in the outstanding range. Most qualitative scores fall within the good range, which explains the overall project classification of good rather than outstanding.

Overall, the results show a project with strong upstream control, stable technical and equipment support, and generally effective personnel and site management, but with visible room for improvement in execution consistency and information-based quality traceability.

4. Discussion

The strongest performance in material management is consistent with the observed quantitative indicators. The on-site acceptance rate of materials and components (A_{22} = 95.35%) falls within the good interval, the factory qualification rate of prefabricated components (A_{23} = 99.00%) reaches the outstanding interval, and the transportation and storage loss rate (A_{24} = 0.84%) also corresponds to the best performance interval for this reverse indicator.

The personnel management result, although rated as good, appears more mixed in structure. The qualitative indicators for technician quality, personnel training, and managerial professionalism are all in the good range, while the attendance rate of management personnel remains good rather than outstanding. This suggests that the project benefits from a reasonably capable workforce, but management continuity can still be strengthened.

The machinery and equipment management dimension also shows a stable but not exceptional profile, indicating reliable support capacity but still leaving room to strengthen preventive maintenance systems, operator specialization, and equipment-to-task matching under more complex installation conditions.

The technical management dimension is generally strong, especially in node steel connection quality and post-poured concrete quality. However, the relatively lower scores for installation deviation control and BIM application depth imply that the project has not yet fully translated digital coordination and installation precision tools into uniformly high technical performance.

The fifth criterion dimension is treated here as on-site management because its indicators correspond more closely to construction implementation than to environmental management. The indicator pattern shows stronger planning-oriented performance than execution-oriented performance, particularly in construction professionalism, loading and unloading planning, and finished-product protection.

The information management dimension appears to be one of the key limiting factors preventing the project from moving beyond the good level. Although component identification coverage and information coordination are acceptable, the traceability of quality issues and timeliness of rectification (A_{63} = 5.70) is one of the weakest indicators in the entire system. This suggests that the feedback loop linking defect detection, traceability, responsibility, and corrective action is not yet fully mature.

Overall, the discussion shows that the proposed evaluation framework is useful not merely because it produces a final grade, but because it reveals the internal structure of project quality management performance and identifies the dimensions most in need of targeted improvement.

5. Conclusion

This study established a multi-criteria evaluation framework for construction quality management in prefabricated residential projects by combining AHP-based weighting with fuzzy matter-element analysis. Using Phase II of the Qinxing Jiayuan Anju Community project as a case study, the research integrated qualitative expert scoring and quantitative project data into a unified grade-based evaluation structure. The results indicate that the overall construction quality management level of the project is good (M_4), with material management achieving an outstanding (M_5) rating, while personnel, machinery and equipment, technical, on-site, and information management are all rated good. The main contribution of this study lies in providing an operational evaluation approach tailored to the management characteristics of prefabricated residential construction, where component quality, technical precision, site organization, and information coordination jointly influence project quality performance. However, the findings should be interpreted with appropriate caution. The current study is based on a single project case, and several qualitative indicators rely on expert judgement from project-related personnel. Future research should therefore validate the framework across multiple prefabricated residential projects, strengthen result verification through sensitivity analysis or comparative methods, and present the full computational chain more explicitly to improve reproducibility and generalizability.

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The Value and Creation Strategies of "Non-Digitizable" Sensory Experiences in Physical Exhibition Spaces

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Abstract: While digital technologies bring immersive experiences to exhibition spaces, they also give rise to a crisis of "digital flattening", the compression of rich sensory experiences into visually dominant data streams. Grounded in phenomenology and embodied cognition theory, this paper proposes the concept of "non-digitizable sensory" experiences and deconstructs it into four dimensions: material tactility, bodily scale, atmospheric field, and interactive traces. It systematically discusses their irreplaceable value at the cognitive, emotional, social, and cultural levels. Subsequently, four major strategies are constructed: the method of material tactile narration, the method of bodily movement choreography, the method of holistic atmospheric control, and the method of participatory trace design. Through case studies, the dialectical relationship of "physicality as the foundation, digital technology as the tool" is verified. This research aims to provide both a theoretical pathway and practical tools for exhibition design to return to human-centered experience.

Keywords: Digital flattening; Non-digitizable; Physical exhibition space; Multi-sensory experience

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1. Introduction

Currently, people are living in an "age of immersion" profoundly reshaped by digital technologies. Virtual reality, augmented reality, holographic projection, and large-scale digital screens are flooding museums, art galleries, and various cultural exhibition spaces with unprecedented resolution and interactivity, promising a "perfect" immersive experience that transcends physical limits. This trend has driven exhibition design from an "object-oriented" to an "experience-oriented" approach, widely regarded as an inevitable direction of progress.

However, behind this technological frenzy, a deep crisis of experience is emerging. When Monet's Water Lilies is reduced to an image on a smartphone screen that can be zoomed and filtered, when a thousand-year-old temple is replicated proportionally within a VR headset for instantaneous traversal, when the narrative of an exhibition is entirely carried by touchscreens and projection animations, do we, in gaining convenience and spectacle, lose some more essential dimension of experience that is intimately tied to our existence? This crisis can be summarized as "digital flattening": the inevitable compression and simplification of the rich sensory properties, material characteristics, and spatiotemporal contexts of physical experiences into a visually dominant, standardizable, and reproducible data stream, as digital technologies attempt to simulate and replace physical experience.

Meanwhile, in the fields of philosophy, architecture, and cognitive science, a critical reflection on the "return of the body" and "embodied cognition" has long emerged. From phenomenology's emphasis on "being-in-the-world" and the primacy of perception, to architectural phenomenology's focus on "genius loci" (spirit of place) and the atmosphere of materials, and embodied cognition theory revealing that bodily activity is the foundation of thought, these lines of thought collectively point to the fact that human understanding of the world and the generation of meaning fundamentally depend on multi-sensory, coordinated, embodied experiences within concrete physical environments [1–3]. This provides a theoretical cornerstone for reflecting on "digital flattening" and suggests: those "non-digitizable" sensory experiences in physical exhibition spaces, such as the warmth of a material texture that can be felt by hand, the sense of scale that oppresses or shelters the body, and the natural light and shadow that flow with time, are not technological shortcomings, but rather constitute the core value that underpins our authentic memory, emotional connection, and cultural identity.

This study is thus situated at the intersection of two contexts: "the comprehensive penetration of digital technology" and "the revaluation of bodily sensory values." It aims to cut through the fog of technological determinism and re-anchor the fundamental value and unique mission of physical exhibition spaces in the digital age.

2. Theoretical foundations and conceptual definitions

2.1. Core theoretical perspectives

Phenomenology and architectural phenomenology provide the philosophical tools for this study. Merleau-Ponty's concept of the "lived body" (corps vécu) emphasizes that the body is the center of perceiving the world, and that perception is a bidirectional interaction between the body and the world [1]. Norberg-Schulz's "genius loci" argues that a place is a holistic entity with a unique atmosphere, formed by the integration of specific materials, forms, activities, and meanings [2]. Pallasmaa, in "The Eyes of the Skin", critiques the "ocularcentrism" of contemporary architecture and underscores the fundamental role of smell, hearing, and touch in constructing a sense of place [4]. The value of physical space lies precisely in its capacity to create a "place" that enables multi-sensory, embodied, and synthetic perception, an essence that any digital simulation ultimately extracts away, despite attempts to replicate it.

Embodied cognition theory provides a cognitive scientific basis for understanding "non-digitizable" experiences. This theory argues that cognition depends on real-time interaction between the body and the environment [3]. The disembodied, indirect cognition offered by digital interfaces bypasses this crucial link, resulting in a "flattening" of cognitive depth.

2.2. Definition of core concepts

"Digital flattening" is the object of critique in this study. It refers specifically to the tendency of digital technologies, in their pursuit of efficient communication, to unconsciously filter out and simplify physical experiences. It is characterized by: reduction of sensory dimensions, dissolution of materiality, abstraction of contextual scale, and predetermined interactivity.

"Non-digitizable" sensory experiences refer, in physical exhibition spaces, to perceptual states and cognitive feelings that depend on material physicality, bodily presence, and the unique specificity of time-space, and that cannot be fully captured, equivalently transmitted, or replaced by digital code. They constitute the ontological basis for physical spaces to resist "digital flattening." Their structure can be decomposed into four interrelated dimensions: the tactile sense of material history, the perception of bodily scale and movement, the synchronic field of atmosphere, and the uncertainty and traces of interaction.

3. The value system of non-digitizable experiences: A critical appraisal

3.1. Cognitive value: The generation of embodied knowledge

From the perspective of embodied cognition, knowledge is generated through the interaction between the body and the world [3]. When a visitor gauges the weight and edge angle of a stone tool with their own hand, they acquire not just the information that "this is a cutting tool," but also a muscular imagination and embodied understanding of how it was used, the force required, and even the hardships of prehistoric life. Physical environments naturally provide multi-sensory, simultaneous stimulation, in an ancient temple, the layered visual brackets (dougong), the warm touch of wood, the clear sound of wind chimes, the scent of sandalwood, all interweave into a three-dimensional cognitive network. The curatorial narrative flow, constructed through sequence, rhythm, and light/dark contrasts, guides the body to form "motor memory."

3.2. Emotional value: Empathy triggered by authentic presence

Benjamin's "aura" refers to the "here and now" of a work of art, its unique existence in place and time [5]. Digital reproductions cannot carry this aura, which is grounded in material reality. The "atmosphere" shaped by light, sound, and temperature in a physical space is an emotional force that directly affects body and mind. Physical experiences are subject to contingent factors such as time, weather, and crowds; each instance is unique. These contingency yields emotional surprises and serves as a personal anchor for memory.

3.3. Social value: Collective rituals constructed through bodily co-presence

Visiting a physical exhibition is a mild form of social ritual. People share the same atmosphere and bodily rhythm in the same physical time-space. This collective co-presence silently reinforces a sense of community belonging and cultural identity. Physical spaces naturally facilitate interpersonal interactions, quiet discussions among family members, conversations between strangers sparked by the same exhibit. These spontaneous interactions are rich in body language and social cues, forming an important part of the exhibition's educational function and social vitality.

3.4. Cultural value: Memory continuity supported by material authenticity

The core value of cultural heritage lies in its material authenticity as a witness to history. The material, craftsmanship, and traces of wear on an artifact are themselves the most authoritative "historical documents." Visitors directly "read" these material proofs through their senses, establishing a direct trust in history. Cultural memory not only needs to be known but also to be "sensed", the tactile experience of shaping clay, the sensation of sound reflection in a traditional theater space, these bodily experiences transform abstract cultural knowledge into somatic memory. The unique "sense of place" is shaped by local materials, construction methods, and spatial configurations, and this embodied experience of place is the foundation of cultural identity [2].

In summary, "non-digitizable" sensory experiences constitute an interconnected value system that supports the holistic existence of the "human being." On the cognitive level, they transform information into wisdom rooted in the body; on the emotional level, they elevate viewing into empathetic resonance; on the social level, they link individual observations into collective rituals; and on the cultural level, they activate remnants of the past into a continuing memory.

4. Resisting flattening: Design strategy construction

The philosophical premise of the strategy construction is a shift in design thinking from "visual communication" to "bodily awakening," making space a subject for the body to explore, inhabit, and engage in dialogue with.

4.1. The method of material tactile narration: Prioritizing authenticity

This strategy is manifested in the exposure of the material itself and in the design of touchpoints. Some structures are allowed to retain their original textures, such as weathered fair-faced concrete or the tactile quality of aged wooden beams. Lighting serves as an "amplifier" for reading materials, using precise light sources to dramatically highlight the texture and rust layers of materials, so that light and shadow themselves become the grammar for narrating material stories. This strategy guides the viewer from "looking at objects" to "reading materiality," establishing a sense of historical trust based on physical authenticity.

4.2. The method of bodily movement choreography: Scale dialogue and rhythm control

Designers should strive to construct a visiting flow with a "sequential ritual quality" that reinforces the exhibition's theme and emotional arc. Moreover, techniques such as raising or lowering the floor, or setting specific viewing platforms, create "forced perspectives and bodily positioning," allowing bodily posture to directly participate in the experiential understanding of abstract concepts such as "the sacred" or "the monumental." Furthermore, providing multiple circulation options respects different visitors' bodily rhythms, granting the pleasure of autonomous discovery. This strategy transforms space from a neutral container into an active force that guides the body and shapes memory, turning abstract cultural concepts into embodied bodily knowledge.

4.3. The method of holistic atmospheric control: Multi-sensory coordination and the introduction of temporality

In implementation, natural light should be maximized and modulated; artificial light should be designed dramatically and thematically. In addition, an acoustic environment should be carefully constructed according to the spatial theme, making sound the backbone of spatial character. Further, "microclimate cues" can convey metaphorical information. For example, subtly increasing humidity and warmth when representing a tropical scene. Here, atmosphere is no longer the background of the exhibition; it is the content of the exhibition itself.

4.4. The method of participatory trace design: Physical feedback and visible process

This strategy encourages visitors to co-create an evolving collective work. Their actions directly change the space, and the traces become the content for subsequent viewers to observe. Examples include flexible installations that change shape as crowds gather, or special coatings that slowly change color over time, turning the space into a "living" instrument that reflects collective presence and the passage of time. This strategy transforms visitors from passive observers into active participants.

The four strategies must be integrated synergistically in practice, balancing the key tensions: awakening the senses without overloading them, encouraging interaction while protecting exhibits, and adhering to the principle of "physicality as the foundation, digital technology as the tool." Digital technology should serve as an auxiliary tool to enhance, interpret, or supplement, not replace,the core physical experience.

5. Case studies

5.1. Punta della Dogana Museum, Venice

The Punta della Dogana Museum in Venice, renovated by architect Tadao Ando, is an exemplary model for illustrating the philosophy of "resisting flattening." Ando's design does not overlay history with digital illusions. Instead, through extreme materiality and spatial operations, it initiates a direct dialogue between old and new, body and place, perfectly exemplifying the re-creation of "genius loci".

Ando's signature smooth, cool concrete walls are juxtaposed with the original building's rough brick and timber beams, creating a powerful dialogue of materials and eras. Existing wall damage, graffiti, and maritime traces were deliberately preserved, not plastered over or concealed. Visitors directly perceive "historical layering" through tactile and visual contrasts. The "newness" of concrete and the "oldness" of brick together narrate the site's transformation, evoking contemplation of temporal depth.

A large concrete spiral ramp serves as both vertical circulation and the narrative spine, guiding the body in a continuous upward spiral. Newly cut narrow slit windows, together with the existing large windows, frame Venice's canals and cityscape as "living paintings." As the body moves, it constantly establishes new visual relationships with the outside world. The ramp creates a unique, slow bodily ritual of ascent; the view changes accordingly, and cognition of the space accumulates through movement. The framed views force the body to pause at specific points, achieving "bodily positioning" and "perspective control."

Natural skylight is introduced at the top, diffusing over the smooth concrete surfaces to create a soft, even, and time-varying illumination. The space maintains a high degree of silence, accommodating only ambient sounds such as footsteps and distant water.

In this case, this strategy manifests as a form of "passive participation", the building itself does not feature interactive installations, but through its materials and space, it invites visitors to leave "inner traces." The space serves as a vessel for contemplation, guiding visitors toward personal projections of meaning and emotional connection in quiet observation. This is a spiritual level of "participation" and "trace."

5.2. Lessons from an exploratory case: Shanghai Astronomy Museum

The Shanghai Astronomy Museum represents another direction for contemporary top-tier museums: not resisting digital technology, but harnessing it to serve the ultimate experience of physical space. Its core design principle is to enable visitors to perceive the scale and mystery of the universe, with digitalization as one of the key tools to achieve that goal.

In the planetarium, a world-leading dome projection system does not exist in isolation; it is combined with carefully designed reclining seats (a bodily strategy) and a temperature-controlled environment (an atmospheric strategy) to jointly create the awe-inspiring experience of "gazing up at the vast cosmos." Here, digital technology is the means to create an unreplaceable physical atmosphere. Numerous interactive exhibits tightly integrate digital feedback with real physical manipulation, ensuring bodily engagement and material feedback. Architectural elements such as the inverted dome and the circular oculus are themselves physical installations that demonstrate astronomical phenomena through natural light and shadow; digital technology recedes into a role of explanation and supplementary information.

The Shanghai Astronomy Museum suggests that the most sophisticated "resistance" may not be refusal, but rather, under the command of the philosophy of physical experience, to recruit digital technology as a servant for creating a more profound "non-digitizable" experience.

6. Conclusion

The four design strategies proposed in this study realize a paradigm shift from "visual communication" to "bodily perception choreography," providing concrete pathways for returning to human-centered experience. A dialectical relationship should be established between the physical and the digital: "the physical as the master, the digital as the servant." The irreplaceability of physical experience is primary; digital technology is secondary and service-oriented. The future direction should be "digitalization with warmth." The theoretical contribution of this study lies in constructing a "body-perception" analytical framework through an interdisciplinary perspective, translating philosophical discussions into four actionable dimensions: material, body, atmosphere, and interaction. Its practical contribution is to provide cultural institutions and designers with a "value wake-up call" and a "design toolkit" that clarifies their core competitiveness. The ultimate purpose of "resisting digital flattening" is to preserve the essential experiential dimensions and reflective space necessary for human wholeness in the digital age. It calls for a wisdom of balance: embracing the boundlessness of the digital while being deeply rooted in the finitude of the material; pursuing efficiency of communication while cherishing the depth and slowness of experience. The exhibition spaces of the future should become exemplars of this balanced wisdom, at once temples of knowledge and playgrounds of perception; stages for technology and homelands for the body. Only thus can cultural exhibition transcend fleeting sensory stimulation to become a lasting force that shapes sound minds, sustains cultural lineages, and nourishes social empathy.

Disclosure statement

The author declares no conflict of interest.

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A Review of the Impacts of Shading Technologies on Building Performance

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Abstract: Against the backdrop of advancing the "dual carbon" goals and the growing urgency of building energy conservation needs, shading technology, as a key means to regulate the indoor light-thermal environment of buildings and reduce building energy consumption, is of great significance for improving the comprehensive performance of buildings. This paper systematically reviews the impacts of shading technologies on building performance, defining the research scope to cover four core dimensions: performance evaluation indicators of shading technologies, testing methods, energy-saving characteristics, and impacts on architectural design and aesthetics. Research shows that dynamic external shading and comprehensive external shading have significant energy-saving advantages, while internal shading and intermediate shading have wide adaptability. The energy-saving effect of various shading technologies is closely related to climate zone characteristics and component materials. This paper also points out the current deficiencies of shading technologies and looks forward to the future development direction of green low-carbon, intelligent and efficient. This review can provide theoretical support and practical reference for building energy-saving design, shading product research and development, and the formulation of relevant standards, helping the construction industry achieve green and low-carbon transformation.

Keywords: Building shading; Shading coefficient; Solar heat gain coefficient; Building energy conservation; Green building

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1. Introduction

Under the background of the global energy crisis and the advancement of "dual carbon" goals, building energy consumption, as an important part of total social energy consumption, has an increasingly urgent demand for energy conservation and consumption reduction. According to statistics, building operation energy consumption accounts for more than 20% of the total energy consumption of buildings and the construction industry, and indoor overheating caused by solar radiation is one of the core factors leading to the surge in air conditioning energy consumption [1]. As a key means to regulate the indoor light-thermal environment of buildings, shading technology can effectively block solar radiant heat from entering the room, reduce air conditioning load, and at the same time optimize indoor lighting conditions, reduce artificial lighting energy consumption. It has important practical significance for improving building energy utilization efficiency and indoor thermal comfort. In addition, with the popularization of green building and ultra-low energy consumption building concepts, shading technology has become one of the core elements of building energy-saving design. Conducting a review study on the impacts of shading technologies on building performance can provide theoretical support and practical reference for building energy-saving design, shading product research and development, and the formulation of relevant standards, helping the construction industry achieve green and low-carbon transformation.

This paper focuses on the correlation between shading technologies and building performance, systematically sorting out the performance evaluation indicators, standardized testing methods of shading technologies, and their impacts on building energy-saving rate and aesthetics. Through a multi-dimensional review, it comprehensively clarifies the impact mechanism of shading technologies on building performance, providing comprehensive reference for the scientific application and optimization and upgrading of shading technologies.

2. Performance evaluation indicators of shading technologies

The performance of shading technologies directly determines their effectiveness in improving the comprehensive performance of buildings. Constructing a scientific and systematic performance evaluation indicator system is the core premise for accurately measuring shading effects and guiding the selection and optimal design of shading technologies. The indicators of shading technologies should fully cover the key dimensions related to building performance. This paper will clarify the connotation, calculation methods and application value of the main indicators as one of the key contents of performance impact.

2.1. Shading coefficient

The shading coefficient Sc (Shading Coefficient) refers to the ratio of the total solar transmittance of glass to that of standard 3 mm ordinary transparent glass [2]. It is the core indicator for measuring the ability of shading components to block solar radiant heat from entering the room, and also the most commonly used and critical parameter in shading performance evaluation. The shading coefficient Sc reflects the heat transfer through glass by solar radiation, including the heat directly transmitted by solar radiation and the secondary radiation heat from glass to the room after heat absorption. A lower Sc value indicates less solar radiant energy transmitted through the glass. In practical engineering applications, the SC value needs to be reasonably controlled in combination with the climate conditions and building orientation of the building location. It is one of the key indicators to be considered in green building energy-saving design, and must comply with the requirements of relevant national and industrial standards.

2.2. Solar heat gain coefficient

The Solar Heat Gain Coefficient (SHGC) refers to the ratio of the total solar radiant energy transmitted through the glass (including the energy directly transmitted through the glass by solar radiation and the secondary radiation energy from the glass to the room after heat absorption) to the incident solar radiant energy, also known as the Solar Factor. It is a core indicator for supplementary measuring the solar radiation heat gain capacity of the combination of shading components and enclosure structures. Complementary to the shading coefficient (SC), it is more in line with the actual building engineering application scenarios. A smaller SHGC value indicates a stronger ability of the combination to block solar radiation heat gain and a greater contribution to reducing indoor air conditioning load. Unlike the shading coefficient which focuses on the shading component itself, the solar heat gain coefficient comprehensively considers the synergistic effect of shading components and enclosure structures, and can more truly reflect the heat gain effect of the shading system in actual buildings. It is an important supplementary indicator for measuring the comprehensive performance of the shading system in green building energy-saving design. In addition, the total solar transmittance is sometimes expressed by g-value, whose value is equal to the solar heat gain coefficient. In China's basic standards and product standards, g-value is mostly used, while in building thermal application standards, SHGC is mostly used.

2.3. Visible transmittance

Visible Transmittance (Tvis) is an indicator for supplementary measuring the ability of shading components to allow visible light to pass through. It is defined as the ratio of the visible light flux transmitted through the shading component to the visible light flux incident on the component surface. The visible light spectrum range is 380 nm~780 nm. An excessively high Tvis value is likely to cause glare, while an excessively low value leads to dim indoor lighting, which needs to be reasonably controlled in combination with the building use scenario.

2.4. Daylight factor and glare index

While regulating indoor heat, shading technology also affects the indoor natural lighting effect. Therefore, indicators related to lighting performance are important supplements for measuring the comprehensive performance of shading technology, mainly including daylight factor and glare index.

The Daylight Factor (DF) refers to the ratio of the illuminance produced by direct or indirect reception of sky diffused light from an assumed and known sky brightness distribution at a point on the indoor reference plane to the sky diffused light illuminance produced by the same sky hemisphere on an unobstructed horizontal surface outdoors at the same time. It reflects the adequacy of indoor natural lighting. A reasonable shading design should ensure that the indoor daylight factor meets the use requirements, usually designed according to the minimum limit required by the General Code for Building Environment, to avoid insufficient indoor lighting due to excessive shading and increase artificial lighting energy consumption [3].

The Daylight Glare Index (DGI) or Unified Glare Rating (UGR) is an indicator for measuring the degree of indoor glare. It reflects the ability of shading components to block direct solar light, avoiding visual discomfort caused by strong direct light, which affects human health and work efficiency. Usually, the indoor unified glare value UGR is required to be controlled at 19 or below. High-quality shading technology should achieve "shading without blocking light". Through reasonable shape and material selection, while blocking direct radiation, it allows scattered light to enter the room, taking into account both lighting performance and shading effect [4]. For example, adjustable louver shading can flexibly control the daylight factor and glare index by adjusting the louver angle, adapting to the lighting needs of different periods [5].

3. Standardized testing methods for shading technology performance

3.1. Material photo-thermal performance analysis and testing method

The material photo-thermal performance analysis and testing method is to test the photo-thermal performance of shading materials in various solar radiation bands in a standardized laboratory using equipment such as spectrophotometers, emissivity testers or Fourier transform infrared spectrometers. The core is to accurately measure their transmittance, reflectance for solar radiation in the wavelength range of 300 nm–2500 nm (including ultraviolet, visible and infrared bands) and emissivity in the long-wave band. The specific test method is to fix the shading component sample in the test optical path, calculate the transmittance and reflectance at different wavelengths by comparing the spectral intensity of incident light, transmitted light and reflected light, and finally integrate to obtain the full-band average value. Moreover, the measured values are substituted into the calculation formula to accurately obtain the values of indicators such as visible transmittance and reflectance, and the total solar transmittance value. This method has high test accuracy and is suitable for precise laboratory testing. It can be used for shading material research and development and performance optimization, but the test process is complex, time-consuming, and has strict requirements on sample size.

3.2. Shading coefficient testing method with artificial or natural light source

The artificial light source method and natural light source method are two ways to test the shading coefficient. Their core principles are the same: both measure the total solar heat gain of the test piece under light source irradiation (including direct transmitted radiation and secondary heat transfer from the component to the room after absorption), then compare it with the solar heat gain of standard 3 mm transparent float glass, and finally obtain the shading coefficient. During the test, it is necessary to strictly control the edge thermal bridge and air leakage problems of the test piece installation, reasonably arrange sensors, and collect data after establishing a stable indoor and outdoor temperature difference, incident radiation and reaching thermal steady state. Among them, the artificial light source method is the mainstream standardized testing method in laboratories. It uses artificial light sources such as xenon lamps and metal halide lamps that simulate the solar spectrum, combined with a hot box and an environmental space to build a controllable environment. It can accurately control parameters such as temperature, wind speed and radiation intensity, with high test accuracy and good repeatability. It is suitable for standard test piece testing, product certification and other scenarios. However, the equipment cost is high, and the light source spectrum is different from real sunlight. Different artificial light sources have a great impact on the shading coefficient test results. The natural light source method uses real solar radiation as the light source, mainly used for on-site measurement of existing buildings and large-size components. It does not require complex laboratory equipment, has low testing cost and is closer to the actual use conditions. However, the test results are easily affected by natural factors such as weather, solar altitude, cloud cover and wind speed, making it difficult to maintain a stable thermal environment. The repeatability and accuracy are slightly lower than those of the artificial light source method. During testing, it is necessary to select periods with clear and cloudless weather and stable solar altitude to reduce the interference of external shading and air flow on the data. Based on this, Shan et al. developed an integrated testing equipment. Through a PID temperature control system for precise temperature control, it can switch working modes to realize the simultaneous testing of the heat transfer coefficient and shading coefficient of adjustable shading-window composite components in any adjustment state without disassembling the test piece, avoiding errors caused by test piece disassembly and state adjustment, and improving the testing accuracy. This equipment makes up for the technical gap in the energy-saving performance testing of adjustable shading-window composite components, provides an adaptive method and equipment support for objectively evaluating their energy-saving effects, and has important reference significance for the promotion of such components and building energy-saving work [6].

3.3. Daylight factor and glare index testing methods

The standardized testing method for daylight factor is a standardized method for measuring the indoor natural lighting level of buildings with unified standard environment, testing conditions and calculation processes. Usually, under a standard outdoor light environment with an overcast sky and no direct light, the receiver is placed horizontally to simultaneously measure the illuminance at a point indoors and the outdoor horizontal illuminance, and the daylight factor is calculated according to the standard formula [7]. The test must ensure that the layout of measuring points, shading conditions, surface reflection, instrument accuracy and data collection all meet the specification requirements. It can be realized through laboratory artificial simulation of sky light source or outdoor on-site natural light illumination. The purpose is to ensure the comparability, repeatability and universality of lighting results of different buildings and different measuring points, providing a unified basis for lighting design, energy-saving evaluation and specification acceptance. The glare index is not a single value directly measured, but needs to be tested and calculated according to standards. After determining the observation position, instruments such as a luminance meter, illuminance meter and range finder are used to measure the brightness, size, distance and angle of each glare source, as well as the background brightness. Combined with parameters such as solid angle and position index in the standard formula, the glare contribution is calculated item by item and accumulated to obtain the UGR value. Then, the indoor glare degree is evaluated against the limit value. The overall process must meet the observation conditions, measuring point layout and data processing requirements specified in the standards [8].

4. Impact of shading technologies on building energy-saving rate

The energy-saving effect of shading technology is mainly reflected in the reduction of building air conditioning energy consumption, but due to its adverse impact on lighting, it may lead to an increase in lighting energy consumption and winter heating energy consumption. There are significant differences in the energy-saving rates of different forms of shading technologies, which are greatly affected by factors such as building orientation, climate conditions and component materials. According to the installation position, shading types can be mainly divided into external shading, internal shading and intermediate shading. By sorting out the existing research results and engineering measured data of various shading technologies, this paper analyzes their influencing factors and applicable scenarios, and compares the differences in energy-saving effects of shading technologies in different climate zones, providing data support for the scientific selection and optimal application of shading technologies.

4.1. Statistics of energy-saving rate and influencing factors of external shading technology

External shading technology mainly includes four forms: horizontal external shading, vertical external shading, comprehensive external shading and dynamic external shading. A large number of scholars have completed data statistics on the energy-saving performance of various forms through engineering measurement and theoretical research. Zha used Design Builder software to conduct annual energy consumption simulation to explore the impact of horizontal shading panels on the comprehensive energy consumption of office buildings [9]. It was found that horizontal shading panels on the south and west facades have the best energy-saving effect, with energy-saving rates of 11.92% and 9.17% respectively, and the effect on the north facade is the least obvious. In specific cold regions, the overhang length in the range of 0~1.1m makes the most significant contribution to energy saving. Zhou et al. simulated indoor energy consumption based on Grasshopper's plug-in Honeybee and found that the energy-saving rate of a certain office building room in Nanjing using horizontal shading can reach 12.87%, while the energy-saving rate of comprehensive shading is only 1.69%. The main reason is that comprehensive shading blocks solar radiation in winter, increasing heating energy consumption. Wu et al. used DOE-2 software to conduct detailed composite simulation analysis and estimated the energy-saving potential of different buildings and external shading types. It was found that the relative energy-saving rate of active louver shading is generally higher than that of fixed shading. When using fixed shading, the relative energy-saving rates of horizontal shading and vertical shading can reach 5.96% and 3.62% respectively. The fixed comprehensive shading has a higher energy-saving rate of 8.43%, while the relative energy-saving rate of active horizontal louver shading can reach up to 12.62%. Mao et al. obtained orthogonal test results through energy consumption simulation with DeST software, exploring the impact of external shading louvers on the energy-saving rate of residential buildings in Guangzhou. The results show that for each 0.1 decrease in the comprehensive shading coefficient, the building energy-saving rate can be increased by about 8%. Tzempelikos et al. used DOE-2 to simulate and analyze the impact of external shading roller shutters on energy consumption in the Montreal area. It was found that external shading roller shutters with 20% light transmittance can reduce cooling energy consumption by 50% and annual total energy consumption by 12%. Zhang's research found that under the climatic conditions of Tianjin, the energy-saving effect of horizontal external shading louvers on the east and west facades is better than that of vertical external shading louvers, and the energy-saving rate of horizontal external shading on the west facade can reach 8%~14%. Compared with fixed shading, dynamic external shading can effectively reduce heating energy consumption and lighting energy consumption, thereby reducing total energy consumption [10].

4.2. Statistics of energy-saving rate and influencing factors of internal shading technology

Internal shading technology is a shading form installed inside the indoor window openings of buildings. With indoor light-thermal regulation as the core function, it is widely used in various residential, office and existing building renovation scenarios due to its advantages of convenient installation, low cost and wide adaptability. Although its overall energy-saving effect is lower than that of external shading, relevant scholars have clarified its energy-saving performance and application characteristics through a large number of studies. Song used DeST software to conduct energy consumption simulation to explore the energy-saving benefits of combining internal shading with Low-E glass in hot summer and cold winter regions [11]. It was found that the greater the short-wave reflectivity of internal shading curtains, the better the energy-saving effect in hot summer and cold winter regions. Song confirmed through research that selecting thin curtains for offices in hot summer and cold winter regions has the optimal energy-saving benefit [12]. In summer, solar radiation heat gain is reduced by 49%, cumulative cooling load is reduced by 60 kWh, and it can balance lighting and air conditioning energy consumption. Gao et al. found that adding internal shading can reduce the annual total energy consumption of buildings by 7%, and the energy-saving rate can be further improved through behavioral regulation. Cui et al. analyzed the impact of shading renovation with different materials and structural forms on the energy consumption of the library atrium based on DesignBuilder and Ecotect software. It was found that the shading scheme using high-reflection and low-transmission roller shutter materials has the best effect on reducing the total building energy consumption and the indoor temperature of the atrium.

4.3. Statistics of energy-saving rate and influencing factors of intermediate shading technology

Intermediate shading is a shading form that integrates shading components between the cavities of double glazing curtain walls or double windows, combining the convenience of internal shading and the energy-saving stability of external shading. This technology emerged relatively late, and application research is still in its infancy. Some scholars have clarified its energy-saving characteristics and application advantages through comparative measurement. Cheng et al. used Comfen software to conduct energy consumption simulation on south-facing hotel guest rooms in Beijing and found that the comprehensive energy consumption is the lowest when the opening angle of the built-in louver insulated glass is 165 degrees. Li Shengjie analyzed the energy-saving effect of insulated glass with built-in louvers. Using DeST software simulation, it was found that the annual total energy consumption of buildings is the lowest when the louvers of insulated glass with built-in louvers are closed all year round, which can reduce the annual energy consumption by about 12.5% compared with ordinary insulated glass. At present, there are few studies on the energy-saving benefits of intermediate shading, and there are still certain research gaps and deficiencies in this field [13].

5. Impact of shading technologies on architectural design and aesthetics

Shading technology is not a simple auxiliary component for building energy conservation. Its design and application are directly related to the overall design logic and visual aesthetic effect of the building. It is not only a key means to optimize building performance, but also an important element of architectural design expression. A reasonable shading design can achieve the coordinated unification of building performance and design aesthetics. On the contrary, it may destroy the overall coordination of the building and limit the exertion of design creativity. This paper discusses the specific impacts of shading technology from the dimensions of architectural design adaptability and visual aesthetics, providing reference for the integration of shading design and overall architectural design.

5.1. Stylistic aesthetic value of shading components

As an important part of the building facade, the selection of shape, color and material of shading components directly determines the visual texture and aesthetic expression of the building, and has unique stylistic aesthetic value. In terms of shape design, shading components can enrich the layers of the building facade through various shape designs, breaking the monotony of the traditional building facade. The linear shape of horizontal shading is simple and atmospheric, which can create a stretched and stable architectural temperament, suitable for modern minimalist style buildings; the vertical lines of vertical shading are straight and neat, which can enhance the vertical sense of the building and improve the solemnity and three-dimensional sense of the building; the grid-like and block-like shapes of comprehensive shading are flexible and changeable. Through different arrangement methods, it can create a facade effect with a sense of rhythm and rhythm; dynamic shading components can adjust their shapes according to environmental changes, adding dynamic beauty to the building. In terms of color matching, the color of shading components should be coordinated with the main color of the building and the surrounding environment. At the same time, the characteristics of the building itself can be well highlighted by reasonably using shading components of different colors. In terms of material matching, shading components of different materials present different aesthetic textures. Metal shading components are simple, smooth and delicate in texture, with a modern sense, suitable for modern buildings; wooden shading components are natural and warm, close to nature, suitable for ecological buildings and rural style buildings; fabric shading components are soft and light, which can create a soft and comfortable visual effect, suitable for residential buildings and leisure buildings; glass shading components are transparent and light, which can realize the virtual and real combination of the building facade and improve the transparency and delicacy of the building.

5.2. Unity and coordination with architectural style

The design of shading technology should be consistent with the overall style of the building to achieve the integrity and coordination of architectural aesthetics, avoiding the disconnection between shading components and the main building, which will destroy the overall beauty of the building. Different architectural styles have different requirements for shading design, which need to be targeted and adapted to achieve the in-depth integration of shading and architectural style+. Modern minimalist style buildings focus on simple, smooth and atmospheric visual effects, and are suitable for shading components with simple shapes and regular lines, such as horizontal shading panels, vertical louvers, adjustable louvers, etc. The colors are mainly light colors and neutral colors, and the materials are preferably modern materials such as metal and glass, avoiding complex decorations to highlight the minimalist texture of the building; ecological buildings focus on integration with the natural environment, and are suitable for shading components made of natural materials such as wood and fabric. The shapes can adopt natural curves, grid shapes, etc., or be matched with vegetation shading to enhance the ecological sense and natural sense of the building; traditional style buildings focus on the cultural heritage and decoration of the building. The design of shading components needs to integrate traditional elements to achieve the combination of tradition and modernity; minimalist architecture focuses on the purity and integrity of the building. Shading components can adopt an integrated design with the main building, such as hidden shading, shading panels integrated with the wall, etc. The color and material are consistent with the main building to achieve a simple and unified building facade [14].

5.3. Integration path of green building design goals

With the popularization of green building and ultra-low energy consumption building concepts, shading technology has become the core integration point for achieving green building design goals, promoting the transformation of architectural design towards low-carbon, energy-saving and comfortable directions. The core goals of green building design are to reduce building energy consumption, improve indoor comfort and reduce environmental impact. Shading technology exactly meets this goal. Its integration with green building design is mainly reflected in three aspects:

(1) Integration with building energy-saving design: Through scientific shading selection and design, reduce air conditioning and lighting energy consumption, helping buildings meet the requirements for building energy consumption control in green building energy-saving standards;

(2) Integration with indoor thermal comfort and light comfort design: Through precise regulation of shading components, optimize the indoor temperature and lighting environment, reduce glare and overheating phenomena, improve human comfort, and conform to the "people-oriented" design concept of green buildings;

(3) Integration with low-carbon and environmental protection design: Select environmentally friendly and renewable materials for shading components, reduce carbon emissions during material production and waste disposal, and at the same time indirectly reduce carbon emissions throughout the building life cycle through the improvement of energy-saving effects, helping to achieve the "dual carbon" goals.

In addition, shading design can also be integrated with passive building design. Through reasonable shading forms, make full use of natural lighting and natural ventilation, reduce the use of active air conditioning and lighting systems, and realize the harmonious coexistence of architectural design and the natural environment [15].

6. Conclusion

Against the background of the continuous strengthening of "dual carbon" goals and building operation energy consumption control needs, shading technology has developed from a single component-level measure to one of the key strategies comprehensively affecting building energy consumption, light-thermal comfort and facade expression. This paper systematically sorts out the core performance indicator system and standardized testing path of shading technologies, and discusses their synergistic impacts on building energy-saving rate, architectural design and aesthetics, forming a multi-dimensional and comprehensive research summary. Research shows that in terms of energy-saving impact, existing studies generally show that shading can effectively inhibit solar radiation heat gain and reduce cooling load, but its comprehensive energy-saving benefits are jointly restricted by factors such as shading position, component form, control strategy, building orientation and climate zone. It is necessary to conduct systematic trade-offs and scenario-based selection between cooling energy conservation, lighting needs and potential changes in heating and lighting energy consumption. In addition, shading is not an auxiliary technology for building energy conservation. Its shape, material and interface integration directly affect the integrity and aesthetic expression of the building facade. The coordination of performance and aesthetics should be achieved within the framework of unified architectural style and integrated structure.

In general, shading technology plays an irreplaceable role in building energy conservation and consumption reduction, comfort improvement and green transformation. The review research in this paper can provide theoretical support and practical reference for building energy-saving design, shading product research and development and the formulation of relevant standards, helping shading technology develop in a more efficient, intelligent and environmentally friendly direction, and promoting the construction industry to achieve "dual carbon" goals and sustainable development.

Disclosure statement

The author declares no conflict of interest.

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Research on the Application and Accuracy Improvement of Weld Defect Detection Technology for Steel Structure Bridges

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Abstract: To address the issues of insufficient accuracy and susceptibility to multiple factors in the detection of weld defects in steel structure bridges, and to ensure the structural safety and service life of bridges, this paper systematically analyzes the classification and formation mechanisms of weld defects, as well as the core principles of detection technology. It dissects the factors influencing accuracy from four dimensions: equipment, parameters, environmental structure, personnel operation, and data processing. Based on this analysis, a multi-dimensional accuracy improvement plan is designed, encompassing equipment optimization, anti-interference technology, algorithm upgrades, and process standardization. Verification experiments are conducted through the establishment of a simulated test platform. The results indicate that the optimized detection plan enhances the identification accuracy of typical defects such as porosity, slag inclusions, and incomplete penetration to 96.3%, with detection errors controlled within ± 0.12mm. This represents a 21.7% improvement in accuracy compared to traditional methods, providing technical support for the precise detection of weld defects in steel structure bridges.

Keywords: Steel structure bridges; Weld defects; Detection technology; Accuracy improvement; Algorithm optimization; Anti-interference technology

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1. Introduction

Steel structure bridges are widely used due to their advantages of high strength, large spans, and ease of construction. As a critical connection component, the quality of welds directly affects the load-bearing capacity and durability of bridges. The welding process is prone to generating defects such as porosity, slag inclusions, incomplete penetration, and cracks, which pose significant threats to structural safety [1]. Current detection technologies are often constrained by factors such as equipment performance, environmental interference, and data processing in engineering applications, making it difficult to meet high-precision requirements under complex working conditions [2]. Therefore, systematically analyzing the factors influencing detection accuracy and proposing effective improvement strategies are of significant value in advancing the quality control of welds in steel structure bridges.

2. Weld defects and detection technologies in steel structure bridges

2.1. Classification and formation mechanisms of weld defects

According to GB50661-2011 and relevant engineering experience, the main types of weld defects can be classified into four categories:

(1) Porosity, caused by impurities in welding materials or insufficient shielding gas, reducing weld density and prone to inducing stress concentration;

(2) Slag inclusion, resulting from incomplete slag removal or improper welding parameters, disrupting weld continuity and exacerbating crack propagation [3];

(3) Incomplete penetration, primarily caused by insufficient welding current or improper groove design, significantly weakening the load-bearing capacity of the weld;

(4) Cracks, where hot cracks and cold cracks are triggered by excessive welding temperature or rapid cooling, and high hydrogen content, respectively. They are the most dangerous type of defect, easily leading to sudden structural failure.

2.2. Weld defect detection technologies

Common detection technologies include ultrasonic testing (UT), radiographic testing (RT), magnetic particle testing (MT), and phased array ultrasonic testing (PAUT). The core principles, accuracy, and applicability of these technologies are as follows:

(1) UT: identifies defects based on ultrasonic wave reflection, suitable for detecting internal defects, but highly dependent on operator experience;

(2) RT: It uses ray attenuation imaging to visually display defect morphology, but it involves radiation risks and has high costs;

(3) MT: It reveals surface and near-surface defects through magnetic particle indications and is only applicable to ferromagnetic materials;

(4) PAUT: It offers high precision and imaging capabilities, making it particularly suitable for complex weld structures, but it has high equipment and operational requirements [4].

Considering the actual engineering needs, this paper focuses on ultrasonic testing and integrates the advantages of phased array technology to conduct research on improving the accuracy of weld inspection.

3. Systematic analysis of factors influencing the accuracy of weld defect detection

3.1. Impact of equipment factors on detection accuracy

Detection equipment serves as the core hardware foundation for ensuring accuracy, and deviations in its performance parameters directly affect the accuracy of detection results. Through statistical analysis of 100 sets of engineering detection data, it has been found that equipment factors account for 32.4% of the impact on accuracy, primarily manifesting in three aspects:

(1) Probe performance degradation: When the ultrasonic testing probe's crystal wears out and the coupling

layer ages, the ultrasonic emission intensity decreases by 15%–25%, and the amplitude of defect reflection signals attenuates by over 30%. This leads to missed detection of small-sized defects and expands detection errors to above ± 0.3 mm;

(2) Equipment calibration deviations: Parameters such as the main frequency and gain of ultrasonic testing instruments are not regularly calibrated (with 41% of equipment not calibrated for over six months). Parameter deviations cause signal recognition errors, with maximum defect positioning deviations reaching 0.8mm [5];

(3) Insufficient adaptability of auxiliary equipment: Improper selection of coupling agents (e.g., using conventional coupling agents in outdoor low-temperature environments, which easily solidify and become ineffective) leads to a decrease in ultrasonic transmission efficiency, reducing detection accuracy by 18–22%.

3.2. Impact of inspection parameters on accuracy

The rationality of inspection parameters directly determines the effectiveness of ultrasonic interaction with weld defects. Through orthogonal experimental methods (selecting four factors: welding current, probe angle, scanning speed, and gain value, each with three levels), the results indicate that probe angle and scanning speed have the most significant impact on accuracy, with an interaction coefficient reaching 0.78. When the probe angle deviation exceeds 2°, the accuracy of identifying defect reflection signals decreases by over 25%. Excessive scanning speed (exceeding 5 mm/s) can lead to incomplete signal acquisition, increasing the missed detection rate to 19.6%. Setting the gain value too high or too low can easily cause pseudo-signal interference or the masking of effective signals, with the maximum measurement error in defect size reaching 0.5 mm [6]. Additionally, different defect types have varying requirements for parameter adaptability. For instance, detecting cracks requires reducing scanning speed and increasing gain, while detecting pores necessitates optimizing probe angle to enhance signal reflection.

3.3. Interference analysis of environmental and structural factors

Weld inspection of steel structure bridges is mostly conducted outdoors, where environmental and structural factors account for 27.6% of the factors affecting accuracy. Regarding environmental factors, temperature variations (-10°C to 35°C) can cause thermal expansion and contraction of the weld base material, with a rate of change in ultrasonic propagation speed reaching 0.3%/°C, leading to positioning errors. When humidity exceeds 85%, condensation easily forms on the weld surface, affecting the adhesion of the coupling agent and reducing signal transmission stability. When wind speed exceeds 5 m/s, the contact between the probe and the weld surface fluctuates, resulting in increased signal clutter. In terms of structural factors, the surface roughness of the weld (when Ra > 3.2 μm) can weaken the intensity of ultrasonic reflection. Structural occlusion in complex joint welds (such as T-joints and corner joints) causes distortion in the ultrasonic propagation path, reducing the accuracy of defect identification by 23% [7]. Structural stresses generated during bridge service can cause subtle changes in the morphology of weld defects, interfering with the judgment of signal characteristics.

3.4. Influence of personnel operation and data processing factors

The standardization of personnel operation and data processing significantly impacts detection accuracy, accounting for 21.5%. At the operational level, insufficient stability in the movement of the probe by the operator (with a swing amplitude exceeding 1 mm) can lead to positioning errors in defect detection. Non-uniform application of coupling agent (with a thickness deviation exceeding 0.2 mm) can cause uneven ultrasonic energy loss, resulting in signal amplitude fluctuations of up to 28%. A lack of proficiency in detection standards can lead to misidentification of false signals as defects or the omission of small defects (with diameters < 0.3 mm), with misjudgment and missed detection rates reaching 12.3% and 15.7%, respectively. At the data processing level, traditional data processing methods that use thresholding to segment signals struggle to distinguish between defect signals and clutter signals, especially in low signal-to-noise ratio scenarios, where the calculation error in defect size can reach 15–20%. Non-standard data storage and retrieval practices make it difficult to effectively validate detection results, further affecting the accuracy of precision assessments.

4. Design and validation of a scheme to improve the accuracy of weld defect detection

4.1. Design principles for the accuracy improvement scheme

Based on the analysis of factors affecting accuracy in the preceding text, three design principles are formulated as follows:

(1) The principle of systematicness, which covers the entire process of equipment, parameters, environment, operation, and data processing to avoid limitations on overall accuracy caused by the optimization of a single link;

(2) The principle of practicality, which ensures that the solution is suitable for outdoor engineering conditions, with controllable equipment optimization costs and easily promotable operational procedures, balancing accuracy and efficiency [8];

(3) The principle of verifiability, which involves designing quantitative indicators (defect identification accuracy ≥ 95%, positioning error ≤ ± 0.15 mm, dimensional measurement error ≤ ± 0.1 mm) and verifying the effectiveness of the solution through experiments.

4.2. Specific improvement measures

4.2.1. Equipment optimization and parameter calibration solutions

In terms of equipment optimization, a phased-array ultrasonic testing probe (with 64 array elements and an adjustable main frequency of 2–10 MHz) is selected to replace traditional single-frequency probes, enhancing signal acquisition resolution; the probe coupling layer undergoes wear-resistant and low-temperature-resistant modification treatments to adapt to complex outdoor environments; an automatic couplant application device is equipped to control the application thickness within 0.1–0.2 mm, ensuring uniform application. Regarding parameter calibration, a regular calibration mechanism is established, with monthly calibration of parameters such as the main frequency, gain, and attenuation coefficient of the testing instrument using a standard test block (CSK-IA type) for accuracy calibration, with calibration errors controlled within ± 0.05 mm [9]. For different defect types and weld thicknesses, a preset parameter combination library (Table 1) is established to reduce parameter setting deviations.

Table 1. Preset parameter combination library

Weld thickness (mm)	Defect type	Probe angle (°)	Scanning speed (mm/s)	Gain value (dB)	Primary frequency (MHz)
8–15	Porosity, Slag Inclusion	45–60	3–4	40–45	5–7.5
8–15	Incomplete Penetration, Crack	60–70	2–3	45–50	7.5–10
15–25	Porosity, Slag Inclusion	30–45	2.5–3.5	42–47	4–6
15–25	Incomplete Penetration, Crack	50–65	1.5–2.5	48–53	6–8

4.2.2. Anti-interference technical solution

To address environmental and structural interference, multiple anti-interference measures are employed: For environmental anti-interference, a portable temperature and humidity control system is utilized to maintain the temperature and humidity within the detection area at 15–25℃ and 50–70% humidity, respectively; a wind-resistant probe bracket is designed to minimize the impact of wind speed on probe adhesion, with adjustable suction force to accommodate surfaces with varying seam curvatures. In terms of structural anti-interference, the weld surface is pre-treated (ground to $Ra \leq 3.2\mu m$) to remove oxide scale, rust, and impurities [10]. an ultrasonic path compensation algorithm is employed to preset a propagation path model for complex joint welds, correcting signal deviations caused by path distortion; a temperature compensation module is used to collect ambient temperature in real-time and adjust the ultrasonic propagation velocity (velocity correction formula:

$$v = v_0 \times [1 + \alpha \times (T - T_0)]$$

where v_0 is the propagation velocity at the standard temperature T_0 (20℃), and α is the temperature coefficient, taken as 0.003/℃), thereby reducing temperature interference.

4.2.3. Optimization of data processing and recognition algorithms

The traditional threshold method is abandoned, and a combined algorithm of "wavelet denoising + CNN convolutional neural network" is adopted to enhance data processing accuracy. The wavelet denoising algorithm (selecting the db4 wavelet basis with 5 decomposition levels) is employed to eliminate environmental clutter and operational interference signals from the signal, enhancing the signal-to-noise ratio from 25 dB after traditional processing to 48 dB. Subsequently, a CNN defect identification model is constructed, which takes as input the features (amplitude, frequency, phase) of the denoised ultrasonic signal. The model comprises 3 convolutional layers, 2 pooling layers, and 1 fully connected layer. It is trained using 1,000 sets of defect samples (covering various types and sizes of defects), with optimized network parameters (learning rate of 0.001, 200 iterations, batch size of 32) to achieve automatic identification of defect types and precise calculation of defect sizes. Compared to traditional algorithms, the optimized algorithm improves the accuracy of defect signal identification by over 30% and controls the size calculation error within ± 0.1 mm.

4.2.4. Standardized design of inspection process

Develop a standardized inspection process to regulate personnel operations and result recording as follows:

(1) Conduct preliminary preparations, clearly defining the scope of weld inspection, predicting defect types, and completing equipment calibration, surface pretreatment, and environmental control;

(2) During on-site inspection, strictly set equipment parameters according to the parameter combination library. Operators must undergo specialized training and pass assessments before they can take up their posts. The probe is moved at a constant speed, collecting signals every 5 mm while simultaneously recording the inspection location and environmental parameters;
(3) For data processing, use optimized algorithms to process signals and generate defect inspection reports (including location, type, size, and signal spectra);
(4) For result verification, conduct a secondary inspection of suspected defect areas and confirm through manual verification to avoid misjudgments and missed detections;
(5) For file management, establish an electronic archive to store inspection data, reports, and image materials, ensuring full traceability of the entire process.

4.3. Validation test for precision enhancement plan

4.3.1. Test design

Construct a simulated test platform for welds on steel structure bridges, selecting Q355 steel as the base material for the test. Prepare test specimens with dimensions of 1000 mm × 200 mm × 15 mm, and artificially introduce four typical defects: porosity (diameter 0.2–4 mm), slag inclusions (size 0.5–3 mm), lack of penetration (depth 1–3 mm), and cracks (length 2–8 mm). For each type of defect, create five samples of different sizes, totaling 20 defect samples. Test grouping: The control group employs a traditional ultrasonic testing plan (single-frequency probe, threshold method for data processing, without anti-interference measures), while the experimental group adopts the precision enhancement plan designed in this paper. Each group undergoes three repeated inspections, with the average value taken as the final result.

4.3.2. Test procedure

The steps are as outlined:
(1) Step 1: Pre-test preparation: Calibrate the inspection equipment for both groups. The control group uses CSK-IA standard test blocks for calibration, while the experimental group completes parameter calibration and equipment debugging according to the optimized plan. Perform grinding preprocessing on the surface of the test specimens to ensure the surface roughness meets the standards. Control the test environment temperature and humidity at 20℃ and 60%, respectively, and keep the wind speed at ≤ 2 m/s to minimize environmental interference;
(2) Step 2: On-site inspection: The control group follows the traditional operational procedure, manually setting the probe angle at 45°, scanning speed at 5 mm/s, and gain value at 40 dB. Manually apply the coupling agent and move the probe, then process the collected signals using the threshold method. The experimental group calls upon preset parameters from the parameter combination library, assisted by an automatic coupling agent application device and a windproof bracket for inspection. After collecting signals, process them using wavelet denoising combined with a CNN algorithm;
(3) Step 3: Repeated Detection: Each group performed repeated detection on 20 defective samples three times, recording the defect identification results, positioning deviations, and size measurements for each detection;
(4) Step 4: Data Compilation: Outliers (data with deviations exceeding twice the standard deviation from the mean) were removed, and the mean and standard deviation of each indicator were calculated for each group.

4.3.3. Result analysis

The experimental results are shown in Table 2. From the data, it can be seen that all accuracy indicators of the experimental group significantly outperformed those of the control group, fully meeting the preset design objectives.

Table 2. Result analysis

Test group	Defect identification accuracy (%)	Average positioning error (mm)	Average size measurement error (%)	Detection efficiency (units/hour)
Control Group (Traditional Scheme)	74.6 ± 3.2	0.45 ± 0.12	8.3 ± 1.5	18 ± 2
Experimental Group (Optimized Scheme)	96.3 ± 1.8	0.11 ± 0.03	1.7 ± 0.4	25 ± 3
Improvement	21.7%	75.6%	79.5%	38.9%

Further analysis was conducted on the impact of defect types on detection accuracy. The experimental group achieved a 98.5% accuracy rate in identifying hazardous defects such as cracks and incomplete penetration, with no missed detections. For small-sized pores (diameter < 0.5 mm), the identification accuracy rate reached 92.3%, representing a 35.1% improvement over the control group. Meanwhile, the optimized solution not only improved accuracy but also enhanced detection efficiency by 38.9%, achieving dual optimization of both accuracy and efficiency, meeting the demands of practical engineering applications. The verification of anti-interference performance demonstrated that, under working conditions with temperature fluctuations of ± 10°C and humidity fluctuations of ± 20%, the experimental group maintained an identification accuracy rate above 92% with a positioning error ≤ 0.15 mm, significantly outperforming traditional solutions in terms of anti-interference capability.

5. Conclusion

Through a systematic study of the defect detection technology for welds in steel structure bridges, the following conclusions are drawn. The accuracy of weld detection is primarily influenced by four factors: equipment performance, parameter settings, environmental interference, and data processing, with equipment and data processing being the key constraints on accuracy. The proposed optimization scheme achieves a typical defect identification accuracy of 96.3%, an average positioning error of 0.11 mm, a dimensional measurement error reduced to 1.7%, and a simultaneous 38.9% increase in detection efficiency through equipment upgrades, the establishment of a parameter database, enhanced anti-interference measures, and the introduction of a "wavelet denoising + CNN" algorithm, demonstrating both high efficiency and practicality. This scheme maintains high-precision detection even under complex environmental conditions, particularly ensuring no missed detections of hazardous defects (such as cracks and incomplete penetration), making it suitable for engineering applications. In the future, further exploration of multi-technology integrated detection approaches, combining methods such as infrared and eddy current for three-dimensional detection, can be pursued. Additionally, continuous optimization of the CNN model can enhance its ability to identify small-sized and minute cracks, providing more comprehensive technical support for the weld quality of steel structure bridges.

Disclosure statement

The authors declare no conflict of interest.

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Research on the Evaluation System for the Revitalization and Utilization of Historical Buildings from the Anti-Japanese War in Chongqing and the Dissemination Path of Digital Study Tours

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Abstract: Against the backdrop of ongoing urban renewal, the dissemination of red culture, and the advancement of smart cultural heritage, the preservation objectives for Chongqing's anti-Japanese War historical buildings are shifting from "preventing disappearance" to "utilization within preservation and dissemination through utilization." This paper, starting from the needs of revitalization and utilization, constructs a five-dimensional evaluation framework encompassing "conservation of the original structure, digital fidelity, narrative dissemination, educational transformation, and operational governance." Furthermore, it proposes a digital study tours product system that connects "heritage sites, online exhibition halls, curriculum resources, research tasks, and urban routes." By examining two digital model samples from Nanquan, namely Tingquan Building and Kong Garden, this paper discusses the differentiated transformation paths for single-dwelling and compound architectural types in digital study tours. The study posits that the revitalization and utilization of Chongqing's anti-Japanese War historical buildings should not be equated with general tourism development. Instead, it should be based on authentic preservation, supported by digital archiving and narrative design, and guaranteed by curricular transformation and platform-based governance, thereby facilitating the transformation of historical buildings from static relics into public learning spaces, urban memory nodes, and continuous communication media.

Keywords: Anti-Japanese war historical buildings; Revitalization and utilization; Comprehensive evaluation; Digital study tours; Dissemination and transformation

Online publication: May 12, 2026

1. Introduction

Chongqing's anti-Japanese War historical buildings serve not only as significant spatial carriers of urban memory but also as crucial material evidence of the historical narratives of the Chinese People's War of Resistance Against Japanese Aggression and the World Anti-Fascist War. Against the backdrop of the growth of digital cultural consumption, accelerated urban renewal, and the normalization of research and learning practices, the preservation objectives for historical buildings are shifting from "preserving them" to "preserving them while ensuring public understanding and sustained use." From the national cultural digitalization strategy to museum reform and development policies, the construction of digital resources, public education, and the synergy between culture and tourism have become important topics in the protection and utilization of cultural heritage [1,2].

Compared to general historical buildings, Chongqing's anti-Japanese War historical buildings possess a higher narrative density and social educational attributes. The spaces behind them correspond to multiple historical contexts, including the political operations of the wartime capital, educational relocation, cultural salvation, social life, and urban air defense. Without effective exhibition translation and educational design, even the most intact buildings can easily be reduced to "old houses" or "check-in spots" in the eyes of the public. Therefore, the significance of digital technology in revitalization and utilization lies not only in "seeing the buildings more clearly" but also in helping the public reconstruct their understanding of history within these spaces.

Based on this, this paper focuses on two core questions: "How to evaluate the quality of revitalization and utilization?" and "How to transform digital resources into research and learning dissemination products?" On the one hand, it establishes operational and comparable comprehensive evaluation indicators; on the other hand, it links digital exhibition halls, AR guided tours, curriculum resources, generative AI explanations, and urban thematic routes to form a continuous chain from site exhibition to knowledge dissemination.

2. The practical basis and main issues in the revitalization and utilization of Chongqing's anti-Japanese war historical buildings

Chongqing has established a relatively solid foundation for displaying anti-Japanese War sites. The Chongqing Anti-Japanese War Sites Museum conducts public exhibitions and research and learning education based on the Huangshan Anti-Japanese War Site Cluster, while the Chongqing Anti-Japanese War Education Museum focuses on the wartime educational relocation and cultural salvation, highlighting Chongqing's historical role in hosting school relocations, the displacement of teachers and students, and cultural continuity during the war. This demonstrates that Chongqing's anti-Japanese War sites not only possess cultural relic value but have also entered the educational and cultural tourism public service system [3,4].

However, from the perspective of utilization forms, several common issues persist as follows:

(1) The exhibition logic often remains at the level of "static viewing + guide narration," with digital achievements and the actual sites not yet deeply connected;

(2) Much content is still primarily displayed at individual points, lacking thematic routes, timelines, and character networks that span multiple sites;

(3) Learning-oriented designs for schools and young people are insufficient, with a lack of effective conversion mechanisms between the visiting experience and curriculum tasks;

(4) The evaluation system is relatively weak, resulting in a lack of comparable bases for assessing issues such as "whether utilization is excessive," "whether dissemination is effective," and "what the educational outcomes are."

From an international perspective, world heritage and digital platforms are transitioning from display-oriented websites to content asset platforms and public interaction platforms. UNESCO's "Dive into Heritage" provides online access paths through 3D models and digital narratives, while the European Cultural Heritage Data Space Strategy further incorporates AI, 3D, XR, interoperability, and governance as future priorities [5–7]. This indicates that the revitalization and utilization of Chongqing's anti-Japanese War historical buildings need to break away from the linear model of "one museum, one building, one visit" and move towards a platform-based organization with "multiple nodes, multiple terminals, and multiple scenarios."

3. A five-dimensional evaluation framework for the revitalization and utilization of Chongqing's anti-Japanese war historical buildings

To determine whether the revitalization and utilization of anti-Japanese War historical buildings are effective, simply observing the open rate, visitor numbers, or online dissemination is insufficient. Revitalization and utilization involve multiple aspects, including conservation of the original structure, digital archiving, public narration, educational transformation, and subsequent governance. Therefore, it is necessary to first break down the evaluation objects into several observable dimensions and then establish a comprehensive indicator system that balances cultural value, technical quality, and public benefits. Based on this approach, this paper summarizes the main evaluation dimensions and observation focuses in **Table 1**.

Table 1. Comprehensive evaluation index system for the revitalization and utilization of Chongqing's anti-Japanese war historical buildings

Primary dimension	Example secondary indicators	Evaluation focus	Application notes
Ontological Protection	Authenticity, Integrity, Structural Safety, Appropriateness of Restoration	Determines whether the principle of protection priority is adhered to	Prevents excessive renovation and symbolic renewal
Digital Fidelity	Acquisition Accuracy, Semantic Completeness, Archival Association, Update Frequency	Determines whether digital outcomes are reliable	Avoids presentation results that are "visually appealing but unusable"
Narrative Communication	Historical Narrative, Spatial Guidance, Interactive Experience, Media Adaptability	Determines whether communication is effective	Emphasizes public understanding and clear information hierarchy
Educational Transformation	Curriculum Integration, Task Sheets, Learning Feedback, Cross-stage Adaptability	Determines whether educational products are formed	Strengthens the connection between field study and curriculum
Operational Governance	Copyright Management, Platform Maintenance, Collaborative Mechanisms, Public Participation	Determines whether operations are sustainable	Emphasizes institutional guarantees and long-term maintenance

Table 1 indicates that revitalization and utilization are not merely a matter of display but a complex system comprising conservation, technology, dissemination, education, and governance. Among these, conservation of the original structure serves as the foundational dimension, digital fidelity provides technological support, narrative dissemination and educational transformation constitute the output link aimed at the public, and operational governance determines whether digital outcomes can be sustained in the long term. These five dimensions can be evaluated separately and also serve as a common reference framework for subsequent project diagnosis and proposal comparison.

In addition to static indicators, it is necessary to clarify that the five dimensions are not simply juxtaposed but are interconnected in a way that they mutually constrain and promote each other. To this end, this paper further transforms them into a five-dimensional interactive framework, as illustrated in **Figure 1**.

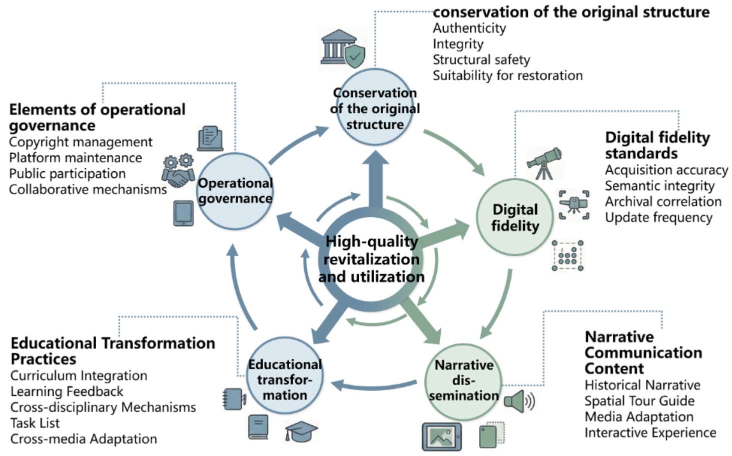

Figure 1. Five-dimensional evaluation framework diagram for the revitalization and utilization of historical buildings from the anti-Japanese war period in Chongqing.

Figure 1 illustrates that high-quality revitalization and utilization do not aim for a single dimension to lead independently but emphasize balance and synergy among all dimensions. If narrative communication is overly emphasized while neglecting ontological protection, historical information is prone to being trivialized or sensationalized. If digital modeling is prioritized without sufficient educational transformation, even the most detailed models may struggle to integrate into the public learning chain. Without operational governance, even the most mature platforms can quickly become obsolete. Therefore, the value of the five-dimensional framework lies in providing a unified evaluation logic for different types of buildings and projects at various stages.

4. System construction and scenario design of digital study tours products

If the evaluation framework answers the question of "what constitutes high-quality revitalization and utilization," then the product system addresses the question of "how to transform historical building resources into content forms that are perceivable, learnable, and disseminable by the public." From the perspective of digital study tours, products should not be limited to a single exhibition page or a one-time guided tour service but should form a continuous product chain ranging from the site location to online platforms and from course packages to urban routes. Based on this approach, this article summarizes the main product types as shown in **Table 2**.

Table 2. Matrix of digital study tours products for historical buildings from the anti-Japanese war period in Chongqing

Product type	Application scenario	Core technology	Target audience	Transformation goal	Product type
Web-Based Digital Exhibition Hall	Online Outreach	Panoramic Roaming, 3D Gaussian Splatting, WebXR	General Public	Building Panoramas, Timelines, and Hotspot Explanations	Web-Based Digital Exhibition Hall
On-Site AR Guided Tour	On-Site Visits	AR Recognition, Positioning and Navigation	Tourists, Primary and Secondary School Students	Component Interpretation, Historical Scene Overlay	On-Site AR Guided Tour

Micro-Learning Courses	School Teaching	Micro-Lecture Videos, Model Slices, Task Sheets	Primary/Secondary Schools and Universities	Formation of Replicable Course Packages	Micro-Learning Courses
Project-Based Course Resources	Professional Teaching	HBIM, GIS, Case Database	Design Students	Support for Surveying, Modeling, and Updating Training	Project-Based Course Resources
City-Themed Itineraries	Cultural Tourism Integration	Map Navigation, Narrative Routes	Tourists, Study Tour Groups	Achieving Multi-Site Integrated Dissemination	City-Themed Itineraries

As can be seen from **Table 2**, different product forms correspond to distinct usage scenarios and dissemination objectives. Web-based digital exhibition halls are suitable for undertaking popular exhibition tasks, on-site AR guided tours are ideal for enhancing the experience of heritage sites, micro-courses and project-based resources are more suited for integration into school teaching systems, while urban thematic routes reposition individual buildings within a broader urban memory network. These elements do not replace one another but should form a combination following the logic of "display–learning–feedback–re-dissemination" [8].

To further illustrate the interconnections among various products, this paper organizes digital study tours products into a closed loop of "heritage site–online exhibition hall–curriculum tasks–learning feedback–dissemination and transformation," as shown in **Figure 2**.

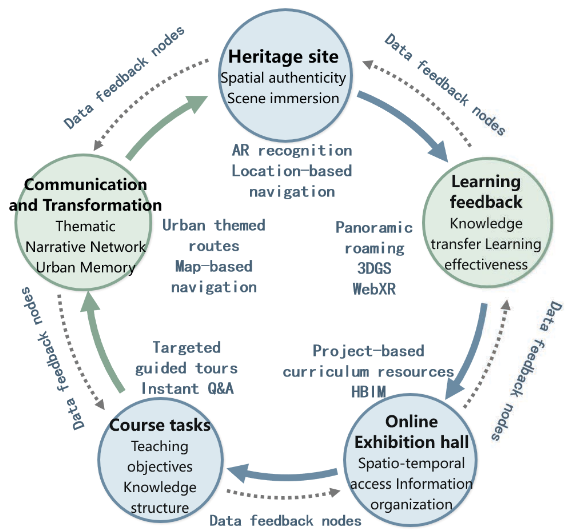

Figure 2. Closed-loop diagram of digital study tours products.

Figure 2 illustrates that Digital study tours does not simply flow unidirectionally from on-site visits to online displays; rather, it constitutes a dynamic system capable of data feedback and continuous content optimization. The heritage site emphasizes spatial authenticity and immersive scenarios, while the online exhibition hall facilitates cross-temporal access and information organization. Curriculum tasks and learning feedback transform the viewing experience into knowledge transfer, ultimately achieving broader social dissemination through urban routes, audience-specific guided tours, and thematic communications. The crux of Digital study tours lies not in merely transferring content but in reorganizing information and learning flows.

5. Case study: The digital study tours transformation path of the Nanquan sample

5.1. Case type identification and transformation logic

This paper selects Tingquan Building and Kong Garden as the Nanquan sample, not solely because digital models of them already exist, but more importantly, because they represent two typical types: single-dwelling and compound architectural forms. The former is suitable for organizing a continuous experience around entrance, courtyard, and indoor nodes, while the latter is more apt for generating a compound learning scenario with multiple nodes and interconnected tasks. Examining both in tandem facilitates observation of the corresponding relationships between architectural types, narrative intensity, and research and learning organization methods.

Based on the aforementioned type differences, this paper summarizes the Digital study tours transformation path for the Nanquan sample into four stages: "resource identification–digital expression–research and learning tasks–dissemination and transformation." The significance of **Figure 3** lies not in listing case names but in demonstrating that, although they all belong to anti-Japanese War historical buildings, different samples do not render themselves to a one-size-fits-all template in terms of spatial characteristics, expression methods, and dissemination channels.

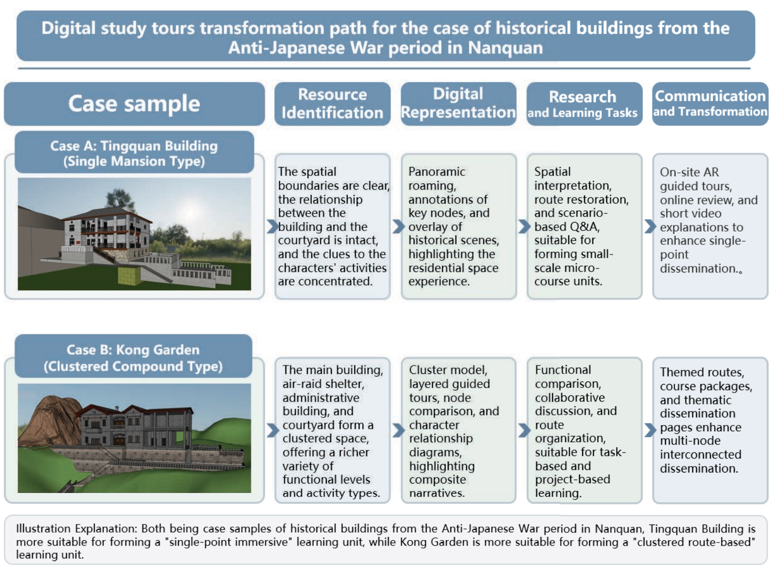

Figure 3. Digital study tours transformation path diagram for the anti-Japanese war historical buildings in Nanquan.

5.2. Differentiated transformation paths for typical samples

5.2.1. Tingquan Building: From single-point display to situational learning units

Tingquan Building features relatively intact spatial boundaries, with clear relationships between the building, courtyard, entrance, and main indoor spaces, making it suitable for organizing a continuous experience of "entering–staying–observing–narrating." For such single-dwelling architectural types, activation and utilization that merely stop at exterior viewing or historical site check-ins are clearly insufficient to unleash their educational potential. A more viable path involves connecting spatial experiences with character activities, wartime life, and place memories through panoramic tours, key node annotations, and historical scene overlays. In designing research and learning products, Tingquan Building is better suited for constructing small-scale, immersive learning units. Tasks such as "spatial interpretation–route restoration–

situational Q&A" can be set around the entrance, main indoor spaces, and courtyard nodes, allowing learners to actively establish connections between spatial evidence and historical narratives, transforming the visit into a discussable and repeatable knowledge chain.

5.2.2. Kong Garden: From grouped spaces to route-based narrative units

Compared to Tingquan Building, Kong Garden exhibits more characteristics of a grouped compound. The main building, ancillary spaces, and courtyard together form a multi-layered activity scene, so its activation and utilization should not only emphasize a single room or interface but also focus on the functional relationships, route organization, and node hierarchy within the architectural group, further transforming the spatial structure into a learning structure.

In terms of digital expression and research and learning design, Kong Garden is better suited for adopting grouped models, layered guided tours, node comparisons, and character relationship diagrams, combined with tasks such as "functional comparison–collaborative discussion–route organization" to guide learners in understanding the roles of different nodes in the overall narrative. Compared to single-dwelling samples, Kong Garden is also more suitable as a key node in urban thematic routes, forming a linkage with surrounding anti-Japanese War buildings.

Overall, single-dwelling samples are better suited for micro-course-based, immersive dissemination, while grouped compound samples are more suitable for route-based, project-oriented organization. Truly effective transformation does not lie in template-based replication but in making targeted expression choices based on architectural type, narrative intensity, and audience needs. This is also an important prerequisite for the Nanquan sample to transition from case analysis to methodological summarization.

Furthermore, the key to digital study tours transformation does not lie in "whether digital models are available" but in whether expression media, task design, and dissemination channels can be matched according to architectural type, narrative intensity, and learning objectives. Only by embedding digital achievements into curricula, routes, and public education scenarios can models be transformed from display materials into sustainably updated knowledge resources.

6. Suggestions for promoting high-quality activation and utilization of Chongqing's anti-Japanese war historical buildings

For the subsequent activation and utilization of Chongqing's anti-Japanese War historical buildings, efforts should continue in at least the following aspects:

(1) Prioritize protection and utilize moderately; for buildings with high historical value and fragile structures, digital displays should be prioritized to alleviate open pressure;

(2) Establish a unified data foundation and metadata standards to enable cultural heritage institutions, universities, and cultural tourism management departments to share surveying and mapping results, historical archives, explanation scripts, and curriculum resources under the same rules;

(3) Promote curriculum-based transformation by embedding digital achievements into ideological and political education, aesthetic education, history, architecture, and environmental design courses;

(4) Reasonably introduce AI-guided tours, large-model Q&A, and audience-specific push notification mechanisms while ensuring historical accuracy through manual verification;

(5) Improve copyright and platform governance mechanisms by planning authorization, usage, and update rules simultaneously at the project initiation stage;
(6) Establish a regular maintenance and evaluation mechanism, incorporating visit volume, learning feedback, platform stability, data update frequency, and public satisfaction into annual monitoring.

7. Conclusion

The high-quality activation and utilization of Chongqing's anti-Japanese War historical buildings, in essence, is not about transforming heritage sites into more lively tourist attractions but about promoting their transition from static preservation objects to active nodes in social knowledge production. The key does not lie in simply increasing visitor numbers but in establishing a sustainable balance between historical authenticity, spatial experience, educational objectives, and digital governance, enabling preservation achievements to enter the processes of public understanding, continuous learning, and urban memory construction. The five-dimensional evaluation framework and digital study tours product system proposed in this paper provide a path for achieving this goal. With the continuous evolution of digital platforms, AI-guided tours, and three-dimensional dissemination technologies, Chongqing's anti-Japanese War historical buildings have the potential to evolve from scattered individual attractions and case achievements into a regionally interconnected digital network of red culture. In the future, what deserves more attention is not just whether individual projects are "spectacular" but whether existing experiences can be distilled into replicable standards, platforms, and collaborative mechanisms, forming stable models in audience-specific explanations, curriculum applications, cross-site linkages, and long-term operations. This way, different types of anti-Japanese War historical buildings can continuously release their cultural, educational, and urban memory values.

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"Numbers Weave Bridges under the Moon, Intelligence Empowers Yongle": Rural Tourism Landscape Planning for Yongle Village, Dongxi Town, Qijiang District, Chongqing City

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Abstract: This study addresses several issues in the rural landscape design of Yongle Village, Qijiang District, Chongqing City, such as outdated updates, severe homogenization, and a lack of innovative industries, proposing solutions accordingly. In line with the national rural revitalization strategy and the concept that "lucid waters and lush mountains are invaluable assets," this research employs policy analysis, field research, and case studies, integrating design experiences from both domestic and international sources. It introduces the "immersive experience" and "all-inclusive pricing" models to alleviate homogenization, activate site-specific characteristics, and create sustainable rural landscapes.

Keywords: Experiential landscape; Intangible cultural heritage; Rural landscape

Online publication: May 12, 2026

1. Introduction

1.1. Project background

In recent years, the Chinese government has placed great emphasis on rural development and landscape construction, introducing multiple policies to support the planning and construction of rural experiential landscape bases. Laws and regulations such as the Urban and Rural Planning Law of the People's Republic of China, the Land Administration Law of the People's Republic of China, and the Guidelines for Beautiful Rural Construction have set requirements for regulating rural spatial layouts and improving living environments. Documents including Chongqing Territorial Spatial Master Plan, the Territorial Spatial Subdivision Plan for Qijiang District, Chongqing, and the High-Standard Farmland Construction Plan for Chongqing emphasize green development and ecological protection, calling for the promotion of sustainable rural landscape construction. Meanwhile, the national "green development concept" and rural revitalization strategy provide clear guidance for immersive agricultural experiences, local cultural heritage preservation, and low-carbon landscape design [1]. These policies lay a solid political foundation and implementation conditions for the construction of a rural experiential landscape base in Yongle Village, Dongxi Town, Qijiang District, Chongqing City.

1.2. Design objectives

1.2.1. Integration of landscape and smart agriculture

By shaping ancient village scenery combined with agriculture, we aim to develop eco-friendly and livable rural tourism, responding to the concept that "lucid waters and lush mountains are invaluable assets." Simultaneously, we will construct a "cloud-edge-end" collaborative smart agriculture system, deploying Beidou agricultural machinery autonomous driving systems and digital twin models for crop growth, applying blockchain NFT technology for full traceability of agricultural products, establishing an agricultural carbon sink monitoring platform, and using carbon credits to redeem agricultural products. This is expected to improve water and fertilizer utilization by 50% and management efficiency by 60%, achieving synergistic development of ecology and industry.

1.2.2. Digital cultural tourism and cultural heritage preservation

Addressing the insufficient promotion and gradual fading of local resources such as Sichuan opera and pomelo culture, we will incorporate traditional elements into landscape design and protect and renovate ancient buildings and homestays. Moreover, utilizing 3D laser scanning and motion capture technology, we will transform stilted buildings and intangible cultural heritage techniques into digital assets; develop an AR time-travel guided tour system to overlay historical scenes; and establish a rural intangible cultural heritage metaverse exhibition hall, supporting interactive experiences such as VR Sichuan opera singing lessons and digital collectible collection, enhancing the efficiency of intangible cultural heritage dissemination and strengthening cultural identity.

1.2.3. Intelligent monitoring and ecological protection

Implementing national ecological protection and green development policies, we will adopt environmentally friendly and energy-saving technologies such as solar power generation systems and rainwater collection and utilization systems to reduce resource consumption. Additionally, utilizing intelligent monitoring and data cloud platforms, we will monitor the ecological environment in real-time, creating a green and sustainable rural tourism landscape and achieving effective protection and sustainable utilization of the ecological environment.

1.2.4. Economic development and rural revitalization

Developing characteristic cultural and creative products such as pomelos, Sichuan opera, and rice, we will drive economic income through tourism exhibitions and sales, as well as carbon credit redemption. By fostering a "culture-ecology-intelligence" synergistic development model, developing rural tourism and smart agriculture, integrating site and surrounding resources, we will increase farmers' incomes, promote industrial prosperity and affluent living, and provide support for comprehensive rural revitalization [2].

1.3. Design significance

1.3.1. Promoting ecological-smart synergy and enhancing resource efficiency

By deeply integrating smart agriculture with landscapes, we will practice the concept that "lucid waters and lush mountains are invaluable assets." Utilizing technologies such as Beidou navigation, digital twins, and blockchain traceability, we will significantly improve water and fertilizer utilization and management efficiency, achieving synergistic development of ecological protection and agricultural industries, and providing technological support for eco-friendly and livable rural areas.

1.3.2. Promoting digital cultural tourism empowerment and revitalizing local cultural heritage

Addressing the dilemma of inheriting local cultures such as Sichuan opera and pomelos, we will employ digital means such as 3D scanning, AR, and digital collectibles to transform ancient buildings and intangible cultural heritage into interactive immersive experiences. This will effectively enhance the efficiency of intangible cultural heritage dissemination, strengthen cultural identity among villagers and tourists, and promote the living inheritance of traditional culture.

1.3.3. Promoting intelligent monitoring and control to safeguard the green foundation

Implementing national ecological policies, we will adopt green technologies such as solar energy and rainwater collection, combined with intelligent monitoring cloud platforms, to achieve real-time control over environmental resources. This will reduce energy and resource consumption, ensure the sustainability of rural tourism landscapes, and promote a virtuous cycle of ecological protection and long-term utilization.

1.3.4. Promoting the integration of three industries for revitalization and driving common prosperity

Developing characteristic cultural and creative products, we will drive income growth through channels such as carbon credit redemption and tourism exhibitions. By constructing a "culture-ecology-intelligence" synergistic development model, integrating regional resources, increasing farmers' employment and incomes, we will promote industrial prosperity and affluent living, providing a replicable demonstration path for comprehensive rural revitalization.

2. Market analysis

2.1. Location analysis

Yongle Village is located in the core area of Dongxi Town, Qijiang District, Chongqing City, adjacent to the nationally renowned historical and cultural town of Dongxi Ancient Town, enjoying significant location advantages. The village covers an area of approximately 667 square meters, with 4,145 acres of arable land, serving as an important agricultural production base in Qijiang District. The terrain within the village is gentle, with fertile land. The Dongding River runs through the village from north to south, serving as a crucial segment of the Dongxi River, providing abundant water resources for agricultural irrigation and landscape creation. Yongle Village has relatively convenient transportation, with national highways and township roads connecting it, and is approximately 30 kilometers away from Qijiang urban area, offering good accessibility. The village has a long history and abundant resources, producing characteristic agricultural products such as rice and pomelos, possessing superior natural and humanistic foundations for developing rural experiential landscapes and smart agriculture.

2.2. Natural conditions analysis

In terms of natural conditions, Yongle Village is located on the southeastern edge of Qijiang District, belonging to the transitional zone of parallel ridge-valley landforms on the southeastern edge of the Sichuan Basin. The terrain is mainly mountainous and hilly, with an overall southwestern high and northeastern low inclination. The village features many isolated mountains, with few complete mountain ranges, and karst and Danxia landforms interspersed, forming unique natural landscapes. The central part of the site is low-lying, with gradually rising surroundings, presenting a typical bowl-shaped catchment terrain conducive to the natural accumulation of surface runoff. The Dongding River runs through the village from south to north, with numerous streams and rivers, providing abundant water resources. The climate is subtropical humid monsoon, with distinct seasons, abundant rainfall, and a long frost-free period, suitable for the growth of various crops such as rice and pomelos, providing excellent natural conditions for agricultural and ecological landscape creation.

2.3. Cultural resources analysis

In terms of cultural resources, Yongle Village in Dongxi Town boasts rich cultural heritage and a long history, but many cultural aspects have low inheritance rates, with most being forgotten or even abandoned. Existing sites include the Chen Family Residence and Ancestral Hall from the Qing Guangxu period, the 270-year-old Wangye Temple, and the 630-year-old Taiping Bridge. Historically, Yongle Village was a crucial commercial route in southwestern China during the Tang Dynasty and an ancient dock on the Qijiang River, as well as the birthplace of the Dai ethnic group, leaving behind monuments such as the "Nanping Liao" stele, Guansuo Bridge ruins, ancient Han tombs, the Mahxiangyue Civil Post, and archways; folk cultures such as Yu-style Sichuan opera and dragon and lion dances require protection. The site has a complete surrounding infrastructure, less than 500 meters away from Dongxi Ancient Town, with scenic spots and historical sites interconnected along the route, providing favorable conditions for rural landscape design.

2.4. Visual analysis

In terms of visual analysis, the overall terrain of the site is relatively flat, with vegetable fields and farmland as the main current features, presenting a native agricultural landscape. The site is surrounded by barriers due to river regulation projects, preventing direct observation of the river's interior; the river maintains a primitive natural state, with small water volumes and overgrown weeds, indicating a relatively primitive water system ecology lacking systematic organization. The region is dotted with old houses, mostly dilapidated and idle due to long-term lack of proper repair and maintenance, making them difficult to utilize effectively. Within the site, there are obvious elevation changes in some areas, with surrounding terraced fields forming relatively clear layered textures influenced by the terrain, with natural topography and agricultural traces jointly constituting the site's base characteristics.

Overall, the current foundation of the site is acceptable, but the overall quality and utilization effect are not ideal. The land within the site is mainly farmland, with some old buildings retained. In subsequent designs, it is necessary to fully revitalize and utilize existing old buildings while incorporating farmland landscapes and functions into the overall planning. The site has a profound cultural heritage and rich surrounding tourist attractions, but unfortunately, the cultural connotations have been gradually forgotten and have not been effectively excavated and highlighted. Additionally, how to protectively update the farmland while developing and utilizing it is also a key issue that this design needs to address.

3. Design principles

3.1. Ecological priority as the primary concept

Development should strictly adhere to the principle that "lucid waters and lush mountains are invaluable assets," with ecological protection established as a fundamental prerequisite. This entails respecting existing topography, natural hydrological systems, and agricultural foundations, while integrating environmentally sustainable technologies, such as solar energy utilization and rainwater harvesting, to develop an intelligent ecological monitoring framework. Such a system is intended to support the conservation of sensitive geological formations, including karst and Danxia landscapes, as well as the integrity of the Dongding River water system.

At the same time, safety-oriented development should be regarded as a core guiding criterion. Infrastructure related to landscape amenities, tourism routes, and agricultural activities must comply with relevant safety standards. Through this approach, it is possible to achieve a coordinated model of development that balances ecological sustainability, low-carbon practices, and safety resilience [3].

3.2. Cultural empowerment as a key approach

Development efforts should prioritize the in-depth exploration of the local cultural resources of Yongle Village, integrating elements such as Chongqing-style Sichuan Opera, Taiping Bridge, Chen's Residence, traditional dragon and lion dances, and agricultural heritage into the overall landscape design. Intangible cultural heritage (ICH) should be incorporated as a complementary dimension, supported by digital technologies, such as augmented reality (AR) guided tours and metaverse-based exhibitions, to facilitate dynamic preservation and innovative presentation.

With cultural education as a central objective, it is essential to create immersive, visually engaging, and interactive experiential environments that enhance public understanding and participation. At the same time, the protection and adaptive reuse of traditional architectural homestays should be promoted, thereby enabling the sustainable transmission and educational function of local cultural heritage through both preservation and revitalization.

3.3. Smart integration as an innovative pathway

Development should be aligned with the strategic objectives of smart agriculture and digital cultural tourism, promoting the deep integration of advanced technologies with landscape design and agricultural practices. This includes the establishment of a "cloud–edge–terminal" collaborative smart agriculture system, incorporating technologies such as BeiDou navigation, digital twin modeling, and blockchain-based traceability to enhance precision management and data transparency.

With experiential landscape design as a defining feature, digital tools, including augmented reality (AR) and 3D laser scanning, should be applied to create immersive cultural tourism environments. In addition, the development of an intelligent monitoring and carbon sequestration platform can further support sustainable resource management while highlighting the distinctive experiential and ecological value of "Smart Yongle."

3.4. Local adaptation as a fundamental prerequisite

Planning and development should fully respect the geographical advantages, natural conditions, and site-specific characteristics of Yongle Village. Key features, such as its bowl-shaped catchment terrain, terraced agricultural landscapes, and the spatial distribution of traditional buildings, should be carefully considered to avoid homogeneous or standardized design approaches.

With rural practice as a central guiding principle, efforts should focus on the adaptive reuse of underutilized buildings and the organic integration of agricultural landscapes with functional spatial planning. At the same time, the Dongding River system and surrounding mountainous topography should be strategically utilized to create a spatially layered and ecologically coherent environment. In coordination with the resources of Dongxi Ancient Town, this approach can further enhance site adaptability while reinforcing the distinctive characteristics of rural development and practice [4].

3.5. Industrial linkage as a developmental support

With rural revitalization as the central orientation, landscape design should be closely integrated with industrial development to establish a “culture–ecology–smart technology” model for the coordinated advancement of the tertiary sector. This includes the development of cultural and creative products based on distinctive agricultural outputs, such as rice and pomelos, while creating diversified value-generation channels, including tourism exhibitions and carbon credit trading mechanisms.

At the same time, the promotion of eco-tourism and smart agriculture experiences should be prioritized to enhance resource integration and utilization. Such initiatives can contribute to expanding employment opportunities and increasing income for local residents, thereby supporting industrial prosperity and improving living standards. In this context, landscape design functions not only as a spatial and aesthetic intervention but also as a critical driver of rural revitalization and sustainable economic development.

3.6. People-orientation as the fundamental guideline

Landscape planning should be guided by the dual needs of local residents and visitors, achieving a balance between functional practicality and experiential quality. On the one hand, design interventions should prioritize the optimization of the living environment and the improvement of infrastructure, thereby enhancing the overall quality of life for villagers. On the other hand, it is essential to develop immersive and interactive landscape experiences that enrich visitor engagement.

Tourism circulation systems should be further refined through the design of integrated and immersive routes, complemented by inclusive pricing models that enhance accessibility and convenience. Particular attention should be given to accommodating diverse user groups, including the elderly and children, ensuring a safe, comfortable, and inclusive experience. Through such a people-centered approach, visitors can fully appreciate both the natural and cultural landscapes while benefiting from a high-quality and accessible tourism experience, thereby realizing the fundamental objective of human-oriented design.

4. Design analysis

4.1. Overview of design concept

Located in Yongle Village, Dongxi Town, Qijiang District, Chongqing, this project establishes a mountain-themed rural tourism landscape design based on the topographical characteristics of mountains, rivers, and villages in Yongle Village. Taking the integration of ancient architecture and natural landscapes as the entry point for rural planning and design, it adheres to the concept of adapting to local conditions and leveraging unique rural resources to create distinctive landscapes with clear elevation differences, excellent ecology, harmonious coexistence, and healthy livability. This approach aims to attract development vitality and popularity, providing an agreeable ecological environment and a strong sense of local livability for residents and tourists, enhancing external tourism appeal, and promoting high-quality development of the local cultural tourism economy.

4.2. Analysis of design approach

Guided by existing site issues, this project comprehensively enhances site quality and breaks through developmental bottlenecks through three major measures: spatial function reconstruction, cultural memory regeneration, and characteristic landscape creation [5]. To address issues such as monotonous activity spaces and insufficient landscape ornamental value, it optimizes and upgrades spatial functions by establishing a composite rural landscape system, creating multi-level experiential spaces, and incorporating interactive landscape nodes. For problems like abandoned buildings and cultural discontinuities, it revitalizes historical buildings, innovatively translates cultural elements, and designs ICH exhibition experiences to awaken site cultural memories and promote dynamic preservation of local cultural heritage. By deeply integrating local aesthetic expressions, immersive experience designs, and ecological smart technologies, it creates characteristic rural landscapes that are ecological, experiential, and cultural, aligning with project design principles and aiding rural revitalization.

4.3. Analysis of axes

The landscape axis adopts a “one belt, three points” landscape sequence, constructing a globally interconnected and hierarchically clear landscape pattern to achieve organic connections and collaborative development among functional areas.

4.3.1. One belt

The Dongding River, the main waterway running through Yongle Village, serves as the core axis. Convenient footpaths are laid on both sides, leading to various functional branch areas. It acts as both the ecological vein of the site and the core link for extracting pomelo elements and connecting the entire landscape, showcasing the site’s water system resource advantages.

4.3.2. Three points

These are landscape distribution centers located around the handicraft market, picking experience area, and agritainment facilities. The distribution centers near the handicraft market and agritainment play a core linking role. The center near agritainment not only provides access to areas for experiencing characteristic agricultural products, agricultural processing plants, livestock experience zones, and agritainment product selection areas but also allows for appreciation of natural and cultural landscapes on the opposite riverbank, achieving bidirectional empowerment of experience and appreciation. The center at the handicraft market organically connects various functional areas, including the tourist center, planting experience area, cultural corridor, folk custom area, seasonal agricultural product viewing area, and ICH cultural exhibition hall, forming a globally interconnected landscape pattern of “three points, one axis” to enhance the landscape’s integrity and experiential continuity.

5. Business model design

5.1. Self-purchased product form

Centered on green ecology and cultural empowerment, leveraging the high-quality agricultural products produced by Yongle Village's smart agriculture, we aim to create a differentiated self-purchased product system that balances environmental protection and cultural significance, aligning with the principles of ecological priority, green sustainability, cultural empowerment, and living heritage preservation.

5.1.1. Direct-sale products

Relying on the "cloud-edge-end" collaborative smart agriculture system, we offer high-quality local specialty agricultural products such as rice and pomelos, directly selling to tourists, nearby residents, and online customers. These products are packaged in eco-friendly, biodegradable materials, highlighting their green cultivation, pesticide-free nature, and smart traceability features. The carbon credit value of the agricultural products is also indicated, meeting the requirements of "green and low-carbon, efficient resource utilization" in the principle of ecological priority, allowing customers to intuitively appreciate the advantages of Yongle Village's ecological agriculture.

5.1.2. Brand story

We create exclusive brands for agricultural products like rice and pomelos, deeply exploring the cultural connotations and farming stories behind them. We focus on introducing Yongle Village's traditional farming methods, the cultivation history of rice and pomelos, as well as their connections to local culture such as Chongqing-style Sichuan Opera and Taiping Bridge, endowing the products with cultural value and educational significance. This aligns with the principles of cultural empowerment and living heritage preservation, enhancing the added value of the products and distinguishing them from ordinary agricultural products.

5.1.3. Experiential purchasing

In the agricultural product exhibition and sales area, we set up an experiential zone where customers can directly purchase products and participate in brief immersive experience activities for free, such as tasting freshly steamed Yongle rice and freshly squeezed pomelo juice, as well as experiencing simple farming activities like hand-peeling pomelos and screening rice grains. This increases the experiential and fun aspects of purchasing, adhering to the principles of people-orientation and experience optimization, boosting customers' willingness to buy while transmitting Yongle Village's farming culture.

5.2. Participatory purchase product forms

Centered on interactive experiences and cultural immersion, integrating smart technologies with local culture, we design diversified participatory purchase forms that balance experiential, personalized, and social aspects, aligning with the principles of people-orientation, experience optimization, smart integration, and cultural empowerment, addressing the challenge of homogenized rural landscapes.

5.2.1. Interactive experience

Relying on Yongle Village's terraced fields and smart agriculture base, we design exclusive interactive experience zones, allowing customers to personally participate in the entire production and cultivation process of rice and pomelos, such as rice sowing, harvesting, and hulling, as well as pomelo picking, peeling, and processing. Simultaneously, leveraging smart technologies like Beidou agricultural machinery displays and digital twin crop growth demonstrations, customers can intuitively feel the charm of smart agriculture, meeting the core needs of agricultural practice while adhering to the principles of smart integration and technological empowerment.

5.2.2. Educational workshops

Based on the principle of cultural empowerment, we host diversified educational workshops, combining resources such as Chongqing-style Sichuan Opera and farming culture to offer deep-processing workshops for rice and pomelos. Customers are taught to make traditional rice cakes, rice wine from rice, and pomelo tea, pomelo jam from pomelos, while learning about the cultural origins and nutritional value of these traditional foods. This balances cultural inheritance and educational significance, aligning with the basic goals of cultural empowerment, living heritage preservation, and cultural education.

5.2.3. Customized services

We provide personalized customized services, allowing customers to choose processing recipes and packaging styles for agricultural products like rice and pomelos according to their preferences. Cultural elements such as Chongqing-style Sichuan Opera masks and Taiping Bridge can be printed on the packaging, or personal exclusive marks can be added to create personalized products, adhering to the principles of people-orientation and experience optimization, meeting customers' diversified and personalized needs.

5.2.4. Souvenir production

Customers are encouraged to add personalized designs or exclusive marks to products they personally make, such as handmade rice cakes, pomelo jam, and rice paintings, combining cultural elements of Yongle Village to turn them into unique rural cultural souvenirs. This not only preserves the experiential memories but also transmits Yongle Village's local culture, aligning with the principles of cultural empowerment and living heritage preservation, enhancing the commemorative value and dissemination of the products.

5.2.5. Sharing and display

In the experience and exhibition areas, exclusive sharing zones are set up to display customers' handmade works. Simultaneously, an intelligent sharing platform is built, providing photo check-in points, free WiFi, and social media sharing templates to encourage customers to share their experience processes and works. Leveraging social dissemination, we expand the brand influence of Yongle Village's "smart + ecological + cultural" image, adhering to the principles of smart integration and technological empowerment while enhancing the project's visibility and attractiveness.

5.3. Education-integrated product design

Centered on "cultural education and practical education," we deeply integrate product production, agricultural production, and educational courses to create educational products that are both knowledgeable and practical, aligning with the principles of cultural empowerment, living heritage preservation, smart integration, industrial linkage, and revitalization empowerment, achieving coordinated advancement in cultural education and industrial development.

5.3.1. Course integration

We deeply integrate the cultivation and processing processes of rice and pomelos with educational courses such as agronomy, ecology, nutrition, and traditional culture, designing immersive practical courses. Agricultural experts and intangible cultural heritage inheritors are invited to teach, allowing customers to learn smart agricultural technologies, farming culture, ecological protection knowledge, and intangible cultural heritage such as Chongqing-style Sichuan Opera in practice, achieving the dual value of "practice + education" and aligning with the principles of cultural empowerment and smart integration.

5.3.2. Study tours

For schools and educational institutions, we design exclusive study tour projects, relying on resources such as Yongle Village's smart agriculture base, intangible cultural heritage experience zones, and historical sites to create "ecological + cultural + smart" study routes. This allows students to learn agricultural knowledge, traditional culture, and ecological protection concepts in practice while driving agricultural product sales and increasing revenue from experience projects, aligning with the principles of industrial linkage and revitalization empowerment, achieving coordinated development in education and industry.

5.4. Social welfare and poverty alleviation

Based on the goal of rural revitalization, combining Yongle Village's local cultural resources and site characteristics, we design poverty alleviation paths that fit the village's actual conditions, aligning with the principles of industrial linkage, revitalization empowerment, cultural empowerment, and site adaptation, injecting new vitality into the rural economy and achieving common prosperity.

We deeply explore Yongle Village's intangible cultural heritage resources such as Chongqing-style Sichuan Opera and dragon and lion dances, exploring poverty alleviation paths through collaborative design innovation of intangible cultural heritage. We create cultural brands with Yongle Village's intangible cultural heritage characteristics, promoting the revival of intangible cultural heritage such as Chongqing-style Sichuan Opera. Relying on idle old buildings, we open intangible cultural heritage workshops, inviting local intangible cultural heritage inheritors to teach, allowing villagers to participate in intangible cultural heritage product production and experience project services, conducting skill training to enhance villagers' employment capabilities. Simultaneously, we combine intangible cultural heritage elements with agricultural products such as rice and pomelos to develop intangible cultural heritage creative products, selling them through channels such as tourism exhibitions, online sales, and carbon credit exchanges, driving villagers' income growth and promoting rural industrial prosperity, achieving coordinated advancement in cultural inheritance and poverty alleviation, ensuring that landscape design and industrial development truly serve rural revitalization.

6. Technical implementation

6.1. Project features

6.1.1. Prime geographic location

The Dongding River runs through the project site, with farmland on both sides symmetrically arranged in a leaf-like pattern. The natural landscape blends harmoniously with the village, creating a pastoral scene reminiscent of "small bridges, flowing streams, and quaint homes," laying the foundation for a "digital-smart" rural tourism landscape.

6.1.2. Rich cultural heritage

The site, established during the Zhenguan period, served as a key location on the ancient Sichuan-Guizhou salt route and the ancient wharf of the Qijiang River. It preserves a wealth of historical buildings and cultural heritage, including Ming and Qing architectural complexes and the Chen family's residence, along with unique cultural elements such as Sichuan Opera and folk performances. Additionally, it integrates the protection and inheritance of Sichuan Opera and pomelo culture.

6.1.3. Diversified educational experiences

Centered on "digitalization + smart agriculture," the project constructs a "one-brain-three-network" system, integrating cutting-edge technologies to create a smart tourism model that combines technology, ecology, cultural tourism, and wellness. It offers rich intangible cultural heritage experiences, facilitating cultural education inheritance and rural industrial upgrading.

6.1.4. Prominent local characteristics

By deeply exploring the site conditions, crops, and local customs, the project creates rural tourism landscapes with distinct local identities, enhancing the project's visibility and appeal, and injecting new vitality into the local economic and cultural development.

6.2. Innovations

6.2.1. New applications in digital cultural tourism, renewed inheritance of old culture

In response to the cultural digitization strategy, technologies such as 3D laser scanning are employed to transform century-old stilt houses and intangible cultural heritage skills into digital assets. An AR guided tour system and a metaverse exhibition hall for rural intangible cultural heritage are developed, innovating the cultural inheritance model and improving dissemination efficiency.

6.2.2. New applications in smart agriculture, keeping pace with the times

A "cloud-edge-end" collaborative smart agriculture system is constructed, integrating technologies such as 5G and AI to achieve intelligent agricultural production. Blockchain technology is used for agricultural product traceability, and an agricultural carbon sink monitoring platform is established, pioneering a new model of modern smart agriculture.

6.2.3. New applications in intelligent monitoring, new greens in ecological protection

Environmental technologies such as solar power and rainwater harvesting are adopted, combined with intelligent monitoring and a data cloud platform, to monitor the ecological environment in real-time. This creates a green and sustainable rural tourism landscape, achieving ecological protection and sustainable utilization.

6.2.4. Promoting development through rural "digital-smart" tourism landscapes

A "culture-ecology-smart" collaborative development model is created, aligning with the requirements of industrial integration for rural revitalization. By driving local economic growth and increasing farmers' incomes through cultural tourism and agricultural development, it provides support for the comprehensive revitalization of rural areas [6].

7. Conclusion

This project, based on the site conditions, resource advantages, and cultural customs of Yongle Village, Dongxi Town, Qijiang District, Chongqing, leverages the local landscape of "small bridges, flowing streams, and quaint homes" and the resources of Ba-Yu stilt houses to create a new model of "digital-smart" empowerment for rural tourism landscape planning. Addressing issues such as homogenization of rural landscapes and cultural inheritance gaps, the project proposes a trinity solution of "intangible cultural heritage activation + ecological education + industrial revitalization." It constructs a "one-brain-three-network" system, integrating cutting-edge technologies such as digital twins and AI to achieve coordinated development of digital cultural tourism, smart agriculture, and ecological protection. By promoting the deep integration of agriculture and education, protecting and inheriting rural cultural heritage, popularizing ecological and environmental protection concepts, and innovating rural education models and learning methods, the project enhances the cultural significance of the site and landscape diversity, providing a characteristic practical path for the revitalization of traditional villages, rural cultural tourism development, and comprehensive rural revitalization.

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Research on the Protection and Micro-Remodeling Practice of Historical Streets and Alleys from the Perspective of Urban Renewal

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Abstract: Historical streets and alleys not only carry the urban spatial memory and regional cultural characteristics, but also face practical problems such as building aging, weak facilities, functional decline, and insufficient living environment quality. Under the guidance of protection, micro-renovation emphasizes promoting the renewal of historical streets and alleys through small-scale, gradual, and low-intervention methods, achieving the coordinated unity of style protection, functional improvement, and community vitality reformation. This paper, from the perspective of urban renewal, analyzes the connotation characteristics, basic principles, and practical paths of historical street and alley protection and micro-renovation, and proposes that the renewal practice should be systematically advanced from aspects such as spatial texture restoration, infrastructure improvement, cultural exploration and inheritance, business optimization, and community creation. On the basis of continuing the historical cultural heritage, the livability, accessibility, and public nature of the streets and alleys should be enhanced, providing practical references for the protection and renewal of historical streets and alleys.

Keywords: Urban renewal; Historical streets and alleys; Protection and utilization; Micro-renovation; Living inheritance

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1. Introduction

As urban renewal enters a new stage that focuses on optimizing the existing stock and enhancing quality, the renewal of historical streets and alleys is no longer suitable to be carried out through simple demolition and construction or overall reconstruction. Instead, it should be realized through micro-intervention, gradual and sustainable renovation methods, respecting the original layout and historical style, and achieving functional repair and value activation. On one hand, historical streets and alleys generally have problems such as outdated infrastructure, insufficient public space, and poor environmental quality; on the other hand, their spatial layout, architectural form, and folk culture have irreplaceable protection value. Therefore, how to coordinate protection and development, inheritance and utilization, improvement of people's livelihood and continuation of the cultural heritage has become an important issue in urban renewal.

2. Characteristics of historical street and alley protection and micro-renovation

Historical street and alley protection and micro-renovation first exhibit a distinct “priority of protection, mainly repair” feature. Historical streets and alleys are different from general urban renewal areas. Their core value not only lies in land use and spatial function, but also in carrying the urban culture, life memories, and regional style. Therefore, the renovation should not be mainly based on large-scale demolition and reconstruction, but should emphasize the continuation of the original street layout, historical building form, spatial scale, and environmental atmosphere. During the implementation process, often through small-scale means such as repair, restoration, patching, and renewal, the damaged interfaces, old facilities, and local spaces are optimized to achieve quality improvement while maintaining the authenticity of the street. Moreover, historical street and alley protection and micro-renovation have the characteristics of “small scale, low intervention, and gradualism”. Compared with traditional large-scale renovation, micro-renovation pays more attention to adapting to the current situation of the street alley, avoiding the impact on the historical environment caused by one-time, strong-intervention construction, and usually adopts a phased, regional, and node-based approach. For example, first carry out partial updates to the road paving, drainage and lighting, facade style, and public nodes, and then gradually extend to courtyard renovation, business adjustment, and cultural display. This approach is conducive to controlling construction costs and construction impacts, and also leaves space for subsequent evaluation and dynamic optimization, making the renovation process more flexible and sustainable. Furthermore, historical street and alley protection and micro-renovation have the composite feature of “prioritizing people’s livelihood improvement and cultural inheritance”. Historical streets and alleys are not static display spaces, but important places for residents’ daily life. Their renovation should not only focus on the restoration of visual appearance, but also pay attention to the improvement of basic functions such as water supply, drainage, fire protection, electricity, accessibility, and garbage collection, effectively improving the living environment and usability. Finally, historical street and alley protection and micro-renovation also have the feature of multi-party collaborative participation. Street alley renovation often involves multiple parties such as the government, residents, merchants, design teams, and social organizations. It is necessary to form a collaborative mechanism in protection control, function implantation, interest coordination, and subsequent operation to achieve the organic unity of historical street alley protection, functional improvement, and community vitality enhancement [1].

3. Principles for the protection and minor renovation of historical streets and alleys

3.1. Principle of authenticity and integrity protection

The protection and minor renovation of historical streets and alleys should first adhere to the principle of authenticity and integrity protection. This is the basic prerequisite for carrying out the renewal practice. Authenticity mainly refers to the preservation of the original spatial layout, architectural form, material texture, historical style and cultural information of the street and alley, so that the historical street and alley loses its original charm. Integrity emphasizes that the protection of a single building or a certain node cannot be isolated, but the spatial continuity, style coordination and cultural connection of the street and alley as a whole should be maintained, including street scale, courtyard relationship, interface characteristics and the overall connection between the surrounding environment. Priority should be given to repair, maintenance and patching methods to carry out necessary rectification for damaged areas, preserve and present historical traces, and minimize large-scale demolition and excessive renewal, achieving "restoring as it was" rather than "restoring and transforming into something new", so as to ensure the real continuation of the spatial form and cultural value of the historical street and alley.

3.2. Principle of people-oriented and progressive minor renovation

The renewal of historical streets and alleys is not only a process of spatial restoration, but also an important practice for improving residents' living quality and optimizing community functions. Therefore, it is necessary to adhere to the principle of people-oriented and progressive minor renovation. Historical streets and alleys usually still undertake multiple functions such as residence, passage, interaction, and business. The renovation should not only focus on landscape improvement and facade restoration, but also pay attention to the most realistic living needs of residents, such as road accessibility, smooth drainage, safe lighting, clean environment, and convenient facilities, to effectively improve the comfort and safety of street and alley use. Minor renovation should avoid one-time, large-scale, and strong-intervention renewal, and prevent damage to the original living order, social relations, and historical environment. Based on the current situation of the street and alley and the urgency of problems, it should be advanced in stages, regions, and levels, starting with filling in the shortcomings, then improving the environment, and finally shaping the characteristics. It should be adjusted and optimized continuously in the dynamic implementation process [2].

3.3. Principle of dynamic inheritance and sustainable development

The protection and minor renovation of historical streets and alleys should also adhere to the principle of dynamic inheritance and sustainable development. Avoiding the simple understanding of historical streets and alleys as static display objects, the renewal practice should not only protect the physical space, but also pay attention to the continuation of intangible culture and daily life scenes, so that the historical street and alley can continue to play a role in real life. It can enhance the life atmosphere and cultural identity of the street and alley by retaining traditional residential functions, continuing local business formats, embedding cultural display and community activity spaces, etc. At the same time, sustainable development also requires considering economic affordability, social fairness and environmental coordination in the renewal process, avoiding excessive commercialization, over-tourism, which may lead to the loss of original residents and the hollowing out of the street and alley. Only by achieving a balance of protection, utilization, inheritance and development can historical streets and alleys truly regain long-term and stable vitality in urban renewal.

4. Practice paths for historical street alley protection and micro-remodeling from the perspective of urban renewal

4.1. Restoration of street alley spatial texture and appearance

In practice, one should start from the overall layout and focus on protecting the original direction, width scale, courtyard relationships, node spaces and building interfaces of the street alleys. Avoiding the random widening of streets, demolition and modification of courtyard walls or reshaping of facades just to achieve uniformity. For dilapidated buildings and street interfaces that have been neglected for a long time, the approach of "minor repairs and patchwork updates" should be adopted. For instance, classify and rectify problems such as roof damage, wall cracking, distorted doors and windows, and aging pavement; try to retain the original materials, colors and construction methods; pay attention to restoring the order of the street alley public space. By removing illegal constructions, organizing store signs, optimizing the street interface, restoring traditional alley entrance signs and street corner nodes, and enhancing the overall visual continuity and spatial recognition. For the parts that need to be updated locally, a dialogue between new and old can be adopted by controlling the volume, material and color relationships to ensure a scale coordination with the historical environment. While preserving the unique spatial rhythm of the historical street alleys, it also enhances their recognizability and accessibility in contemporary urban life.

Taking the renewal of a certain historical and cultural district as an example, the main street of this district is approximately 420 meters long, and the width of the street alleys is mostly between 3.5 and 5.0 meters. There are 68 traditional brick and wood or brick and concrete buildings on both sides. However, there have been problems such as unauthorized construction, chaotic store signs, local facade damage and inconsistent street pavement over a long period. During the renewal process, the historical texture of the street alleys was first mapped and sorted out, and the original width and turning points of the alleys were clearly retained. 23 temporary structures that affected traffic and appearance were demolished. Then, the buildings along the street were classified for repair. For the facades with high preservation value, local brick patching, joint repair, wood component reinforcement and old door and window restoration were carried out. For the parts that were later added and had conflicting styles, hidden rectification was carried out. The ground pavement adopted a graded approach of main street stone slabs and branch street permeable bricks. At the alley entrances, the old street name signs, traditional wall paintings and small rest areas were restored. The overall spatial continuity of the street alley was significantly enhanced, the original living scale was retained, and residents and tourists could more intuitively feel the historical style of the district.

4.2. Improvement of infrastructure and enhancement of environmental quality

Improvement of infrastructure and enhancement of environmental quality are the most direct paths in the micro-renovation of historical streets and alleys that directly relate to the residents' sense of gain and the sustainable use of the streets. In practice, the principle of "prioritizing implicit renewal and focusing on filling functional gaps" should be adhered to. Infrastructure such as water supply, electricity, communication, gas, lighting, and fire protection should be included in the overall renovation plan, and key issues affecting the safety and environmental hygiene of residents' lives should be prioritized for resolution. For example, through rainwater and sewage separation, undergrounding of weak current lines, minor street renovations, supplementary lighting at nodes, reorganization of fire access routes, and embedding of micro-convenience facilities, the operational capacity of the streets can be enhanced. In terms of environmental quality, through pocket space organization, wall cleaning and repair, greening, addition of rest facilities, and optimization of garbage classification points, the comfort and tidiness of the streets can be improved.

Taking a traditional street renovation project in an old urban area as an example, this area has over 560 permanent residents. The original drainage pipes in the street were of small diameters, resulting in many water accumulation points during rainstorms. The overhead power and weak current lines were intertwined, and the average night illumination was less than 8 lx. The fire-fighting facilities were not well-equipped. The most common problems reported by residents were "difficult access, messy environment, and unsafe living conditions". The project team, based on the original road section, implemented segmented updates, buried about 780 meters of rainwater and sewage separation pipelines, raised the main alley lighting to 20–30 lx, added wall-mounted lighting and directional signs at 6 nodes, and simultaneously reorganized the overhead cables along the street. Using a "partial undergrounding + wall-mounted concealed laying" method to reduce visual interference, 4 micro-rest areas and 2 garbage classification collection points were set up at street corners and small open spaces, and fire extinguisher boxes, fire hydrant signs, and emergency passage guidance facilities were supplemented. The drainage and night traffic conditions of the streets have significantly improved, and the environmental cleanliness and residents' satisfaction have significantly increased. The renovation of historical streets and alleys should not only focus on "visible facades", but also through invisible but useful infrastructure renovations, truly enhance the quality of the street life and long-term operational capabilities [3].

4.3. Exploration and live transmission of local culture

Exploration and live transmission of local culture is an important path in the protection and micro-renovation of historical streets and alleys to "retain the cultural roots and continue the place spirit". In urban renewal practices, systematic review of the historical evolution, local memories, and cultural symbols of the streets should be conducted, and representative cultural elements should be extracted and transformed into part of spatial display, public activities, and daily use. Specifically, through restoring old street names, setting up oral history display points, preserving traditional shop signs, showcasing local craftsmanship processes, introducing cultural experience activities and community festivals, the street culture can evolve from "textual records" to "life reproduction". At the same time, the original residents, old merchants, folk artists, and community organizations should be encouraged to participate in cultural dissemination, allowing the street culture to naturally continue in real-life scenarios.

Taking a traditional street renovation project in an old city as an example, this street has a history of over 100 years and once long-term gathered local pastry workshops, bamboo weaving shops, and traditional festival parades. However, with population mobility and commercial relocation, these cultural contents gradually faded. In the micro-renovation, the project team first conducted oral interviews with 18 old residents and 12 old shops in the street, sorted out materials on the formation of the street, industry distribution, traditional festivals, and folk skills, and based on this, extracted three cultural themes: "Old Skills, Old Taste, and Old Street Names". Six small cultural display nodes were set up along the main street, embedding old photos, industry stories, street names, and craftsmanship processes in simple ways on the walls and shop windows. Two traditional pastry shops and one bamboo weaving workshop were retained in their original operating positions, guiding them to open part of their production displays during daily operations. The community also revived small-scale folk processions and neighborhood market activities in conjunction with traditional festivals, preventing cultural inheritance from remaining merely in static displays. The recognition of street and alley culture has significantly improved, residents' sense of identification with the local history has strengthened, and tourists can also experience the cultural connotations of the place in real-life scenarios. Thus, the streets and alleys have achieved an extension from "space restoration" to "cultural regeneration" [4].

4.4. Optimization of business models and enhancement of community vitality

The optimization of business models and the creation of community vitality are the key steps in the micro-renovation of historical streets and alleys, moving from “formal renewal” to “functional activation”. In urban renewal, the principles of prioritizing protection, moderate functionality, and life orientation should be adhered to. Selective optimization and configuration of street and alley business models should be carried out. On one hand, priority should be given to preserving basic functions such as convenience retail, small restaurants, repair services, and community activity spaces that are closely related to residents’ daily lives, maintaining the street and alley’s “livable, usable, and accessible” nature. On the other hand, in line with the historical and cultural characteristics of the street and alley, cultural experiences, creative retail, specialty bookstores, handicraft workshops, community exhibitions, and light leisure business models can be moderately implanted, but the business scale, decoration style, and operating intensity should be controlled to ensure their coordination with the street and alley’s spatial scale and community carrying capacity [5].

Taking a historical street and alley improvement project as an example, before the renovation, there were 41 storefronts along the street, among which 9 were vacant. Some business contents were low-end and repetitive, lacking uniqueness and unable to meet residents’ daily needs. During the renovation process, the project did not simply introduce a large number of restaurants and trendy stores. Instead, based on the street and alley’s scale, resident distribution, and cultural characteristics, the storefront functions were classified and guided. 16 convenience business models such as community breakfast shops, grocery stores, and repair points were retained to ensure basic life services for residents. 8 vacant storefronts were introduced with local handicraft stores, community reading spaces, intangible cultural experience rooms, and small tea shops, with each store area controlled at around 20–40 square meters to avoid large-scale commercial buildings squeezing the street and alley space. In an idle courtyard, a shared courtyard and residents’ discussion space were implanted, and regular activities such as handicraft markets, neighborhood festivals, and small cultural lectures were held. The daily flow of the street and alley increased significantly compared to before the renovation, but the overall life rhythm remained stable. The original residents were not marginalized. The street and alley had both a sense of warmth and certain cultural appeal. The optimization of the business models of historical streets and alleys is not about “introducing how many new businesses”, but whether it can form a street and alley vitality system that takes into account residents’ needs, cultural expression, and continuous operation on the basis of protecting the original community life [6].

5. Conclusion

In the context of the continuous deepening of urban renewal, the protection of historical streets and alleys and their micro-renovations have become an important path for preserving the urban cultural heritage, improving the living environment, and stimulating community vitality. Compared with large-scale demolition and reconstruction, micro-renovation places greater emphasis on protection as the premise, people’s livelihood as the foundation, and culture as the bond. While preserving the spatial texture and historical features of the streets and alleys, it also achieves functional repair, quality improvement, and dynamic inheritance. In the future, a multi-party collaborative mechanism should be improved to promote the protection and renovation of historical streets and alleys towards a more refined and long-term direction.

Disclosure statement

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Research on Quality Inspection System and Disease Prevention and Control of Asphalt Pavement

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Abstract: To effectively prevent issues such as cracking, deformation, and surface damage in asphalt pavements, improve pavement quality and performance, and extend pavement service life, this paper studies its quality inspection system and disease prevention and control. Based on the main quality issues of asphalt pavements, a quality inspection system is constructed from three aspects: raw materials, construction process, and operation, and reasonable prevention and control strategies are proposed. It is hoped that this study can provide a scientific reference for subsequent quality inspection and control of asphalt pavements.

Keywords: Asphalt pavement; Quality inspection system; Disease prevention and control; Quality

Online publication: May 12, 2026

1. Introduction

Asphalt pavement offers numerous advantages such as convenient construction, smooth and comfortable driving, and low maintenance costs, making it widely used in current highway engineering. In practical applications, the quality of asphalt pavement directly affects highway traffic efficiency and safety, as well as the service life of the pavement. Therefore, engineering units should clarify the main quality issues of asphalt pavement, adopt reasonable measures for quality inspection, and implement targeted prevention and control for various quality issues based on actual conditions. This will further enhance the overall quality of asphalt pavement and provide strong support for its long-term, safe, and stable operation.

2. Main quality issues of asphalt pavement

2.1. Cracking issues

Cracking is one of the common quality issues in asphalt pavement, which can be classified into transverse cracks, longitudinal cracks, and reticular cracks. Transverse cracks are generally perpendicular to the driving direction, appearing as regular or irregular straight lines with widths ranging from a few millimeters to several centimeters. Longitudinal cracks are parallel to the driving direction and usually distribute along the wheel tracks of the lanes, severely penetrating the full width of the pavement. Reticular cracks are irregularly distributed in a net-like pattern, typically appearing on the pavement surface. The causes of such damage are related to factors such as thermal expansion and contraction due to temperature changes, uneven settlement of the subgrade, reflective cracking of the base layer, improper construction joint treatment, and traffic loads. If not effectively prevented and controlled, these cracks will allow rainwater to penetrate into the pavement structure, eroding the base course aggregates, softening the subgrade, and causing secondary damage such as potholes and loosening of the pavement, further reducing the pavement's bearing capacity and even threatening traffic safety.

2.2. Deformation issues

Pavement deformation damage mainly includes rutting, waves, and corrugations. Rutting is the most common pavement deformation damage, which appears as permanent depressions in the wheel track area under prolonged heavy vehicle loads, with depths typically ranging from 5 to 50 mm and becoming more pronounced at higher ambient temperatures. Waves refer to wavy undulations on the local pavement surface, while corrugations are local pavement uplifts, commonly found on uphill sections or at intersections. Generally, the main causes of deformation damage in asphalt pavement include poor high-temperature stability of the mixture, insufficient compaction of the subgrade, inadequate strength of the base layer, excessive frequency or magnitude of loads, etc. If not promptly and effectively prevented and controlled, these deformations will adversely affect driving comfort, increase driving resistance, and even cause vehicle deviation in severe cases. They will also rapidly deteriorate the pavement's health condition, further shortening its service life [1].

2.3. Surface damage issues

Surface damage in asphalt pavement mainly includes potholes, bleeding, and loosening. Potholes refer to local depressions formed after the pavement surface material peels off, characterized by varying depths and irregular shapes, commonly found on sections with poor drainage or frequent rainwater scouring. Bleeding occurs when excess asphalt in the asphalt mixture is squeezed onto the pavement surface during high-temperature seasons, forming an oil film. Loosening refers to situations where the adhesion between the asphalt mixture and the pavement surface fails, causing the pavement to sand or peel off. These damage issues are mainly related to factors such as rainwater infiltration damage, asphalt aging, poor aggregate quality, improper asphalt content, or insufficient compaction. If not promptly and properly addressed, the overall performance of the asphalt pavement will significantly decline, adversely affecting traffic safety and tire service life, further damaging the integrity of the asphalt pavement, shortening its service life, and even causing traffic accidents in severe cases.

3. Quality inspection system for asphalt pavement

3.1. Raw material quality inspection

Raw materials have a fundamental impact on the quality of asphalt pavement. During specific inspections, engineering units should focus on key raw materials such as asphalt, aggregates, mineral powder, and additives, and conduct quality inspections in strict accordance with engineering design standards. Among them, the key inspection indicators for asphalt quality include softening point, penetration, ductility, and aging performance, etc. For modified asphalt, the dosage and storage stability of the modifier should also be inspected to prevent substandard asphalt performance from causing pavement bleeding or cracking. For aggregates, engineering units should classify them into coarse and fine aggregates during inspection and focus on inspection indicators such as abrasion value, crushing value, flakiness particle content, and asphalt adhesion to prevent substandard aggregate quality from causing potholes or loosening on the pavement [2]. For mineral powder, its hydrophilic coefficient and fineness should be the focus during inspection to ensure that all indicators meet engineering design standards. For additives, engineering units should focus on inspecting their performance and dosage and ensure the rationality of the asphalt mixture mix ratio to improve the accuracy of raw material quality inspection.

3.2. Quality inspection during construction process

Quality inspection and control throughout the construction process are crucial in asphalt pavement quality inspection. During specific inspections, engineering units should inspect core construction indicators such as paving and compaction of the asphalt mixture to effectively prevent and control key quality issues such as deformation, cracking, and surface damage of the asphalt pavement. Generally, the main quality inspection indicators during the construction process should comprehensively cover all damage types such as cracking, deformation, or surface damage of the asphalt pavement, and the mix ratio of the asphalt mixture and the construction quality of mixing should also be included in the inspection system. Typically, compaction should be inspected using a nuclear density gauge or core sampling method, with a detection frequency of two points per 200m for single lanes to ensure that the compaction meets engineering design standards and prevent rutting or loosening caused by substandard compaction. For flatness, it should generally be inspected using a 3m straightedge or laser flatness meter to ensure that it meets design requirements, which will make driving more comfortable and effectively reduce the probability of cracking caused by uneven loads. The basic inspection methods and requirements are shown in **Table 1**.

Table 1. Basic inspection methods and requirements for pavement during construction process

No.	Test indicator	Test method	Test frequency	Acceptance standard
1	Compaction Degree	Nuclear densitometer, Core drilling method	Two points per 200m per single lane	≥ 98%
2	Laying Thickness	Ultrasonic thickness gauge	One cross-section every 20m, 3 points per cross-section	Deviation ± 5mm
3	Smoothness	3m straightedge, Laser profilometer	Continuous testing	Standard deviation ≤ 1.0mm
4	Laying Temperature	Thermometer	3 tests per shift	≥ 130°C

3.3. Quality inspection during the operation period

During the operational period of roads, the primary objective of inspecting asphalt pavement distress is to promptly identify various types of distress and scientifically evaluate their performance, thereby providing a solid basis for subsequent operation, maintenance, and conservation decisions. Typically, inspection contents should include pavement distress conditions, evenness, skid resistance, and structural strength, among others. Distress detection should primarily be conducted through a combination of automated detection equipment and manual inspections. For pavement distress conditions, it is necessary to investigate each type of distress, such as cracks, potholes, and rutting, along with their locations and severity levels. Laser evenness meters should be used to comprehensively inspect pavement evenness, enabling the timely identification of substandard areas. The skid resistance of asphalt pavements should be tested using friction coefficient measurement vehicles or pendulum testers to determine whether their skid resistance meets standards [3]. For structural strength, deflection meters should be used for inspection, and the pavement's load-bearing capacity should be scientifically evaluated based on the inspection results to promptly identify areas with insufficient strength and prevent the further expansion of distress such as cracks or deformations caused by inadequate strength. During the operational phase, engineering units must strictly adhere to pre-established operation, maintenance, and conservation standards and regularly inspect asphalt pavement distress. This ensures that various types of distress are identified and addressed early, effectively delaying pavement aging.

4. Main prevention and control strategies for asphalt pavement distress

4.1. Raw material optimization

As the foundational condition for asphalt pavement quality control, raw material optimization is the primary strategy for preventing pavement distress. During optimization, engineering units should scientifically determine the amount of asphalt, aggregate gradation, and additive dosage based on the climatic conditions and traffic volume in the area where the road is located. This helps to reasonably optimize the raw material mix ratio, thereby achieving good control over the high-temperature stability, low-temperature crack resistance, and water stability of the mixture. For asphalt materials, modified asphalt should be preferred during optimization to further enhance the crack resistance and aging resistance of the asphalt, significantly reducing the incidence of distress such as pavement cracks and bleeding. At the same time, aggregates should be strictly screened to ensure that the crushing value and flakiness content of coarse aggregates meet engineering design standards, and fine aggregate angularity and sand equivalents should be strictly controlled according to design values to maintain good adhesion between the aggregates and asphalt, preventing distress such as pavement potholes or raveling [4]. For all incoming raw materials, engineering units should strictly conduct batch sampling inspections as required and prohibit the transportation and use of substandard raw materials on-site, thereby effectively controlling the quality of asphalt pavements from the source.

4.2. Improvement of construction techniques

To avoid adverse effects on asphalt pavement quality caused by construction technique issues, engineering units need to standardize asphalt paving techniques during the specific distress prevention and control process [5]. The full-width multi-machine paving method should be used to reasonably reduce cold joints, and paving speed and temperature should be strictly controlled. At the same time, real-time monitoring and handling of segregation phenomena in asphalt mixtures should be carried out to prevent pavement distress caused by asphalt aging or insufficient compactness. The asphalt pavement compaction process should be divided into three stages: initial compaction, intermediate compaction, and final compaction, with strict control over the number of compaction passes, speed, and temperature at each stage. Typically, initial compaction should be achieved through static compaction with a steel-wheel roller; intermediate compaction should be carried out using a rubber-tired roller or vibratory roller; and the main objective of final compaction is to eliminate wheel marks, with a steel-wheel roller generally meeting actual construction requirements [6]. During compaction, hot joints should be set as much as possible, and the joint positions should be thoroughly cleaned and compacted to effectively control crack distress in these areas. **Table 2** presents the basic process optimization indicators for different compaction stages.

Table 2. Basic process optimization indicators for different compaction stages

No.	Parameter	Initial compaction	Secondary compaction	Final compaction
1	Number of Rolling Passes	1–2	3–4	2
2	Rolling Speed (km/h)	2–3	3–4	2–3
3	Rolling Temperature (°C)	≥ 110	≥ 100	≥ 70

4.3. Subgrade and base course reinforcement

Since the subgrade and base course also have a direct impact on the quality of asphalt pavements, engineering units should also carry out reasonable reinforcement treatments on the subgrade and base course during specific distress prevention and control processes. For the subgrade, fillers should be strictly screened during construction to ensure sufficient water stability and high bearing capacity, and the degree of compaction should be strictly controlled to guarantee the uniformity and stability of the subgrade, minimizing the occurrence probability of distress such as cracks or subsidence caused by uneven settlement [7]. For soft soil subgrades, reinforcement treatments such as grouting or replacement should be carried out during construction to ensure that the bearing capacity meets design requirements and prevent pavement deformation due to insufficient subgrade strength. During base course construction, engineering units should reasonably determine its thickness and mix ratio in strict accordance with design requirements and strengthen treatments such as compaction and curing to improve the strength of the base course, ensuring its integrity and stability and preventing reflective crack distress. Simultaneously, the pavement drainage system should be scientifically improved, with drainage ditches or side ditches reasonably set up based on the actual site conditions to promptly drain accumulated water on the pavement and prevent water from infiltrating into the internal structure of the asphalt pavement, which could cause distress such as raveling or potholes [8].

4.4. Maintenance and control during the operation period

During the operation of asphalt pavements, engineering units should establish a normalized distress inspection mechanism, with dedicated personnel responsible for regularly inspecting pavement distress. Pavement distress should be detected through a combination of automated equipment and manual inspections to promptly identify and comprehensively grasp the occurrence and development of various types of pavement distress. On this basis, a comprehensive digital archive of asphalt pavement distress should be established, with different types and severities of pavement distress recorded and classified in the archive for classified management. At the same time, engineering units should also carry out preventive maintenance work on asphalt pavements, promptly repairing minor cracks through methods such as crack sealing tapes or crack filling; implementing slurry sealing or micro-surfacing treatments on areas with surface aging or reduced skid resistance to effectively delay the development of distress [9]. For areas with severe distress, engineering units should promptly carry out repairs through methods such as partial excavation and replacement or milling and repaving to prevent further expansion of pavement distress. Moreover, during operation and maintenance, traffic management should be strengthened, with strict restrictions on overloading of heavy-duty vehicles to effectively reduce the incidence of pavement damage distress caused by vehicle loads, thereby further extending the service life of the pavement [10].

5. Conclusion

In summary, during the quality control process of asphalt pavements, the reasonable establishment of a quality inspection system can strictly control the overall pavement quality, enabling timely and accurate identification of various types of pavement distress and effective prevention of many types of distress. During specific distress prevention and control processes, through the reasonable application of measures such as raw material optimization, construction technique improvement, subgrade and base course reinforcement, and maintenance and control during the operation period, asphalt pavement distress can be effectively addressed and prevented from further developing, thereby effectively controlling the overall quality of asphalt pavements. This not only enables further improvement in the quality of asphalt pavement engineering but also reasonably extends its service life and achieves effective reduction in operation and maintenance costs.

Disclosure statement

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Research on Key Technologies for Traffic Organization in the Reconstruction and Expansion of Complex Interchanges and Elevated Lifting Sections

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Abstract: Complex interchanges and elevated lifting sections represent critical nodes in the reconstruction and expansion projects of expressways and urban express roads, characterized by the most intricate structures, highest risks, and greatest traffic disruptions. Under conditions of heavy network traffic, limited construction space, frequent structural transitions, and interweaving multi-directional traffic flows, conventional traffic organization methods struggle to ensure both construction safety and network efficiency. To systematically address core challenges such as traffic dispersion, safety management, construction transitions, and network coordination faced during the reconstruction and expansion of complex interchanges and elevated lifting sections, this paper outlines the engineering characteristics and traffic pain points of these projects. It proposes key technologies for traffic organization in both complex interchange reconstruction and elevated lifting section reconstruction, aiming to provide technical references for similar complex node reconstruction projects. These technologies hold significant engineering value in enhancing traffic safety during construction, reducing congestion risks, and ensuring the smooth operation of the road network.

Keywords: Complex interchange; Elevated lifting section; Reconstruction and expansion; Traffic organization; Traffic transition; Safety management; Road network coordination

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1. Introduction

After years of operation, early-built expressways in China generally face issues such as saturated capacity, degraded service levels, and structural aging. Reconstruction and expansion have become the primary means to enhance the service capacity of the road network [1]. In reconstruction and expansion projects, complex interchanges and elevated lifting sections, due to their critical functions, dense structures, and strict alignment controls, have emerged as core nodes that constrain the overall project duration and safe operation. These nodes are typically located at the heart of regional road networks, experiencing heavy traffic volumes and complex vehicle compositions. Moreover, construction must proceed under the condition of "traffic flowing while construction is ongoing," making the traditional half-closure construction mode prone to causing long-distance congestion, traffic accidents, and construction safety hazards. With the advancement of regional integration, the functions of expressway interchanges are becoming increasingly complex, and the demand for elevated lifting reconstruction is on the rise. Traffic organization is no longer a simple road section management task, but requires coordinated linkage among mainlines, ramps, parallel road networks, and local roads. Based on the reconstruction and expansion project practice of the Wenzhou Nanbaixiang to Zhejiang-Fujian Border Section of the Yong-Tai-Wen Expressway, this paper systematically analyzes the engineering characteristics, traffic impacts, and risk sources of complex interchanges and elevated lifting sections. It refines key technologies for traffic organization, providing implementable and replicable technical solutions for similar projects.

2. Engineering characteristics and traffic impacts of reconstruction and expansion projects for complex interchanges and elevated lifting sections

2.1. Engineering structural features

Complex interchanges and elevated lifting sections exhibit distinct technical characteristics in reconstruction and expansion projects, which are also the fundamental reasons for the difficulty in traffic organization. Complex interchanges are mostly hub interchanges or composite interchanges, undertaking multi-directional conversion functions between expressways and expressways, as well as between expressways and urban express roads. The mainlines and ramps crisscross, with dense bridge structures and strict horizontal and vertical alignment indicators [2]. During the reconstruction and expansion process, it is often necessary to carry out demolition and reconstruction, in-situ splicing, off-site relocation, or synchronous implementation with the ongoing hub projects. The connection between old and new structures is complex, and construction procedures are highly overlapping. Elevated lifting sections are mainly constructed to meet clearance control, alignment optimization, or urban development needs. They involve raising the overall longitudinal profile of the existing subgrade or bridge, transforming the subgrade into an elevated structure. The construction process includes a series of procedures such as old bridge demolition, pile foundation construction, scaffold erection, beam and slab installation, and splicing of new and old bridge decks. The lifted sections are usually long, with a continuous construction period, and are closely adjacent to existing roads, resulting in extremely limited working space. Both types of nodes collectively present characteristics such as diverse structural forms, complex connections between old and new structures, narrow construction space, high demand for temporary works, and frequent overlapping of construction procedures. A fully closed construction mode cannot be adopted, and construction must proceed while ensuring traffic flow, highlighting the prominent contradiction between traffic and construction.

2.2. Main impacts of construction on traffic operations

Reconstruction and expansion construction will alter the traffic operation state from multiple aspects such as traffic capacity, driving conditions, and road network distribution [3]. Firstly, there is a significant decline in traffic capacity. Construction occupies existing lanes, reduces the lateral clearance, and sets up long-term work zones, resulting in a decrease in the number of mainline lanes and a reduction in speed limits, leading to an obvious reduction in overall traffic capacity. Moreover, driving conditions deteriorate. The alignment in the construction area is frequently adjusted, lanes become narrower, and visibility is limited. Vehicles need to change lanes, merge, and diverge multiple times, substantially increasing the driving workload. Meanwhile, the traffic disturbances caused by construction will quickly spread to the regional road network. Congestion on the mainline will directly lead to a sudden increase in traffic volume on parallel national and provincial roads, ring expressways, and connecting lines, causing local road sections to quickly reach saturation and resulting in road network-wide congestion. In addition, construction activities such as high slope excavation, bridge hoisting, and steel bar processing are adjacent to the driving lanes. Mechanical operations and personnel movement directly interfere with passing vehicles, further exacerbating the instability of traffic operations.

2.3. Main risk points in traffic operations

Under the combined effects of high traffic volume, strong interference, and multiple conversions, traffic operations during the construction period of complex interchanges and elevated lifting sections exhibit obvious high-risk characteristics as follows:

(1) There is the risk of multi-directional traffic flow intersection and conflict. In the interchange area, mainline traffic, ramp traffic, and turning traffic frequently converge in a narrow space. With insufficient acceleration and deceleration distances, rear-end and scraping accidents are prone to occur;

(2) There are driving risks associated with sudden alignment changes. In traffic conversion sections, S-shaped transitions, mismatched cross slopes, and lane offsets are formed, making vehicles prone to deviating from their lanes, especially at night and in rainy weather;

(3) Emergency rescue is difficult. With lane closures and insufficient emergency space in the construction area, it is challenging to quickly clear obstacles in case of an accident, which can easily lead to long-distance congestion and secondary accidents [4];

(4) There is the risk of wrong-way driving due to inadequate temporary facilities. Incomplete temporary signs, protections, and lighting, along with drivers' unfamiliarity with temporary routes, can lead to wrong-way and reverse driving;

(5) There are risks associated with the management and control of large vehicles. The proportion of trucks in the project road section is high. With their long bodies, high centers of gravity, and long braking distances, their safety is significantly reduced in speed-restricted, lane-changing, and turning sections.

3. Key technologies for traffic organization in the reconstruction and extension of complex interchanges

3.1. Staged traffic conversion organization technology

Staged traffic conversion is the core aspect of reconstruction and extension projects for complex interchanges and is crucial for ensuring smooth traffic flow. During actual construction, the overall approach of "ensuring traffic flow first, then proceeding with construction; constructing new structures first, then demolishing old ones" is consistently followed. Based on the interchange type and traffic flow characteristics, the entire renovation process is clearly divided into four key stages: subgrade widening, ramp construction, structural demolition and reconstruction, and full-line conversion. The dynamic balance between construction areas and traffic flow at each stage is precisely controlled to avoid interference between construction and traffic movement.

For interchange nodes requiring demolition and reconstruction, priority is given to planning and constructing temporary bypass ramps or temporary passage structures before construction begins. Traffic is smoothly redirected from existing routes to temporary passages through guidance. Once traffic is fully diverted and stable, demolition of old structures can commence, minimizing the impact on mainline and ramp traffic and avoiding prolonged traffic interruptions. For complex hub interchanges with multiple connecting routes and concentrated traffic flows, an end-modification and phased construction approach is adopted. Normal traffic flow on the mainline and major ramps is prioritized, with temporary control measures implemented only in localized areas requiring renovation. This reduces the scope of control measures and minimizes the impact on the regional road network.

For continuous interchanges with close spacing, simultaneous construction can easily cause congestion in the regional road network. In practice, an alternating closure and staggered construction strategy is employed, reasonably staggering the closure times of adjacent interchanges to avoid simultaneous traffic interruptions and effectively reducing the diversion pressure on the regional road network. For key processes such as ramp bridge demolition and reconstruction and overpass mainline bridge modifications, which significantly impact traffic, a half-closure construction method is used, allowing two-way traffic on the other half. Reasonable transition zones and gradual lengths are set up, along with optimized traffic guidance signs, to ensure smooth and continuous traffic flow without sudden braking or lane-cutting, thereby eliminating safety hazards. Throughout the traffic conversion process, the principles of "uninterrupted traffic flow, minimal road closures, short closure durations, and rapid conversions" are upheld, achieving deep coordination between traffic and construction organizations and ensuring that both construction and traffic flow proceed smoothly without mutual interference.

3.2. Multi-directional traffic diversion and control technology

The construction sites of complex interchange reconstruction and extension projects are characterized by a diverse range of traffic flows, including long-distance through traffic, interval traffic, and short-distance distribution traffic, with frequent crossings and interweaving, making them prone to congestion and safety hazards. Therefore, an integrated diversion system must be established, incorporating "source induction, road network diversion, hierarchical control, and vehicle-type restrictions" to achieve precise control and scientific diversion of various traffic flows.

In specific implementation, traffic induction points are set up at distant hub interchanges. Construction information is disseminated in advance through signs and electronic display screens, guiding long-distance through traffic to bypass parallel expressways such as the Yongguan Expressway and Wenzhou Ring Expressway, thereby reducing traffic pressure in the construction area from the source. At interchanges upstream of the project, diversion points are established with dedicated personnel on duty to forcibly divert traffic approaching the construction area and prevent a concentrated influx into the construction section. At the entrance of the construction interchange, control points are set up to implement real-time flow control and vehicle-type restrictions based on construction progress and on-site traffic capacity, ensuring that traffic in the construction area remains within controllable limits.

Based on regional road network conditions, different types of traffic flows are diverted accordingly: long-distance through traffic is prioritized for diversion to parallel expressways to ensure its efficiency; interval traffic relies on hub interchanges and connecting lines for rapid conversion, reducing detour distances; and short-distance distribution traffic is diverted using national and provincial roads and urban roads for the convenience of the public. In terms of vehicle-type control, the principle of "prioritizing the diversion of trucks and the passage of passenger vehicles" is followed. Large trucks are diverted remotely to prevent them from entering the construction area, reducing safety pressures and traffic congestion. Meanwhile, dynamic entrance control measures are implemented, with intermittent release of traffic at local interchanges during peak hours to reasonably control mainline traffic density, prevent overflow congestion in the construction area, and ensure orderly traffic flow.

3.3. Safety protection and facility layout technology

The construction sites of complex interchange reconstruction and extension projects feature dense work points, concentrated personnel and machinery, and interweaving traffic flows with construction areas, posing high safety risks. Therefore, a standardized and integrated safety protection system must be adopted to comprehensively prevent construction and traffic safety hazards and ensure the safety of construction personnel, equipment, and passing vehicles [5].

According to traffic engineering construction specifications, warning zones, transition zones, buffer zones, work zones, and termination zones are uniformly set up in the construction area. The lengths of each zone are strictly controlled in accordance with standards, ensuring that gradual lengths, isolation facilities, and speed limits are mutually matched to form a complete safety protection chain. High-grade anti-collision movable barriers are used at the edges of work zones to achieve hard isolation between the construction area and the roadway, effectively preventing vehicles from accidentally entering the construction area and protecting construction personnel and machinery. For key areas with poor visibility and frequent traffic interweaving, such as ramp curves, downhill sections, and merging zones, additional deceleration markings, reflective warning facilities, and nighttime lighting equipment are installed to enhance visibility at night and in adverse weather conditions, guiding drivers to decelerate in advance and proceed with caution. Fully enclosed protection measures are adopted for high-risk work areas such as bridge edges and high slopes, prohibiting unauthorized personnel and vehicles from entering. During construction, blasting is strictly prohibited, and mechanical excavation methods are prioritized to avoid falling objects from blasting operations that could damage passing vehicles and interrupt traffic. Traffic monitoring equipment and information dissemination equipment are installed at key construction nodes to monitor traffic flow and road conditions in and around the construction area in real-time, promptly disseminate road condition information, speed limits, and congestion warnings, achieve proactive safety warnings, and guide drivers to reasonably adjust their driving speeds and routes, reducing safety risks caused by driver errors.

4. Key technologies for traffic organization in the reconstruction and extension of elevated sections

4.1. Traffic conversion technology for elevated construction

Traffic conversion for elevated construction must be tailored to local conditions, flexibly adopting differentiated modes such as bypass road diversion, outer-side super-widening and splicing, half-width alternating construction, and separation of new and old alignments based on the functional positioning of the road section, elevation height, and existing structural forms to achieve a dynamic balance between construction and traffic flow.

For long-distance overall elevation of main road sections with high traffic density and demand, priority is given to constructing solid temporary bypass roads on both sides of the mainline. Vehicles are guided to bypass the construction area through complete signs and markings, allowing for full closure of the mainline for construction. This approach completely separates the construction area from traffic flow, avoiding cross-interference and creating a safe environment for high-precision elevation operations. For medium-length elevated sections, an "outer-side super-wide splicing" scheme is adopted. The outer-side newly added bridge structure is constructed and opened first. Once it meets traffic conditions, the inner-side old bridge is gradually demolished and elevated and renovated. Traffic flows bidirectionally in the splicing section, effectively reducing the closure scope and minimizing the impact on the surrounding road network. For general road sections with open terrain, a conventional "two-side widening and half-width alternating" traffic maintenance mode is adopted. Half of the lanes maintain normal bidirectional traffic flow, while the other half is used for bridge elevation construction, progressing segment by segment and restoring traffic segment by segment to ensure that the overall road network continuously meets basic traffic capacity requirements. At nodes where new and old alignments overlap and construction space is extremely limited, a two-way two-lane traffic maintenance standard is adopted, significantly reducing the traffic section and strengthening segmented control to prioritize meeting the public's traffic needs. All traffic conversion links must strictly adhere to the technical standards of "advance notice, smooth transition, opposite-direction hard isolation, and unified speed limits." The alignment of transition sections must be continuous and smooth, and central isolation facilities must be sturdy and reliable to eliminate safety hazards caused by opposite-direction collisions and lane changes from the source.

4.2. Safety protection technology for elevated work zones

Elevated construction is a typical high-altitude edge work, and safety protection must focus on "preventing falls, preventing overturning, and preventing intrusion" to build a comprehensive and multi-layered protection system. High-strength, high-toughness protective railings must be set up on the side of the work bridge deck, with dense mesh safety nets fully hung to form a closed physical barrier. Key facilities such as scaffolding, formwork, and large lifting equipment must be equipped with sufficient anti-overturning devices to ensure structural stability. Construction materials are subject to zoned centralized stacking and enclosed management to eliminate the risk of falling objects from high altitudes. When roads are still in use below the elevated section, a sturdy anti-fall protection shed must be erected across the entire section to achieve absolute physical isolation between the construction area and ground traffic. In terms of traffic control, a unified speed limit is implemented across the entire line. The conventional speed limit is 80 km/h, which is further reduced in key sections such as bridge elevation, traffic conversion nodes, and tunnel transitions. Large vehicles are mandated to keep to the right and are prohibited from overtaking to reduce lateral traffic interference with the construction area. Nighttime construction requires full-coverage continuous lighting, strobe warning lights, and delineators to enhance nighttime visibility. In case of severe rain, strong winds, or other adverse weather conditions, high-altitude work must be immediately suspended, and the work zone must be closed to guide vehicles to bypass, ensuring absolute safety.

4.3. Integrated traffic organization technology for upper and lower layers

Elevated sections are mostly grade-separated projects, and their construction organization must be integrated with the lower-level ground roads and urban main roads to achieve upper-lower coordination and simultaneous diversion. The construction of the upper elevated section and the diversion routes of the lower roads must be uniformly planned and implemented simultaneously, strictly avoiding simultaneous bottlenecks for upper and lower traffic during the same period. For key processes such as beam installation and large-volume concrete pouring, which occupy a long time and have a wide impact range, construction plans must be carefully arranged to avoid peak ground traffic hours as much as possible, minimizing interference with public travel. Meanwhile, an upper-lower traffic emergency linkage mechanism must be established. Emergency rescue channels must be uniformly planned and reserved to enable rapid linkage and obstacle clearance in case of traffic accidents, preventing concurrent congestion on upper and lower sections and regional road network paralysis. Additionally, parallel expressways, national and provincial roads, and surrounding urban road networks must be fully utilized as diversion channels to implement balanced diversion and avoid excessive concentration of traffic flow in the construction section. Through scientific regulation, the load on the regional road network can be evenly distributed, comprehensively improving overall traffic reliability and risk resistance.

5. Conclusion

Complex interchanges and elevated sections are the most complex and safety-risk-prone key nodes in expressway reconstruction and extension projects. The core conflicts lie in the spatial conflict between high-intensity construction and high-volume traffic flow and the temporal conflict between frequent structural conversions and continuous traffic flow. Practice has shown that adopting systematic traffic organization technologies can achieve the goals of uninterrupted mainline traffic, reduced congestion, lower accident rates, and orderly construction progress, thereby ensuring the smooth implementation of reconstruction and extension projects while minimizing the impact on social traffic. This technology system is applicable to the reconstruction and extension of complex nodes on coastal high-volume expressways and can provide reliable references for similar domestic projects. With the development of intelligent transportation and vehicle-road coordination technologies, future traffic organization during construction periods will upgrade towards dynamic perception, real-time regulation, and global coordination, further enhancing safety levels and traffic efficiency.

Disclosure statement

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Analysis of Key Points in Engineering Project Management under the EPC Model

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Abstract: The construction process of engineering projects is complex, encompassing multiple critical stages such as engineering design, raw material procurement, and construction. Although the nature of work varies across these stages, they are highly interconnected. Any issues arising in one stage can impact the effectiveness of work in other stages. Under the EPC model, engineering project management can integrate the processes and resources of project construction, thereby enabling full-process control and thereby enhancing management efficiency while reducing risks. This article primarily analyzes the concept and characteristics of the EPC model and summarizes the key points of engineering project management under the EPC model at different stages, including decision-making, design, procurement, construction, and completion acceptance. Finally, it proposes optimization suggestions for engineering project management under the EPC model, providing a reference for the high-quality implementation of the EPC model in engineering management.

Keywords: EPC model; Key points of engineering project management; Cost control; Quality management; Safety management

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1. Introduction

In recent years, driven by urbanization, China's engineering construction industry has gained broader development space. The number and scale of construction projects have continuously expanded, while the requirements for construction quality have also increased. This has made it difficult for the traditional decentralized engineering management model to meet the current needs of construction project management. Traditional decentralized management divides engineering projects into different stages, with different contractors for each stage, leading to issues such as poor communication, inconsistent management objectives, and disjointed project management across stages, which severely impact the return on investment in engineering projects. The emergence of the EPC (Engineering, Procurement, and Construction) general contracting model has transformed decentralized engineering project construction management into an integrated management model, achieving the integration of project resources and tasks, which is of great significance for improving construction efficiency and controlling construction costs.

2. Concept and characteristics of the EPC model

The EPC model is primarily applied in the field of construction engineering, emphasizing the integration of design, procurement, and construction into a unified general contracting model. The general contractor is required to strictly adhere to contractual provisions to ensure quality control across the design, procurement, and construction phases, and to assume risks related to quality, safety, cost, environmental protection, and other aspects that may arise during construction [1]. Compared to traditional decentralized engineering contracting methods, EPC general contracting model offers more significant advantages, which can be manifested in the following aspects:

2.1. Integrated engineering management and control

Under the EPC model, project management and control can coordinate the entire process of the project, effectively addressing issues such as poor communication and information barriers across different stages of traditional construction projects. The general contractor can start with an overall grasp of the construction process, effectively connecting various engineering stages, which facilitates the preparation of a unified overall project management and control plan.

2.2. Strong controllability over engineering management risks

In EPC contracting, the owner only needs to sign a contract with the general contractor, with subsequent quality control, progress control, and cost management being undertaken by the general contractor, thereby centralizing construction risks. This not only facilitates comprehensive risk management but also avoids issues of unclear division of responsibilities and rights in the later stages [2].

2.3. Demonstrates high efficiency in engineering cost control

In EPC project management, the general contractor is responsible for cost control at all stages of the project, aligning the contractor's cost control with its interests, thereby enhancing the effectiveness of cost control.

2.4. Achieves high construction efficiency

Under the EPC model, project management and control can integrate engineering design, procurement, and construction, making the connection between construction stages more convenient, reducing technical handover and communication time, thereby significantly shortening the construction period and improving project efficiency. To ensure a clearer comparison between the advantages of the EPC general contracting model and the traditional decentralized contracting model, their operational models are summarized in **Table** 1.

Table 1. Comparison between EPC general contracting model and traditional decentralized contracting model

Dimension	Traditional decentralized contracting mode	EPC general contracting mode
Management Entity	The owner needs to coordinate with contractors of each link separately	The owner interfaces with the EPC general contractor
Responsibility Allocation	Overlapping responsibilities, unclear division	EPC general contractor assumes full responsibility; no ambiguity in division of rights and responsibilities

Communication Efficiency	High communication difficulty, information barriers	Integrated control, collaborative communication
Change Management	High probability of changes, high risk	Enables coordinated management of design and construction, low probability of changes
Schedule Control	High difficulty in linking each phase, affecting project efficiency	Seamless connection between phases, shortening construction period
Risk Bearing	High risk for the owner	General contractor bears the risks

3. Key points of project management under the EPC model

3.1. Key management points in the project decision-making phase

In project management under the EPC model, the decision-making phase is a critical stage for studying decision-making content such as project feasibility demonstration, calculation of construction benefits, and preparation of project implementation plans. Decisions made during this phase are crucial for subsequent project control and corporate profitability. Therefore, it is essential to clarify the construction requirements of the project and select partners based on project objectives [3].

3.1.1. Comprehensive feasibility demonstration

Comprehensive feasibility demonstration of the project should be conducted. Before initiating the project, the owner should collaborate with a professional team specializing in construction project development to evaluate the project's comprehensive conditions, including investment, technology, and environment, thereby defining the overall project objectives [4].

3.1.2. Functional positioning of the project

The project's functional positioning should be determined, and the rights and responsibilities of all parties involved should be clarified to avoid issues such as passing the buck in case of project problems.

3.1.3. General contraction selection

The EPC general contractor should be selected reasonably. During the bidding process for the general contractor, comprehensive indicators such as the contractor's business capabilities, construction experience, industry reputation, and corporate financial status should be considered. Priority should be given to cooperating with enterprises that have a high reputation and strong risk resistance capabilities [5].

3.2. Key management points in the project design phase

The design phase of an EPC project involves overall planning for project construction, and the construction plan developed during this phase is crucial for subsequent project control quality. In EPC projects, the design is the responsibility of the general contractor, but the owner needs to review the design content to ensure it meets the owner's requirements.

3.2.1. Identification of the owner's requirements

Project design should be based on the owner's requirements for construction, clarifying technical and functional standards. The general contractor should further survey the construction site based on geological survey data provided by the owner and design the project plan based on the survey results. Moreover, BIM technology should be used to create a three-dimensional digital model of the design plan, which should be shared via an online platform with participants such as the construction party, supervision party, and owner. Each party should provide feedback on the design plan from their respective professional perspectives to ensure its rationality and reduce the likelihood of subsequent design changes [6].

3.2.2. Through review of the design plan

The design plan should be thoroughly reviewed. The review of the engineering design plan should also primarily take place on an online platform, where all parties involved use the BIM model to conduct a joint review of the final design plan, focusing on comprehensive considerations such as the completeness of the design drawings, the feasibility of the engineering design, and the controllability of costs.

3.2.3. Procurement lead and construction development

Design should lead procurement and construction to develop synergistically. Under the EPC model, the general contractor is responsible for design, procurement, and construction. Therefore, designers should not only fully consider the ease of procurement of design materials and cost control but also consider construction site conditions and the difficulty of implementing processes to ensure that the design meets the owner's requirements and facilitates subsequent procurement and construction [7].

3.2.4. Strengthening control of design changes

Control over design changes should be strengthened. Design changes during construction pose severe challenges to project cost control and schedule management. Therefore, it is essential to combine the review of two-dimensional drawings with BIM three-dimensional models during design to predict potential risks and minimize subsequent changes. If changes are unavoidable due to unforeseen circumstances or special reasons, a thorough change assessment should be conducted to minimize change risks and costs.

3.3. Key management points in the project procurement phase

The primary tasks in the project procurement phase involve the procurement of project materials and equipment. The formulation of procurement plans and control over material quality can significantly impact construction progress, quality, and safety management. Therefore, procurement planning should be conducted before procurement.

3.3.1. Formulation of procurement plan

A reasonable procurement plan should be formulated [8]. Given the long construction period of engineering projects, to avoid excessive accumulation of materials at the construction site and reasonably control procurement costs, the general contractor should develop a batch procurement plan. The plan should specify material names, specifications, quantities, and transportation times to provide a sufficient basis for procurement work.

3.3.2. Establishment of supplier selection system

A supplier selection system should be established. The current construction materials market is mixed, and to ensure the quality of raw materials, the procurement department should conduct a meticulous screening of suppliers. During the supplier screening process, the procurement department can establish a supplier cooperation resource library, input supplier names into the library, and the system can comprehensively rank suppliers based on their reputation, quotations, and corporate operational status. Procurement personnel should include the top-ranked suppliers in the cooperation resource library and select the most suitable partners from them. This screening method facilitates establishing long-term cooperative relationships with suppliers and quickly finding alternative partners after terminating cooperation with one company, avoiding passivity in procurement work. Additionally, after determining cooperation intentions, procurement personnel should visit the supplier's factory to inspect their supply capabilities and avoid subsequent supply disruptions that could affect construction progress.

3.3.3. Strengthening of the procurement process

Control over the procurement process should be strengthened. After procurement and before materials enter the site, they should be monitored throughout to ensure their quality meets industry standards and construction requirements. Materials can only enter the site after passing the "three inspections" [9]. If materials do not comply with contract specifications, they are not allowed to enter the site under any circumstances.

3.3.4. Attention to cost risk management in procurement

Attention should be paid to cost risk management in procurement. The prices in the construction materials market fluctuate significantly, and batch procurement can easily lead to increased procurement costs due to subsequent material price increases. Therefore, price fluctuation agreements can be used to control prices within a reasonable range and reduce procurement risks.

3.4. Key management points in the project construction phase

The construction phase is a critical stage for the physical realization of the project, involving comprehensive and detailed management tasks that require simultaneous attention to quality, safety, progress, and cost control. Therefore, fine management is essential.

3.4.1. Optimization of construction organization design

The construction organization design should be optimized. Before construction begins, the general contractor should optimize the construction organization design based on engineering design, site survey results, and construction standards to provide an effective basis for subsequent construction management. Special management plans should be designed for special construction processes (such as deep excavations and high-formwork) to improve construction quality and ensure project safety.

3.4.2. Strengthening of construction quality management

Construction quality management should be strengthened. Before construction, the project manager should organize construction teams for construction training and technical disclosures to ensure that construction personnel are familiar with construction processes and procedures, thereby effectively reducing quality and safety accidents caused by human errors. For critical processes, a "sample" approach should be adopted to test construction processes and ensure their feasibility before full implementation.

3.4.3. Attention to construction safety management

Attention should be paid to construction safety management. Safety management has always been the core of project control. In safety management, AI image recognition technology can be used to identify on-site violations and help avoid safety issues caused by inadequate safety control [10]. Construction personnel safety training should be strengthened, and AI-immersive safety accident scenarios can be used to enhance safety awareness. Additionally, a construction safety management ledger should be established to provide a reference for improving subsequent safety management standards.

3.4.4. Strengthening of construction progress control

Construction progress control should be strengthened. To ensure the efficiency of progress control, BIM technology can be used to construct a construction progress control model and compare the designed progress model with the actual project progress model to understand progress control situations. This facilitates managers in promptly identifying progress deviations and adjusting progress plans.

3.4.5. Strict control of construction costs

Construction costs should be strictly controlled. A dynamic engineering cost control model should be constructed to more accurately track the application of engineering materials and equipment, facilitating the regulation of construction materials, equipment, and personnel and avoiding resource waste, thereby improving construction cost control effectiveness.

3.5. Key management points in the project completion acceptance and operation and maintenance phase

Project completion acceptance and operation and maintenance represent the continuous service phase after project construction and serve as the final checkpoint for project quality control.

3.5.1. Project completion preparation

Project completion preparations should be made. After construction is completed, the general contractor should organize all parties involved in construction to conduct a self-inspection of the project's main body to ensure compliance with contract specifications.

3.5.2. Initiation of completion acceptance process

The completion acceptance process should be initiated. The primary party responsible for completion acceptance is the owner, who needs to conduct a comprehensive inspection of the project's quality, duration, and functionality according to contract specifications and handle acceptance procedures after confirmation of compliance. Subsequently, specialized acceptance should be conducted by departments such as fire protection and environmental protection to ensure compliance with regulations.

3.5.3. Implementation of operation and maintenance phase control

Operation and maintenance phase control should be implemented. The operation and maintenance control period is relatively long, and during the warranty period for various services of the building, the general contractor should dispatch professionals to regularly inspect the project's operational status and explain building maintenance methods to the property management company or owner to improve building maintenance efficiency. After the building operation and maintenance period expires, operation and maintenance authority transfer procedures should be handled in writing.

4. Optimization suggestions for project management under the EPC model

The application of EPC project management effectively eliminates the drawbacks of traditional decentralized construction contracting models, forming a collaborative and unified management model that significantly improves management efficiency. However, current EPC project management is not yet perfect and requires further optimization based on existing issues.

4.1. Leveraging of collaborative role of EPC projects

The collaborative role of EPC projects should be fully leveraged by establishing a collaborative control mechanism in project management to provide a more favorable platform for communication among departments. Data standardization among departments should be promoted to improve data sharing efficiency.

4.2. Strengthening of risk control in EPC project management

Risk control in EPC project management should be strengthened. Artificial intelligence and big data technologies should be used to enhance risk identification capabilities and construct a full-process risk control mechanism to achieve precise control over various stages of project implementation.

4.3. Introduction of modern technological means

Modern technological means should be actively introduced to transform traditional manual control models into digital control models, ensuring the fine development of management work.

4.4. Strengthening of industry supervision

Industry supervision should be strengthened. The EPC model differs significantly from traditional decentralized contracting methods, and traditional industry standards and regulations are not applicable to EPC projects. Therefore, the improvement of the industry supervision system is necessary to lay the foundation for the long-term development of the EPC model.

5. Conclusion

In summary, the EPC model can integrate the various management stages of construction engineering projects into a unified management mechanism, facilitating control over project quality, safety, progress, and costs, thereby improving project economic benefits and reducing risks. However, the EPC model is not yet fully mature and still has certain deficiencies. Future research should expand in areas such as the characteristics of modern construction and the application of digital technologies to promote continuous innovation in the EPC model, thereby laying the foundation for the high-quality development of the construction industry.

Disclosure statement

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Design Strategies for Cultural and Creative Products of Haihe River Bridge Culture

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Abstract: As the mother river of Tianjin, the Haihe River hosts bridges along its course that serve not only as vital carriers of urban transportation but also as cultural symbols embodying Tianjin's regional culture, historical heritage, and engineering craftsmanship. Taking Haihe River bridge culture as the core research subject, this paper combines visual communication design theory with the logic of cultural and creative product development. Through a systematic examination of the cultural connotations, typological characteristics, and value dimensions of the Haihe bridges, it analyzes current problems in product design, including homogenization, superficial cultural expression, and insufficient audience adaptation. Consequently, from four dimensions, cultural symbol extraction, design language transformation, functional scenario integration, and communication model innovation, this study constructs design strategies for Haihe River bridge cultural and creative products that possess cultural significance, innovation, and practicality. This research aims to provide theoretical support and practical reference for the design of cultural and creative products related to Tianjin's regional culture, promote the living inheritance and innovative dissemination of Haihe River bridge culture, and facilitate the construction and development of Tianjin's urban cultural IP.

Keywords: Haihe River bridges; Regional culture; Cultural and creative products; Design strategies

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1. Introduction

Tianjin has long been known as the "lower reaches of the nine rivers" and a "vital strategic passage where rivers meet the sea." The Haihe River traverses the city, nurturing its unique bridge culture. From the Jingang Bridge, initially constructed in 1903, to the Yongle Bridge and Chifeng Bridge completed in the 21st century, dozens of bridges along the Haihe River are strung together like pearls, witnessing the historical transformation of Tianjin from a water transport wharf to a modern metropolis. In terms of architectural structure, these bridges encompass various types, including beam bridges, arch bridges, cable-stayed bridges, and suspension bridges. At a cultural level, they integrate Chinese and Western architectural styles, folk traditions, and the spirit of the times, serving as highly distinctive visual symbols of Tianjin's regional culture.

In their study on the cultural and creative products of Wuhan's bridges, Song *et al*. point out that bridge-themed cultural and creative products should delve into cultural connotations, integrate engaging appeal with practical utility, and forge a distinctive urban brand. This perspective provides crucial insights for the cultural and creative design of the Haihe River bridges [1].

With the flourishing development of the cultural and creative industry, cultural and creative products have become an important vehicle for the dissemination of regional culture. Zhong *et al*. employed the Analytic Hierarchy Process (AHP) to quantify consumer needs, thereby providing a scientific design approach for bridge-themed cultural and creative products [2]. In her study on Liuzhou's bridge-themed cultural and creative products, Zhang proposes integrating the extraction of regional elements, morphological transformation, and scenario-based design to develop products that possess both cultural significance and practical utility[3]. Chen *et al*. propose that Haihe-themed cultural and creative products should deeply explore cultural resources, highlight regional characteristics, and balance practicality with aesthetics, which provides a practical reference for bridge cultural and creative design [4]. By combining cultural elements with modern design and practical functions, these products achieve a dual transformation of cultural and economic value. However, current cultural and creative products related to Tianjin's Haihe River bridges largely remain at the level of simple pattern printing and model replication. Several problems exist, such as superficial exploration of cultural connotations, monotonous design forms, and a disconnect from consumer needs, failing to fully leverage the unique charm of bridge culture. As a research direction in the field of visual communication design, the design of regional cultural and creative products requires not only solid design skills but also a profound interpretation of the connotations of cultural symbols to construct scientific and reasonable design strategies. Therefore, taking Haihe River bridge culture as the research object, this paper explores the design paths and methodologies for cultural and creative products. This serves as both a response to the inheritance of regional culture and an in-depth study on the application of visual communication design in the field of cultural creativity.

2. Current status and problems of cultural and creative product design for Haihe River bridges

2.1. Analysis of current status

Currently, cultural and creative products related to Haihe River bridges on the market primarily fall into the following categories:

(1) The first category consists of model products, such as replica models of iconic bridges like the Jiefang Bridge and the Tianjin Eye, which are primarily made of metal or plastic and targeted at the tourism market;

(2) The second category comprises daily necessities, such as T-shirts, mugs, keychains, and postcards printed with bridge patterns, where the design approach typically involves the direct printing of bridge photographs or simple line sketches;

(3) The third category includes cultural souvenirs and collectibles, such as bridge-themed stamps, commemorative coins, and calligraphy and painting works, which are primarily intended for collection purposes.

In terms of sales channels, these cultural and creative products are primarily concentrated in tourist attractions, museums, and bookstores along the Haihe River, while online sales channels remain relatively weak. Regarding consumer groups, the primary consumers are non-local tourists, whereas local residents demonstrate a relatively low willingness to purchase, resulting in a narrow audience coverage for the products. In terms of design entities, the majority of products are mass-produced by tourism souvenir manufacturers, lacking the participation of professional design teams, which leads to uneven design quality.

2.2. Major existing problems

Insufficient excavation of cultural connotations and serious homogenization. The majority of current Haihe River bridge cultural and creative products remain at the level of simple replication of the bridges' appearance, failing to deeply excavate the historical stories, cultural symbolism, and folk elements behind them. From the perspective of Jingu cultural genes, Zhou reveals that Haihe cultural and tourism products generally suffer from the superficial extraction of cultural elements and the inadequate expression of regional characteristics. Furthermore, she notes that bridge-themed cultural and creative products exhibit similar deficiencies [5]. Monotonous design language and lack of innovation. In terms of design form, Haihe River bridge cultural and creative products mostly adopt traditional pattern printing and model replication methods, lacking the application of modern design language. Traditional communication modes and insufficient brand influence. The dissemination of Haihe River bridge cultural and creative products mainly relies on offline sales at tourist attractions; the construction of online communication channels is imperfect, and there is a lack of effective brand promotion strategies.

3. Design strategies for cultural and creative products of Haihe River bridge culture

3.1. Deep excavation and systematic organization of regional cultural symbols

The extraction of cultural symbols serves as the foundation for the design of cultural and creative products, necessitating the deep excavation of the core elements of Haihe River bridge culture, as well as their systematic organization and refinement. Symbol elements should be extracted from the dimension of architectural morphology, encompassing structural forms (e.g., arches, cables, tower columns), morphological features (e.g., curves, straight lines, geometric figures), and color combinations (e.g., red, gray, gold), which are then simplified and abstracted into identifiable visual symbols. Symbol elements should be extracted from the dimension of historical culture, encompassing historical events related to the bridges, anecdotes of famous figures, and the origins of their names, thereby transforming this textual information into visualized design language. Symbol elements should also be extracted from the dimension of folk culture, including folk activities, traditional handicrafts, and specialty foods surrounding the bridges, integrating these elements with bridge symbols.

3.2. Transformation of design language under the fusion and innovation of tradition and modernity

The transformation of design language is a crucial link in converting extracted cultural symbols into design schemes for cultural and creative products; it requires achieving the fusion and innovation of tradition and modernity. In terms of form design, it is necessary to break away from the monotonous forms of traditional model replication and pattern printing by adopting modern design methods such as modular design, interactive design, and biomimetic design. In terms of color design, it is essential to combine the original colors of the bridges with modern aesthetic trends to carry out color reconstruction and innovation. In terms of material selection, emphasis should be placed on the unity of environmental sustainability, practicality, and texture, selecting appropriate materials based on the product's function and positioning.

3.3. Integration of functional scenarios to meet diversified consumer needs

The design of cultural and creative products should emphasize the integration of function and scenario, developing products that are practical and convenient according to consumers' usage scenarios and needs. Based on the Censydiam model, Cao *et al*. point out that cultural and tourism products should align with users' emotional motivations while balancing practicality and experiential value, which provides a basis for the scenario-based design of bridge-themed cultural and creative products [6]. Targeting daily usage scenarios, daily necessities that combine aesthetics with utility should be designed. For instance, bridge forms can be integrated with stationery design to develop products such as bridge-shaped pen holders, bookmarks, and rulers, allowing consumers to perceive the charm of bridge culture in their daily lives. Targeting tourism and sightseeing scenarios, tourism cultural and creative products that are portable and possess strong commemorative value should be designed. Targeting educational and learning scenarios, cultural and creative products with educational significance should be designed.

3.4. Innovation of communication modes: Constructing a diversified promotion system

The communication and promotion of cultural and creative products constitute a crucial link in realizing their cultural and economic value, necessitating the construction of diversified communication modes. Online sales channels should be expanded by utilizing e-commerce platforms and social media platforms for product promotion and sales. For instance, official flagship stores can be opened on e-commerce platforms such as Taobao and JD.com to display and sell cultural and creative products; through formats such as short videos and live streaming, consumer attention can be attracted, thereby enhancing product awareness and influence.

Based on research concerning Haihe culture, Ma points out that developing serialized IP images and enhancing practical functions alongside emotional resonance serve as a crucial pathway to elevating the appeal of Haihe's cultural and creative products [7]. A brand IP system should be constructed to achieve the serialization and large-scale development of products. By designing unified brand logos, packaging, and promotional copy, a recognizable brand image can be formed; serialized cultural and creative products can be developed, categorized by criteria such as the historical period, architectural style, and functional type of the bridges, to form multiple product lines that satisfy the diverse needs of consumers.

Emphasis should be placed on the depth and breadth of cultural communication, integrating cultural and creative products with regional cultural tourism. For example, cultural tourism routes centered on bridges can be designed, with cultural and creative products serving as complementary items to the itinerary, enabling tourists to purchase these products while touring the bridges; collaborating with travel agencies and tourist attractions to conduct promotional activities for cultural and creative products can achieve a win-win situation for both cultural dissemination and the tourism economy.

4. Conclusion

As an important component of Tianjin's regional culture, Haihe River bridge culture possesses unique value and rich connotations, providing abundant materials and inspiration for the design of cultural and creative products. Through a review of the cultural connotations and value dimensions of Haihe River bridge culture, this paper analyzes the problems existing in current product design and constructs design strategies from four dimensions: cultural symbol extraction, design language transformation, functional scenario integration, and communication mode innovation. The study suggests that the design of regional cultural and creative products requires deep excavation of cultural connotations, combining cultural symbols with modern design and practical functions, while emphasizing audience needs and communication promotion, to achieve the dual transformation of cultural and economic value. Looking to the future, with the continuous development of the cultural and creative industry and the continuous progress of science and technology, the design of Haihe River bridge cultural and creative products will face more opportunities and challenges. In terms of design philosophy, greater emphasis should be placed on the innovative transformation and creative development of culture, combining traditional elements with modern trends and technological means to create cultural and creative products with characteristics of the times. In the dimension of experience, further exploration should be made into the application of immersive design and interactive design in cultural and creative products to enhance the emotional connection and sense of participation between products and consumers. In terms of industrial development, cooperation between industry, academia, and research should be strengthened to integrate design resources, cultural resources, and market resources, building a complete cultural and creative industry ecosystem chain and promoting the development of Haihe River bridge cultural and creative products towards scale, branding, and internationalization.

Disclosure statement

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Preliminary Study on Design Theory and Practice of Coking and Refractory Specialties

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Abstract: This paper takes the 73-year technological development of MCC Coking & Refractories Engineering Technology Co., Ltd. (abbreviated as MCC Coking & Refractories) as the research object. As a leading enterprise in the field of coking and refractory engineering technology, MCC Coking & Refractories has undergone a 73-year development journey since its establishment in 1953. The evolution of its design theories and practices reflects the complete trajectory of China's coking industry from technology introduction and independent innovation to global expansion. The paper systematically reviews the historical development and practical achievements of its professional design theories in coking and refractories. The study reveals that MCC Coking & Refractories' design theories have gone through four stages: initial absorption of imported technologies, independent exploration during the growth phase, technological breakthroughs in the maturity phase, and green intelligent transformation during the transition phase. These stages have formed unique technical characteristics centered on furnace structure innovation, based on refractory material research and development, and aimed at energy conservation and emission reduction. Through an in-depth analysis of this historical process, the paper elucidates the internal logic of its design theory evolution, summarizes its implications for the development of the coking industry, and aims to provide references for engineering technology history research and future industry development.

Keywords: MCC coking & refractories; Coking design; Refractory materials; Design theory

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1. Introduction

The coking industry is a pillar industry in metallurgy and chemical engineering, exerting significant influence on national economic development. China, as the world's production and consumption center for coke, accounts for over 68% of global annual coke output. Behind this massive industrial system, the technical accumulation and theoretical innovation of engineering design units play a crucial supporting role. MCC Coking & Refractories, as the sole member of the "national metallurgical construction team" in China's coking, refractory materials, and lime sectors, has seen its 73-year development journey deeply integrated with the modernization process of China's coking industry. Currently, systematic research on this important engineering technology institution remains insufficient in academic circles. Existing literature predominantly focuses on the introduction of specific technological achievements, lacking historical reviews and academic analyses from the perspectives of design theory and professional practice.

2. Incubation and exploration phase: From technology introduction to independent design

2.1. Technical accumulation and technology introduction in the reconstruction of Ansteel

The initial stage of MCC Coking & Refining coincided with the critical phase of laying the foundation for the new China industrial system. The Ansteel Ferrous Metallurgy Design Company, established in 1953, was initially tasked with assisting Soviet experts in the reconstruction and development of Ansteel. During this period, the design team primarily relied on Soviet technical documentation and design specifications, gradually establishing a professional system for coking plant design through the process of assimilation and absorption [1].

Notably, technology introduction during this period was not merely about imitation and replication. Through collaboration with Soviet experts, Chinese technical personnel gradually mastered the fundamental methods of coking process design, including core aspects such as coal yard layout, coke oven configuration selection, and gas purification processes. This "learning by doing" approach to knowledge accumulation laid the groundwork for talent development and technological reserves for subsequent independent innovation.

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2.2. The emergence of type 58 coke oven and its design theory innovation

The year 1958 became a significant turning point in the history of coking design in China. Building on the completion of large-scale design projects such as the Ansteel Chemical Plant, Benxi Iron and Steel Coking Plant, and Wuhan Iron and Steel Coking Plant, MCC Coking & Refractories successfully innovated the design of China's Type 58 coke oven. The birth of this furnace model had dual significance: from a technical perspective, it propelled China's coking technology into the ranks of world leaders; from an industrial perspective, it marked China's capability to independently design large-scale coke ovens.

The design theoretical breakthrough of the Type 58 coke oven is reflected in multiple aspects. In terms of furnace structure, China's technical personnel adapted and improved the Soviet furnace model based on domestic coal quality characteristics and refractory material conditions. Regarding heating systems, they explored combustion control parameters suitable for China's operational conditions. The coke oven was first built and put into operation at Beijing Coking Plant, making significant contributions to celebrating the 10th anniversary of the founding of New China and addressing the gas supply issue for the Great Hall of the People. This case vividly demonstrates that engineering design not only holds technical value but also bears the mission of serving national strategies [3].

2.3. Design practices and theoretical reflections during the "three-line construction" period

In 1964, in response to the CPC Central Committee's call for the' Third Front Construction,' technical personnel from MCC Coking & Refractories headed to the Panxi Plateau to undertake the design of the Pangang Coking Project under extremely challenging conditions.

The Panzhihua Steel Group coke oven was originally designed for a 25-year service life, yet it operated for an impressive 39 years before being decommissioned in 2009, earning the title of "Red Flag Coke Oven." This remarkable longevity stands as the ultimate testament to the effectiveness of its original design principles. Throughout its nearly four-decade operational history, the facility underwent multiple major overhauls and technological upgrades. Its structural design intentionally incorporated ample space for future modifications, showcasing the engineers' visionary engineering expertise and strategic foresight.

The practical experience accumulated during this period, particularly the understanding of coke oven long-term operational patterns, provided valuable feedback data for subsequent design theories.

The hardworking spirit of Northwest China embodied by Jiao Nairen, 'using three stones to support a pot and setting up tents in mountain hollows', has also become a vital component of the cultural traditions within engineering and technical teams.

3. Autonomous construction of technological systems during growth and maturity phases

3.1. Technological leap and design theory enhancement in Baosteel engineering construction

Reform and opening-up ushered in a new phase of development for MCC Coking & Refractories. As a landmark project of China's modern steel industry, the Baosteel project provided MCC Coking & Refractories with a historic opportunity to benchmark against international advanced levels. MCC Coking & Refractories was fully involved in the construction of the Baosteel coking project, a process characterized by distinct "introduction-digestion-transcendence" features.

The first phase of Baosteel's coking project was entirely imported from Japan, while the second phase required performance standards matching or exceeding those of the first phase. The third phase, however, was entirely independently planned and designed by MCC Coking & Refining. When Baosteel's second-phase coking project commenced operations in 1991, its domestic production rate exceeded 90%, with the coke oven section achieving a remarkable 100% localization rate, the highest among all major projects in the second-phase development.

Compared with the first phase, the localized design has cumulatively saved the country over $300 million in foreign exchange. In 2001, the Baosteel Phase III Coking Project won the National Design Gold Award. This achievement marks that China's coking design theory has gained the capability to compete with international advanced levels.

3.2. Formation of large-scale coke oven design theory

In the 1990s, large-scale coke oven design became a global trend in coking technology development. Building on Baosteel's expertise, MCC Coke & Refractories gradually established a systematic theory for large-scale coke oven design. The core components of this theory include: the matching relationship between carbonization chamber height and width, heating uniformity control mechanisms, and thermodynamic stability analysis methods for furnace structures.

The large-scale development of coke ovens is not merely an enlargement in size, but also involves a reevaluation of fundamental issues such as heat transfer laws, combustion control, and structural mechanics. Through theoretical analysis, numerical simulation, and engineering validation, the design team of MCC Coke & Refractories gradually mastered the design principles for large coke ovens. By the late 1990s, China had acquired the capability to independently design 6-meter-class coke ovens, laying the theoretical foundation for subsequent breakthroughs in 7-meter and 7.65-meter-class coke ovens.

3.3. Institutional reform and theoretical inheritance in design

In 1998, with the reform of national institutions, MCC Coking and Refractories was placed under the direct administration of China Metallurgical Construction Group. In August 1999, it was renamed China Metallurgical Construction Group Anshan Coking and Refractories Materials Design and Research Institute. In October 2004, the company's first chairman, Mr. Yu Zhendong, restructured the company into MCC Coking and Refractories Engineering Technology Co., Ltd., with Ms. Tan Ping as its first general manager. The institutional reforms during this period had a profound impact on the inheritance and development of design theories.

After restructuring, MCC Coking & Refining has evolved from a standalone design institute into an international engineering company with EPC capabilities. This transformation necessitates expanding design theory beyond technical specifications to encompass the entire lifecycle dimensions of procurement, construction, and operation. Designers must not only evaluate technical feasibility but also coordinate multiple factors including cost control, schedule management, and risk mitigation. The transition to a "design-construction + operational services" model has opened new avenues for enriching and advancing design theory.

4. Breakthrough and leadership phase: Independent innovation and international leadership

4.1. Theoretical breakthroughs in National 863 program's clean and efficient coking technology

Entering the 21st century, facing mounting environmental pressures and intense international competition, MCC Coking & Refining launched a new round of technological breakthroughs. In 2008, MCC Coking & Refining took the lead in collaborating with Beijing University of Science and Technology and Angang Steel to apply for a National 863 Program key project under the theme "Development of Ultra-Large Capacity Top Charging Coke Oven Technology and Equipment" with the Ministry of Science and Technology. The project was officially approved in December 2009, marking the beginning of a technology innovation model featuring deep integration of industry, academia, and research.

The hallmark of innovation during this phase was a significant enhancement in theoretical depth. The research team not only addressed engineering design challenges but also delved into the fundamental mechanisms of coke oven heating technology and clean production technology. By establishing a NOx generation model for coke ovens, developing air cascade supply technology, and inventing an enclosed exhaust gas recirculation hole structure, they achieved source control of pollutant formation.

4.2. Systematization of large-scale coke oven design theory

The successful implementation of the 863 Program has propelled the systematic development of large-scale coke oven design theory at MCC Coking & Refining. The core components of this theoretical framework include as follows:

(1) Furnace type innovation theory: Building upon the 7-meter top-loading coke oven and 6.25-meter ramming coke oven, MCC Coking & Refining rapidly developed the 7.65-meter top-loading coke oven and 6.78-meter ramming coke oven. These furnace designs represent not mere scale-up but systematic optimizations based on in-depth understanding of heat transfer principles, combustion control, and structural mechanics;

(2) Combustion control theory: By implementing multi-node coupled regulation of heating technology, the longitudinal temperature difference of coke cake is maintained within $\leq 50°C$, while the temperature coefficient of the coke oven's crosswise arrangement reaches ≥ 0.95. This achievement stems from precise simulation of airflow distribution within the combustion chamber and in-depth research on the regulation mechanism;

(3) Longevity design theory: Constructing a full-scale structural thermal-structural stability decomposition model for combustion chambers, and developing an integral mosaic large-biting coke oven combustion chamber structure, which increases the ultimate side load of furnace walls by over 10% and extends coke oven service life by more than 15 years.

In 2017, the project "Development and Application of Technology and Equipment for Ultra-large Capacity Top-loading Coke Ovens" won the only Special Prize in Metallurgical Science and Technology. In 2018, the project "Development and Application of Clean and Efficient Coking Technology and Equipment," with MCC Coking & Refractories as the first completing unit, won the National Science and Technology Progress First Prize, achieving a breakthrough in winning the National Science and Technology Progress First Prize for the first time for China Minmetals, MCC Group, and China Metallurgical Construction Industry.

4.3. Deep integration of dry quenching technology with energy conservation and emission reduction theory

Dry quenching technology serves as a critical component for achieving energy conservation and carbon reduction in coking processes. The large-scale serialized dry quenching technology independently developed by MCC Coking & Refining won the Second Prize of National Science and Technology Progress Award in 2009. The core theoretical innovation of this technology lies in the integrated design of coke cooling processes with waste heat recovery systems, enabling efficient cascaded energy utilization.

In theoretical research, MCC Coking & Refining has conducted in-depth studies on the thermodynamic principles of dry quenching coke technology, flow characteristics of circulating gases, and thermodynamic matching of boiler systems. By optimizing gas distribution devices and waste heat boiler parameters, the thermal recovery efficiency of dry quenching coke systems has been significantly enhanced. These project achievements have been applied to numerous domestic and international engineering projects, providing critical technical support for energy conservation and emission reduction in the coking industry.

4.4. Innovation and integration of flue gas treatment theories

Coke oven flue gas treatment remains a key challenge in coking environmental protection technologies. MCC Coke & Refining has achieved significant breakthroughs in flue gas desulfurization and denitrification, developing an activated carbon-based multi-pollutant synergistic control technology. The theoretical innovation of this technology lies in via studying the reaction mechanisms of activated carbon's high-efficiency denitrification and multi-pollutant synergistic control, researchers developed an adsorption reactor featuring zoned desulfurization-denitrification reactions and mobile layered activated carbon control. This approach has achieved industrial application results with denitrification efficiency exceeding 80%.

5. Transition and innovation phase: Green low-carbon and intelligent manufacturing

5.1. Theoretical transformation of design under dual carbon goals

The introduction of the "dual carbon" goals has posed new challenges and requirements for the coking industry. During this period, the design theories of MCC Coking & Refractories exhibited distinct characteristics of green transformation. From the perspective of integrated pollution and carbon reduction management, the R&D team systematically integrated multiple technologies including low-NOx combustion, efficient heat transfer, and waste heat recovery, establishing a theoretical framework for comprehensive optimization of coking processes.

In 2024, the "Development and Application of Synergistic Pollution Reduction and Carbon Mitigation Coking Technology" project led by MCC Coking & Refining achieved significant progress. The innovation lies in integrating source emission reduction, process control, and end-of-pipe treatment through unified design to achieve multi-objective optimization. The 65 coking projects implementing this technology can reduce NOx emissions by 40,000 tons annually, save 850 million yuan in gas costs, and cut CO2 emissions by 13.18 million tons.

5.2. Theoretical breakthrough in heat recovery technology for coke ovens

Heat recovery coke ovens represent another technical approach distinct from traditional chemical recovery coke ovens. MCC Coking & Refining has also achieved significant breakthroughs in this field. China's earliest heat recovery coke oven was designed by MCC Coking & Refining and put into operation in Houma, Shanxi in 2002. Over the following two decades, heat recovery coke ovens underwent four generations of design evolution and refinement.

In 2023, the fourth-generation JNHR4.2 clean horizontal tamping heat recovery coke oven independently developed by MCC Coking & Refractories was successfully commissioned at Henan Angang Zhoukou Iron & Steel Co., Ltd. The theoretical innovations of this fourth-generation heat recovery coke oven are reflected in multiple aspects: a full-process negative pressure operation design to eliminate unorganized emissions; optimized integration of furnace structure with advanced refractory materials; and synergistic improvements in coke oven mechanical automation coupled with cold-end control solutions.

The new-generation heat recovery coke oven has achieved an advanced level of controlling dry coal consumption at approximately 1.34 tons per ton of coke while generating over 1,000 kWh of electricity per ton of coke. Compared to traditional chemical recovery coke ovens, this technology significantly reduces carbon dioxide emissions under identical coke and power production conditions, making it a widely recognized environmentally friendly coke production process.

5.3. Digital evolution of intelligent manufacturing and design theory

In the field of coke oven heating control, intelligent heating control systems based on infrared temperature measurement, wireless sensor networks, and machine learning algorithms have been widely adopted. The system employs vertical fire channel automatic temperature measurement technology and dual-level regulation technology for rich gas main pipelines and branch pipelines, achieving a "main pipeline coarse adjustment + branch pipeline fine adjustment" two-tier control architecture. In a 5.5-meter ramming coke oven application, this system significantly improved furnace temperature stability and uniformity while reducing manual temperature measurement labor intensity. In the realm of coke oven mechanical automation, the fully automated ramming coke oven vehicle system enables one-touch full automation operations for coke pushers, coke interceptors, coal chargers, coke quenchers, and flue gas guide vehicles. The accompanying coke oven operation management system utilizes multi-dimensional dashboards and scenario analysis functions to achieve digital monitoring and management throughout the entire equipment operation process.

6. The intrinsic logic and historical implications of design theory evolution

6.1. Stage characteristics of technological paradigm evolution

Looking back at the 73-year development journey of MCC Coking & Refractories, the evolution of its coking and refractory professional design theories exhibits distinct phased characteristics as follows:

(1) The first stage was characterized by technology absorption and independent exploration, achieving a leap from technological dependence to autonomous design. The birth of the 58-type coke oven marked the initial formation of China's coking design technical paradigm;

(2) The second stage featured system construction and capability enhancement, with Baosteel projects enabling benchmarking and alignment with international advanced levels. Large-scale coke oven design theories gradually took shape, while refractory material design theories developed synergistically;

(3) The third stage was defined by independent innovation and international leadership, leveraging major scientific initiatives like the 863 Program to achieve systematic breakthroughs in clean and efficient coking technologies, earning the National Science and Technology Progress First Prize;

(4) The fourth stage was characterized by green transformation and intelligent upgrading, restructuring design theory systems toward dual-carbon goals and deeply integrating smart manufacturing technologies throughout coking design processes.

6.2. Core elements of design theory innovation

From the 58-type coke oven to the 7.65-meter top-loading coke oven, and from traditional ramming coke ovens to fourth-generation heat recovery coke ovens, furnace design has consistently served as the core vehicle for technological innovation. Each generation of furnace development has been accompanied by profound advancements in understanding heat transfer principles, combustion control, and structural mechanics. The evolution of coke oven technology has been deeply integrated with progress in refractory materials. The application of new materials such as high-conductivity silicon bricks, silica-based insulating bricks, and nanoscale thermal insulation coatings has provided the material foundation for performance enhancement. From reducing coking heat consumption to controlling NOx source generation, from waste heat recovery in dry quenching coke systems to coordinated multi-pollutant control using activated carbon, energy conservation and emission reduction objectives have consistently guided the direction of technological innovation.

6.3. Implications for the study of engineering technology history

The 73-year development journey of MCC Jiaonai has provided abundant case resources for the study of engineering technology history. Several universally significant insights can be distilled from this case: the cumulative and leapfrog nature of engineering technology knowledge. Advances in engineering technology manifest not only as incremental improvements in daily operations but also as breakthroughs at critical junctures. The success of the 863 Program demonstrates that organized industry-academia-research collaboration can effectively facilitate technological leaps; the interdependent relationship between design theory and engineering practice. Design theory originates from engineering practice and, in turn, guides it. Leveraging extensive empirical data accumulated from numerous engineering projects, MCC Jiaonai continuously refines its design theories, while these theoretical achievements are validated and refined in new projects. MCC Jiaonai's technological innovation is not an isolated corporate endeavor but is achieved through collaborative interactions with universities, research institutes, equipment manufacturers, and project owners. The formation and evolution of such a technological innovation ecosystem represent a crucial dimension for understanding the development of China's engineering technology.

7. Conclusion

The 73-year development journey of MCC Coking & Refractories is a microcosm of the modernization process of China's coking industry. MCC Coking & Refractories has always stood at the forefront of China's coking engineering technology development, leading industry technological progress through independent innovation. The design theory of MCC Coking & Refractories has undergone an evolutionary process from technology introduction and independent exploration to system construction and international leadership, forming a unique technical paradigm centered on furnace structure innovation, based on refractory material research and development, and guided by energy conservation and emission reduction goals. Facing the constraints of dual carbon targets, the wave of intelligent manufacturing, and the challenges of international competition, design theory innovation remains a long and arduous task. As long as independent innovation are adhered to, serve the national interests, and deepen the integration of industry, academia, and research, China's coking engineering technology will surely write new glorious chapters. MCC Coking & Refractories will undoubtedly contribute more wisdom and strength to the high-quality development of China's coking industry on the new journey of building a world-class enterprise.

Disclosure statement

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Buckling-Restrained Brace Arrangement in Regular RC Frames Based on Pushover Analysis

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Abstract: To improve the seismic performance of existing reinforced concrete (RC) frame structures with insufficient lateral resistance, this study investigates the influence of different buckling-restrained brace (BRB) arrangements on a typical five-story, 4 × 4 bay regular RC frame. Based on the original benchmark model, four retrofit schemes were developed by considering two brace forms, namely single diagonal and chevron braces, and two planar locations, namely mid-bay and end-bay arrangements. Five numerical models, including one unstrengthened structure and four BRB-retrofitted structures, were established in SAP2000 V26 for nonlinear static pushover analysis. Geometric and material nonlinearities were incorporated to simulate the inelastic behavior of beams, columns, and BRBs. Pushover analyses were conducted under uniform and inverted triangular lateral load distributions to evaluate the global seismic performance of the structure. The results indicate that all retrofit schemes significantly enhanced the base shear capacity and deformation capacity of the original frame. Under the uniform load pattern, the maximum base shear capacities of the four strengthened models increased by 295%, 148%, 145%, and 148%, respectively, relative to the original structure. Under the inverted triangular load pattern, the corresponding increases were 232%, 128%, 124%, and 127%, respectively. Among the investigated configurations, the mid-bay single diagonal brace arrangement achieved the most effective improvement in lateral resistance and was identified as the optimal retrofit scheme. These findings demonstrate that mid-bay BRB placement is more effective than end-bay placement for enhancing the seismic performance of regular RC frame structures.

Keywords: Reinforced concrete frame; Buckling-restrained brace; Seismic retrofit; Brace arrangement; Pushover analysis; Nonlinear static analysis

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1. Introduction

In recent years, earthquake activity has been frequent, and near-fault earthquakes are more destructive to buildings compared to far-field earthquakes. By studying the Parkfield and Pacoima earthquakes, Bolt first used the term "near-fault" [1]. Liao studied the seismic response of reinforced concrete frame structures under near-fault earthquake motions in Jiji and compared it with the response under far-field earthquake motions [2].

Mazzara and Vulkano examined the effectiveness of code provisions on the nonlinear dynamic response of reinforced concrete frame structures under near-fault earthquake motions [3]. Several past earthquakes, such as the 2001 Bhuj earthquake, the 2005 Kashmir earthquake, the 2006 Sikkim earthquake, the 2015 Nepal earthquake, and the 2023 Turkey earthquake, all resulted in partial or total collapse of RC buildings designed as MRF structures [4]. Therefore, BRB has been applied to the seismic reinforcement of steel frame structures and reinforced concrete (RC) frame structures [5–8].

2. Initial structural parameters

The building structure is a reinforced concrete frame structure, with a total of 5 stories and a total height of 16.5 m. Each story has a height of 3.3 m, and the plan dimensions are 16 m × 16 m (4 × 4 bays, with each bay 4 m). The seismic fortification intensity of the site is grade 8, and it is classified as a Class II construction site. Under rare earthquakes, α_{max} = 0.9, and under frequent earthquakes, α_{max} = 0.16. The site characteristic period Tg = 0.35 s. For the specific dimensions of the structural layout (**Figure 1**).

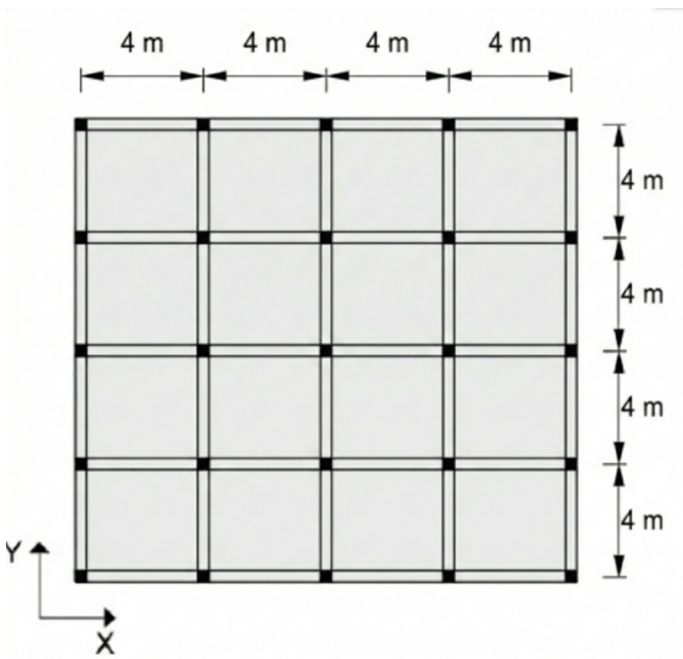

Figure 1. Structural plan layout.

3. Reinforcement configuration and model development

This study investigates the seismic retrofit of a typical five-story, four-by-four bay RC frame structure with inadequate seismic capacity. To improve the global seismic performance of the structure, buckling-restrained braces (BRBs) were installed along one side of the perimeter frame [9,10]. Based on the original structural model, four BRB arrangement schemes were developed by considering both the bracing form and the planar location of the braces. The bracing forms include a single diagonal brace and a chevron brace, while the planar locations include the mid-bay and end-bay positions of the perimeter frame. Accordingly, the following four strengthening schemes were designed (**Figure 2**).

(1) Single diagonal brace, mid-bay arrangement;

(2) Single diagonal brace, end-bay arrangement;

(3) Chevron brace, mid-bay arrangement;

(4) Chevron brace, end-bay arrangement.

In total, five structural models were established and analyzed in this study: one unstrengthened original benchmark model and four strengthened models with different BRB configurations.

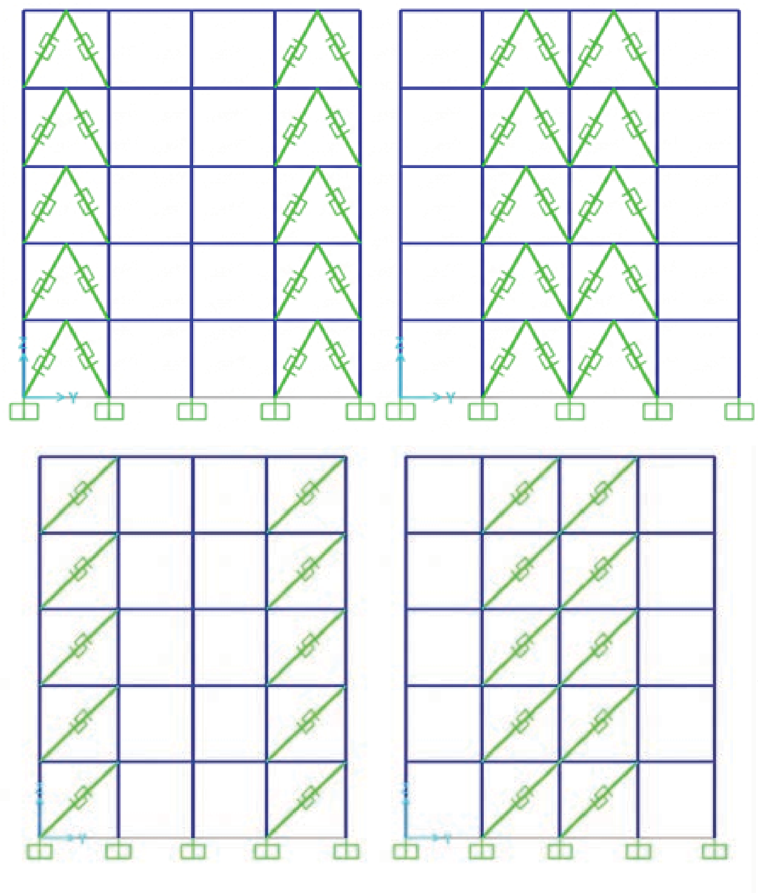

Figure 2. BRB reinforcement layout diagram

3.1. Strengthening scheme design and model establishment

This study focuses on a typical five-story, 4 × 4 bay reinforced concrete frame structure with insufficient seismic performance. To effectively enhance the overall seismic behavior of the structure, a strengthening strategy was proposed by adding buckling-restrained braces (BRBs) to one side of the exterior frame [9,10]. Based on the unstrengthened benchmark model, four BRB configuration schemes were designed by considering the bracing type and its planar location. The two bracing types were a single diagonal brace and a chevron brace, and the two planar locations were the mid-bay and end-bay positions. Therefore, the following four retrofit schemes were developed:

(1) Single diagonal brace at the mid-bay position;

(2) Single diagonal brace at the end-bay position;

(3) Chevron brace at the mid-bay position;

(4) Chevron brace at the end-bay position.

Accordingly, five numerical models were established for comparative analysis, including one original unstrengthened model and four strengthened models with different BRB layouts.

3.2. Modeling

To evaluate the seismic performance of the structure, three-dimensional finite element models were developed using SAP2000 V26 [11](**Figure 3**). Both geometric nonlinearity, including P-Delta effects and large-displacement effects, and material nonlinearity were taken into account [11–13]. For the nonlinear simulation of beams and columns, the fiber plastic hinge approach (Fiber P-M2-M3 hinges) was adopted. The structural members were modeled as frame elements, with nonlinear fiber sections assigned at critical locations to capture local inelastic behavior [11–13].

For the material constitutive laws, concrete behavior was represented using the Mander confined concrete model to account for the enhanced strength and ductility of core concrete under transverse reinforcement confinement [14]. The peak compressive strain was set to 0.002, and the elastic modulus was taken as 23,500 MPa [14]. Both longitudinal and transverse reinforcement bars were modeled using a nonlinear steel constitutive model with isotropic hardening. The elastic modulus was set to 200 GPa, and the post-yield hardening ratio was 0.005 [11,12].

For the BRB components, equivalent simulation was conducted using the nonlinear link element (Plastic Wen) in SAP2000 [13]. The BRB core was idealized with a rectangular cross-section of 150 × 20 mm², and its axial hysteretic properties were assigned to reflect the stable energy dissipation capacity of the brace under cyclic tension and compression loading [8,10].

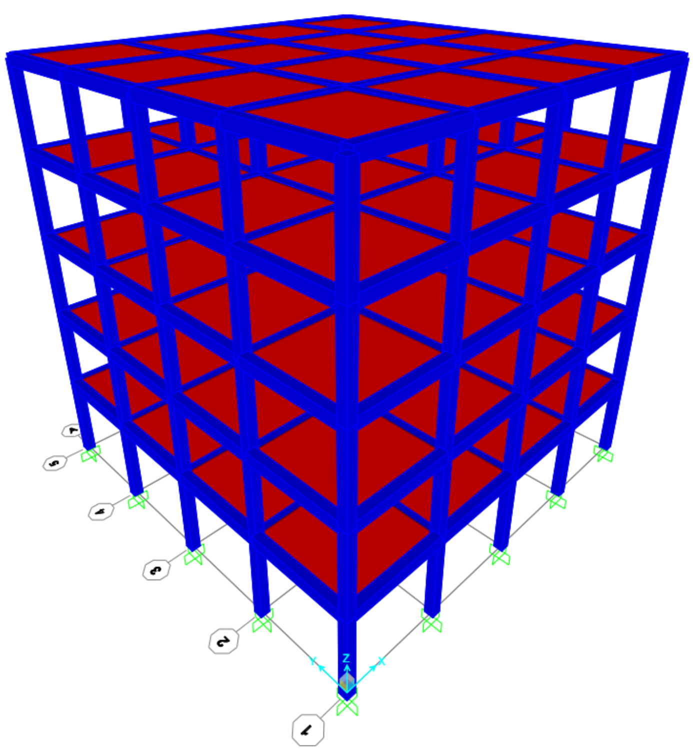

Figure 3. Three-dimensional structure.

4. Static elastic-plastic analysis (pushover analysis)

4.1. Analysis principles and parameter settings

Static elastic-plastic analysis, commonly referred to as pushover analysis, is an important nonlinear procedure for evaluating the seismic performance of structures and is widely used in both new building design and the assessment of existing structures [15–18]. The method establishes the nonlinear relationship between roof displacement and base shear, i.e., the capacity curve, thereby enabling systematic evaluation of the structural strength, stiffness degradation, and ductility characteristics [15–18].

In the analysis, lateral forces are incrementally applied to the structural model until the target displacement is reached. Owing to the symmetry and regularity of the five-story, 4 × 4 bay reinforced concrete (RC) frame structure considered in this study, seismic action was simulated only in the X direction. To comprehensively evaluate the lateral load-resisting performance of the structure, two horizontal load patterns were adopted in the pushover analysis: the uniform distribution pattern and the inverted triangular distribution pattern [15–18].

4.2. Comparison of load-bearing characteristics and configuration schemes

The base shear-roof displacement curves in the X direction for each model are shown in **Figures 4** and **5**. The results indicate that both the original structural model and the four BRB-retrofitted models were able to smoothly reach the prescribed target displacement of 0.33 m, which preliminarily confirms the effectiveness of buckling-restrained braces in improving the seismic performance of existing RC frame structures [15–20].

Based on the quantitative analysis of the pushover curves, the improvement in base shear capacity under the uniform load pattern is significant. Compared with the original structure, the maximum base shear capacities of the models with single diagonal braces at the mid-bay position, chevron braces at the end-bay position, chevron braces at the mid-bay position, and single diagonal braces at the end-bay position increased by 295%, 148%, 145%, and 148%, respectively [15–20].

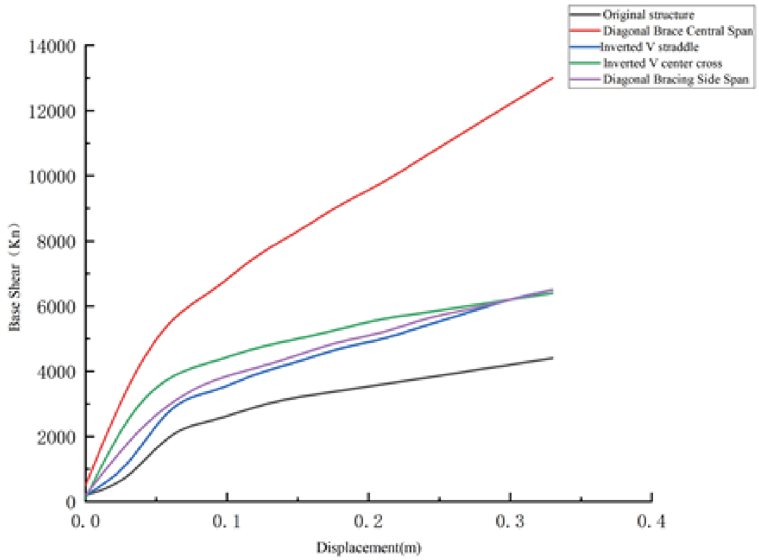

Figure 4. Push-over capacity curves of each model under uniform load

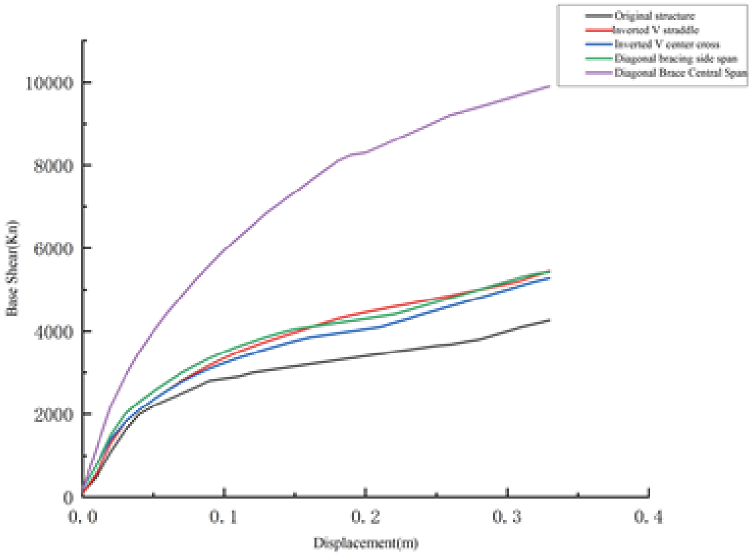

Figure 5. Overturning capacity curves of each model under inverted triangle load

Under the inverted triangular load pattern: the bearing capacity increase of the above four configuration schemes is 232%, 128%, 124%, and 127%, respectively.

The comparison results indicate that the BRB scheme with diagonal braces arranged at the central span most significantly enhances the base shear capacity of the original structure, making it the optimal reinforcement configuration within the scope of this study. In addition, the study found that placing braces at the central span can significantly improve the overall seismic performance of the structure.

5. Conclusion

Results have shown the effects of different horizontal load distribution patterns on structural response. The comparison indicates that the shear capacity of all models under uniform load is higher than that under the inverted triangular load pattern. Since the inverted triangular distribution simulates a more severe seismic effect (producing larger moments at the upper parts of the structure), it thus appears as a more critical load distribution pattern in seismic performance evaluation.

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Disclosure statement

The author declares no conflict of interest.

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Research and Application of Construction Technology for Adjacent Structures Foundation Pits

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Abstract: The construction technology for the excavation of the foundation pit of adjacent structures first involves conducting an engineering investigation to determine the key and difficult points of the project as well as potential safety hazards. On the premise of ensuring the elimination or reduction of safety risks, targeted measures are taken to eliminate or reduce the safety hazards, and necessary detection methods are employed to digitally and intuitively represent the safety of the project. Based on the anticipated working conditions as determined through on-site investigation and the actual data reflected by the investigation, effective engineering measures are adopted to ensure the safety of the project construction.

Keywords: Adjacent structures; Foundation pit; Excavation plan; Pile extraction and grouting

Online publication: May 12, 2026

1. Introduction

With the acceleration of the urban capacity renewal process, the development and utilization of urban above-ground and underground spaces have been increasing, and the construction technology of adjacent structures has become an important research topic in the field of construction engineering. This project focuses on the influence mechanism of foundation pit excavation on important adjacent structures, as well as the adaptability of excavation technology under different geological conditions. After studying a series of key factors affecting the safety of foundation pit excavation, and based on this, targeted technical improvement measures were proposed, providing useful references for similar projects. This construction technology research has important theoretical and practical significance for promoting the development of foundation pit excavation technology for adjacent structures, ensuring project safety, improving construction efficiency, and promoting the sustainable development of the civil engineering industry [1].

2. Project overview

This project is the first section of the post-disaster reconstruction of the Jialu River (from Chemical Road to Chenzhuang Bridge) in Zhengzhou. The project is adjacent to the Chemical Road Bridge and the Jialu River, and belongs to the post-disaster reconstruction project. The Chemical Road Bridge is a major transportation road in Zhengzhou, and both sides are filled with water, electricity, gas, heating, etc. pipelines. Due to the severe damage to the slopes on both sides of the Chemical Road Bridge caused by the 7.20 flood, many pipelines were destroyed, and it was necessary to re-arrange the comprehensive pipelines.

The main purpose of this river-crossing pipeline design is to reserve space for the overpass of damaged water-supply, gas, etc. pipelines during the 2021 July 20 flood damage. The overpass pipeline adopts the pipe jacking construction method, and the receiving well and working well are supported by steel sheet piles for excavation. Each single pipe is 115m long, and three DN1000 reinforced concrete pipes are arranged in parallel, with a total length of 345m. The top elevation of the overpass pipe is 99, the bottom elevation of the pipe in the pipe is 97.9, and the elevation of the left and right banks of the construction site is approximately 111.65, the elevation of the overpass section is approximately 101.7, and the maximum burial depth is 12.65m.

3. On-site investigation and scheme design

According to the design drawings and the construction goals of this project, this river-crossing pipeline project mainly focuses on the repair of cross-river pipelines damaged in the 2021 July 20 flood in Zhengzhou. The river-crossing pipeline project of this project is adjacent to the existing bridge, Chemical Road Bridge, and the cross-river section of the pipeline project is 3*115m DN1200 construction. The inspection well of the pipeline is 12.65m deep, and the concrete inspection well with specifications of 9.8*9.4 (m) is cast in place. The well position is adjacent to the north side of the Chemical Road Bridge. The specific engineering environment is shown in **Figure 1**.

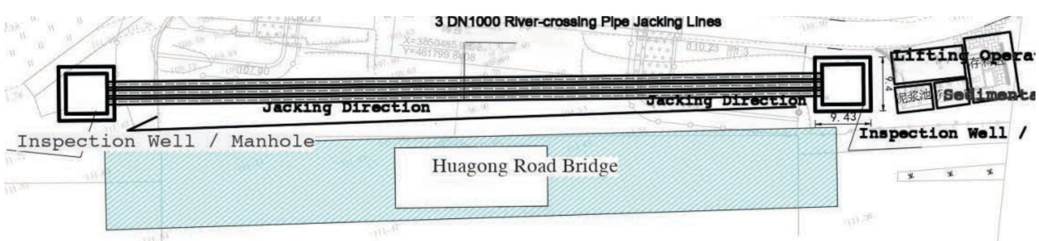

Figure 1. Engineering environment floor plan.

The original design was for static pressure steel sheet pile support + pipeline burial + inspection well sinking construction. Considering the on-site investigation results, the current condition of the project is severely damaged by water erosion. The static pressure steel sheet pile support for the river-crossing pipeline and the direct burial of the pipeline construction take a long time, require a large investment in steel sheet piles, and affect the original river flow surface. Moreover, the pipeline construction in the riverbed has strict requirements for dewatering, and the pipeline construction will affect the 2022 annual river flood control target of the ongoing river. Additionally, the two inspection wells are located in the high backfill areas of the bridge abutments. The original design adopted the cast-in-place sinking well construction scheme. However, due to the long construction period of the cast-in-place sinking well and the use of lowering the surrounding soil friction resistance to achieve sinking, the sinking construction process will disturb the surrounding soil. In the bridge abutment backfill area, the sinking construction of the steel sheet pile causes soil disturbance, and the stability of the bridge pile foundation or the bearing platform and the concrete foundation is prone to negative friction, resulting in a high risk of bridge safe operation and traffic [2].

Considering the urgency of the post-disaster reconstruction construction tasks, the importance of river flood control, and the overall construction interrelation, the project department proposed reasonable suggestions to the design unit. After a joint investigation and detailed discussion among the five responsible entities, a construction scheme consisting of pipe jacking with steel sheet pile-supported foundations and cast-in-place inspection wells was finalized. Based on this, the project department optimized and determined the construction plan for the pipeline project, which adopts pipe jacking engineering to accelerate the construction period, does not affect the river flow surface, and ensures the river flood control target. The inspection wells adopt two layers of support → long-arm excavator excavation → micro-dewatering + bottom sealing → main construction → grouting → full-scale settlement observation. The special construction plan was submitted for review and approval, and was strictly implemented according to the relevant plans to ensure the overall safety and orderly progress of the project.

4. Construction procedures

Figure 2 shows the construction procedures.

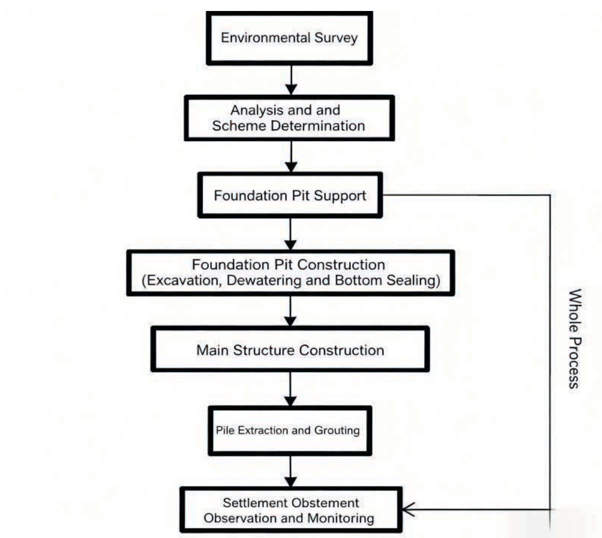

Figure 2. Construction process flow chart.

5. Foundation support for inspection wells

Due to the severe damage caused by the 7.20 flood disaster, the area of the bridge abutment's backfill soil was severely damaged, and the inspection wells at both ends of the bridge head were very close to the bridge abutment, with a vertical distance of only 4.3 meters. To prevent the construction of the inspection well foundation from affecting the stability of the bridge abutment's backfill area and the traffic safety of the chemical road bridge, the project department, in accordance with the design drawings and expert suggestions, determined a construction plan for the foundation support of the inspection wells, which included setting up two layers of supports. The first layer of support was set between the inspection well and the bridge abutment, blocking and weakening the influence on the backfill area of the bridge abutment. It also played a supporting and stabilizing role for the soil of the bridge abutment's backfill area. It could prevent the soil from sliding along the support surface due to the removal of the second layer of support when the river channel was eroded. The second layer of support was set around the inspection well to provide excavation protection. The other two layers of support were arranged in a stepped pattern to avoid the occurrence of cracks at the end of the support steel sheet piles and their development into large cracks.

After the foundation support of the pit was completed, the first layer of support was set between the bridge abutment and the inspection well. The two layers of support were arranged in a stepped pattern. The first layer of support had a deeper burial depth and the top of the second layer of support was 2–3 meters above the ground. The specific layout is shown in **Figures 3** and **4**.

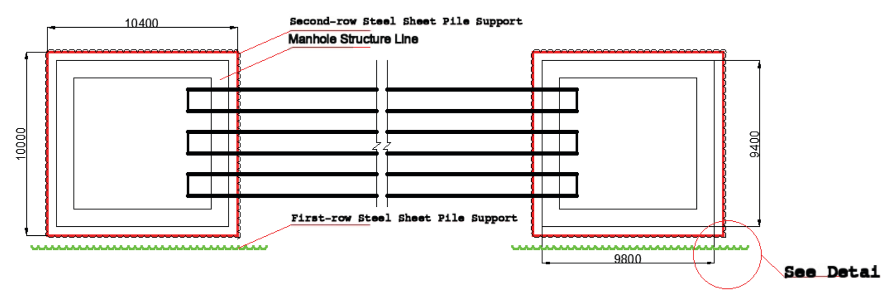

Figure 3. Plan view of the inspection well support at the bridge abutment of the bridge.

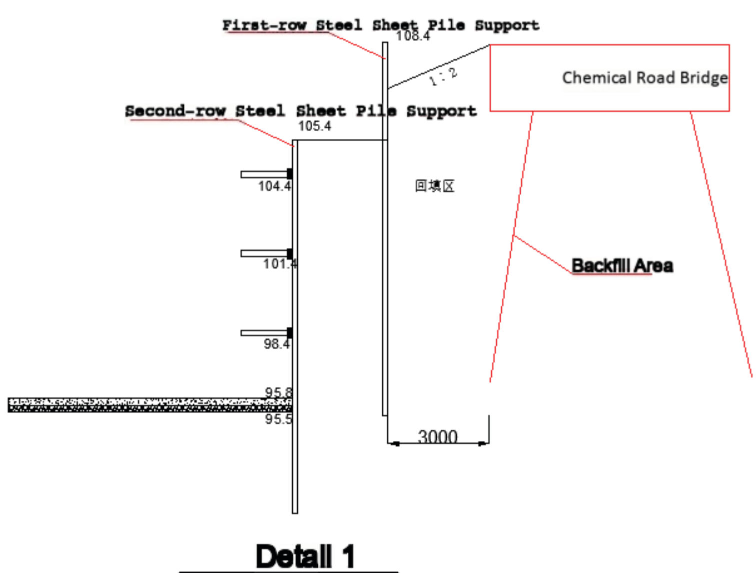

Figure 4. Sectional view of inspection well at the abutment of the bridge.

The retaining structure of the inspection well, which is the second supporting structure, uses 15-meter-long Larson steel plate IV-type steel sheet piles. The top elevation of the foundation pit is 107.45 meters. Before construction, the on-site soil and earthwork were excavated downward by 2 meters to level the site, reducing the site elevation to 105.45 meters. The perimeter of the foundation was excavated with two-step inclined slopes at 2 meters each, with the bottom elevation of the pit being 96.00 meters. Three sets of 45b steel beams were set at the top of the pit, with the first set of support located 1 meter below the top of the steel sheet piles, the second set 3 meters away from the first set, and the third set 4 meters away from the second set. The tie beams all use double-sliced 45b steel beams, and the corner braces are also double-sliced 45b steel beams, forming a 45° angle with the tie beams (**Figures 5** and **6**).

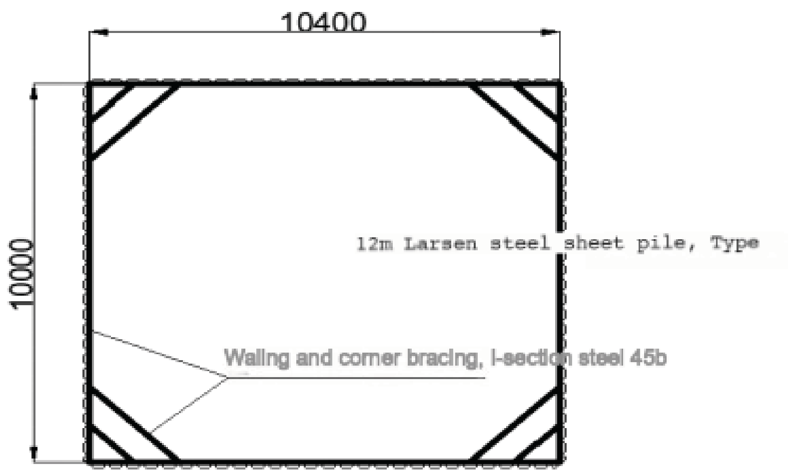

Figure 5. Plan view of inspection well support structure.

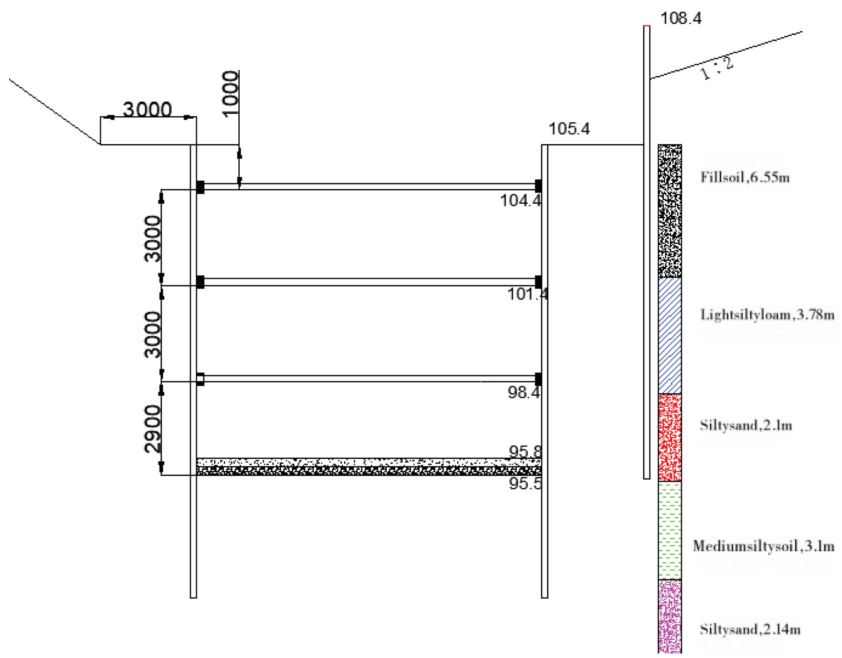

Figure 6. Geological section diagram for inspection and support at abutment area.

5.1. Layout of settlement observation points

After the completion of the two rows of foundation pit supports, settlement monitoring points were installed. Settlement observation points for the bridge were arranged at the pedestrian railing on the north side of the bridge. Observation points for the original soil of the foundation pit were established at locations with exposed large tree roots in the undisturbed green area and at the existing brick-lined inspection well wall within the exposed soil area of the foundation pit. In addition, settlement observation points were arranged for temporary and permanent support quality inspection to monitor soil settlement variations throughout the construction process.

6. Foundation pit construction

6.1. Construction of inspection well dewatering

Based on the depth of the working well in this project and the groundwater level elevation (below the ground surface by 4.42–8.51 meters), the main water affecting the foundation pit is groundwater. Dewatering started 7 days before the foundation pit excavation. The drainage in the foundation pit uses a combination of light well-point dewatering and open drainage. Before the foundation pit is excavated to the design elevation, the water level in the foundation pit should be lowered to no less than 50 cm below the bottom of the pit to reduce the moisture content of the foundation pit soil, facilitate the excavation of the foundation pit and subsequent construction operations, and ensure the stability of the soil in the pit. At the same time, monitoring should be done to minimize the settlement of the surface and the surrounding environment caused by dewatering.

6.1.1. Calculation of foundation pit water inflow

Based on the design data in the drawings and the groundwater level conditions in the geological investigation report, the water inflow will be calculated using a groundwater well. The calculation formula is as follows:

$$Q = \pi k \frac{(2H_0 - s_o)s_o}{\ln\left(1 + \frac{R}{r_0}\right)}$$

In the formula, Q: the water inflow volume of the foundation pit (m^3/d);

k: the permeability coefficient (m/d), according to the survey report, based on relevant standards and regional construction experience, the permeability coefficient of the sandy silt layer ③ is 1 m/d;

H 0: the thickness of the aquifer (m), take 20 m;

s 0: the water level drop of the foundation pit (m), take 2.3 m;

R: the precipitation influence radius (m); R = 2 s 0; $\sqrt{K^H}$ =20.6m

r_0: the equivalent radius of the foundation pit (m); The ratio can be expressed as r_0 = $\sqrt{A/\pi}$ =6.55, where A is the area enclosed by the connection line of the precipitation well group.

It is calculated that the water inflow volume Q = 191.5 m^3/d;

The water volume of a single well q = $120\pi rl\sqrt[3]{k}$;

Q: the allowable water discharge capacity of a single well, m^3/d;

K: the permeability coefficient (m/d); take 1 m/d

I: the working length of the filter pipe; take 1.5 m

R: the radius of the filter device's outer edge (m); take 0.25 m

$q = 120 * 3.14 * 0.25 * 1.5 * \sqrt[3]{1} = 141.3\ m^3/d$

The calculation formula for the number of precipitation wells

$N = 1.2Q/q = 1.2 * 191 / 141.3 = 2$ units. Considering that the inspection well is close to the river and the surrounding area is a sculpture park green irrigation area, the water volume may temporarily increase, so 4 well points are used for precipitation.

6.1.2. Design of rainwater wells

Based on the analysis of various factors such as geological and hydrogeological data from exploration, the surrounding conditions of on-site construction, the situation of underground pipelines, and the influence of existing structures, it is determined that the groundwater in the area where this project is located is approximately 1.3 meters above the base plate. Before the earthwork excavation, a scheme of arranging ring-type light well points inside the foundation pit and one observation well outside the pit is proposed. The layout of the well points is shown in **Figure 7**.

The water extracted from the well points is collected through a main pipeline that connects all the well points and discharged to the sedimentation tank. The water in the sedimentation tank is tested for quality and can be used for construction after passing the test. The observation wells are used to promptly understand the groundwater situation and the implementation effect of the well point system. Based on the observed groundwater level, the pump type and pump capacity are adjusted in a timely manner to ensure a good well point effect. The water level observation wells are sealed after the foundation pit construction is completed.

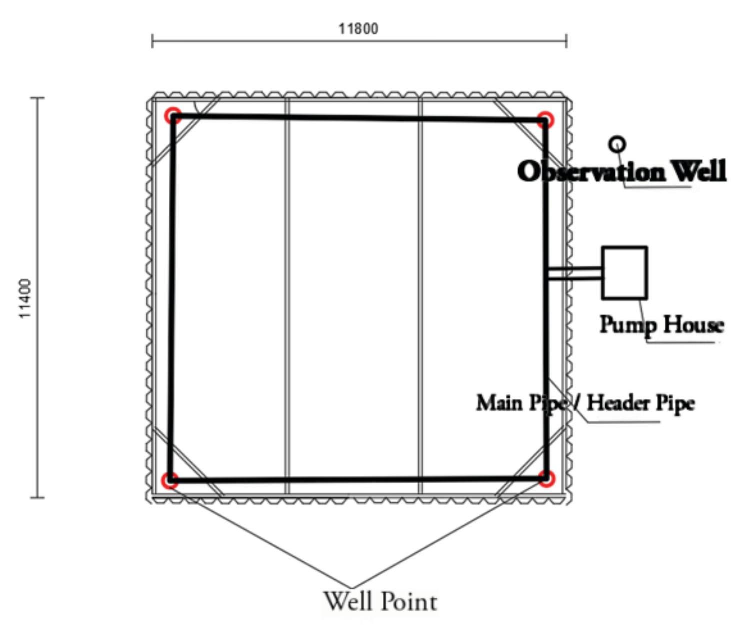

Figure 7. Layout plan of the dewatering system showing the well points arranged around the excavation perimeter, connected to the main/header pipe leading to the pump house, with an observation well provided for groundwater monitoring.

6.2. Excavation

On the side away from the bridge abutment backfill area, an excavator is used to cut and level the high slopes around the inspection well and to provide an operation platform for the long-arm excavator.

According to the requirements of the approval and review plan, when the long-arm excavator digs to a position 1m below the working platform and 50cm below the first horizontal tie beam, the excavation operation stops. The first tie beam and corner brace construction is carried out by the support operation team, and the excavation is continued until the design base level is approximately 20cm above the base of the inspection well.

At the bottom of the inspection well pit, a 400*400 (mm) water collection pit is excavated, avoiding the third tie beam, corner brace and inspection well wall position. The water collection pit is manually excavated to a depth of 75cm below the design base level, and a Φ300 reinforced concrete pipe is placed, with a height 30cm above the design base level. If there is water accumulation in the water collection pit, a self-suction pump is used to drain the water, and the water stability is measured using a measuring rope. The water stability in the water collection pit is basically stable, and the water stability height is basically below 75cm and not higher than the design base level. When the water level drops below 50cm, the drainage speed should be reduced to avoid excessive precipitation and affect the water and soil balance state of the surrounding bridge abutment backfill area.

After the manual excavation and leveling are completed, 15cm of graded crushed stone is laid on the base, and 15cm of C20 concrete slab is poured on the upper part, making the top of the pipe joint with the Φ300 reinforced concrete pipe at the same level. The pipe is filled with the same material as above.

7. Main structure construction

After the sealing of the pipe well is completed, the reinforced concrete works within 2.5m below the inspection well are carried out; when the reinforced concrete works of the inspection well below the base are completed and the strength is up to standard, the pipeline jacking construction across the river is carried out; after the pipeline jacking construction is completed, the layered pouring of the inspection well and the batch removal of the tie beams are carried out; when the part of the inspection well outside the base pit is constructed, the periphery of the well is layered backfilled and compacted layer by layer.

8. Pile extraction and grouting

When extracting the support steel sheet piles around the inspection well, grouting operations are carried out simultaneously. The specific construction is as follows:

For the insertion and extraction of the steel sheet piles in this project, the EP60 hydraulic pile driving machine is mainly used for the steel sheet piles. Due to the limitations of the mechanical extraction machine head, it is clamped at the top of the steel sheet pile, and the vibration is slowed down for 1–2 minutes to loosen the soil around the steel sheet pile. The grouting operation is carried out simultaneously. On the one hand, it strengthens the soil, and on the other hand, the slurry forms a liquid sliding membrane between the steel sheet pile and the soil, reducing the friction resistance of the soil on the steel sheet pile. Then, it is slowly lifted upwards. If there are difficulties in extracting the pile or abnormal situations occur, the extraction should be stopped immediately, and it is observed whether the operation arm of the extraction machine head is perpendicular to the steel sheet pile, whether there is deviation or angle due to human factors, and confirm that there is no error before vibrating for 1–2 minutes or slowly hammering down 0.5m before extracting again.

Before the steel sheet pile extraction construction, the grouting pipeline is buried. Along the circumference of the inspection well, 50cm away from the edge of the well wall, a ring-shaped grouting pipe is laid. The pipe spacing is 0.8m. On the side of the bridge abutment backfill area away from the inspection well, an additional grouting pipeline is set 0.8m outside the ring-shaped grouting pipe.

At the design position around the inspection well pit in the drawings, holes are drilled using a drilling machine or hand drill to a design depth, with a diameter of about 75mm. Then, a 50mm diameter grouting pipe is inserted into the hole. At the bottom of the pipe, a grouting hole is set, and a casing is provided outside the grouting pipe. A sand is filled between the grouting pipe and the casing. The gaps on the surface of the grouting platform are filled with 1:3 cement mortar or clay, and then the casing is pulled out.

According to the geological and hydrological report provided by the surveying unit, an appropriate grouting pressure is selected. In sandy soil, it should be 0.2MPa to 0.5MPa, and in cohesive soil, it should be 0.2MPa to 0.3MPa. For dense grouting, the slump of the cement mortar slurry should be 25mm to 75mm, and the grouting pressure should be 1.0MPa to 7.0MPa. Grouting reinforcement construction is carried out in combination with the geological conditions, settlement observation conditions and the extraction conditions of the steel sheet piles, and the pressure is adjusted slightly [3].

9. Conclusion

By analyzing each construction process such as foundation support, dewatering, excavation, settlement observation, and grouting reinforcement, as well as conducting research on the force balance of soil and water, two sets of support methods were adopted to ensure the traffic safety of the adjacent chemical road and bridge. During the excavation construction of the inspection well foundation project, through micro-dewatering + settlement observation + grouting reinforcement, the disturbance impact of the foundation excavation on the existing structures and the surrounding soil was reduced. While ensuring the normal traffic of the chemical road and the stability of the abutment backfill soil, the rapid construction of the pipeline across the Jialu River and the inspection well project was guaranteed. This promoted the successful completion of the post-disaster reconstruction project of the Jialu River, significantly saving the construction period and reducing the management cost. It has achieved remarkable economic benefits.

Disclosure statement

The author declares no conflict of interest.

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Integrated Services Platform of International Scientific Cooperation

Innoscience Research (Malaysia), which is global market oriented, was founded in 2016.Innoscience Research focuses on services based on scientific research. By cooperating with universities and scientific institutes all over the world, it performs medical researches to benefit human beings and promotes the interdisciplinary and international exchanges among researchers.

Innoscience Research covers biology, chemistry, physics and many other disciplines. It mainly focuses on the improvement of human health. It aims to promote the cooperation, exploration and exchange among researchers from different countries. By establishing platforms, Innoscience integrates the demands from different fields to realize the combination of clinical research and basic research and to accelerate and deepen the international scientific cooperation.

Cooperation Mode

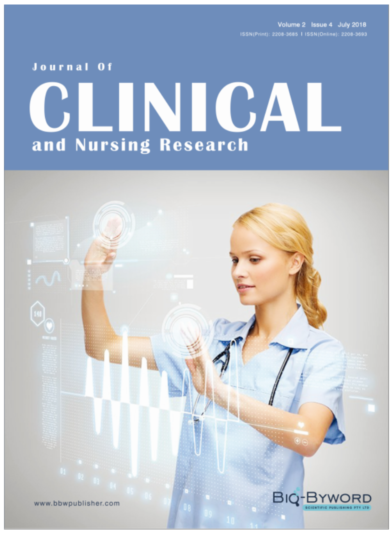
Our Journals

The *Journal of Architectural Research and Development* is an international peer-reviewed and open access journal which is devoted to establish a bridge between theory and practice in the fields of architectural and design research, urban planning and built environment research.

Topics covered but not limited to:

- Architectural design
- Architectural technology, including new technologies and energy saving technologies
- Architectural practice
- Urban planning
- Impacts of architecture on environment

Journal of Clinical and Nursing Research (JCNR) is an international, peer reviewed and open access journal that seeks to promote the development and exchange of knowledge which is directly relevant to all clinical and nursing research and practice. Articles which explore the meaning, prevention, treatment, outcome and impact of a high standard clinical and nursing practice and discipline are encouraged to be submitted as original article, review, case report, short communication and letters.



Topics covered by not limited to:

- Development of clinical and nursing research, evaluation, evidence-based practice and scientific enquiry
- Patients and family experiences of health care
- Clinical and nursing research to enhance patient safety and reduce harm to patients
- Ethics
- Clinical and Nursing history
- Medicine

Journal of Electronic Research and Application is an international, peer-reviewed and open access journal which publishes original articles, reviews, short communications, case studies and letters in the field of electronic research and application.

Topics covered but not limited to:

- Automation
- Circuit Analysis and Application
- Electric and Electronic Measurement Systems
- Electrical Engineering
- Electronic Materials
- Electronics and Communications Engineering
- Power Systems and Power Electronics
- Signal Processing
- Telecommunications Engineering
- Wireless and Mobile Communication