Research on the Evaluation System for the "Three Foundations" Construction of Work Safety in Expressway Operation Enterprises

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Abstract. The work safety level of expressway operation enterprises directly affects public safety and the operational efficiency of the road network. To scientifically evaluate the construction level of the foundational work, grassroots construction, and basic skills training (referred to as the "Three Foundations") for work safety in expressway enterprises, this paper constructs an evaluation system comprising 3 first-level indicators, 10 second-level indicators, and 35 third-level indicators through literature analysis, expert interviews, and field research. The Analytic Hierarchy Process (AHP) is used to calculate the weight of each indicator, establishing a quantitative scoring method based on weighted addition and a graded evaluation standard, thus forming a complete "evaluation-feedback" tool. An empirical application was conducted on an expressway operation enterprise in Sichuan. The results show that this system possesses strong scientific validity and operability, and can effectively evaluate the construction level of the "Three Foundations" for work safety in expressway operation enterprises.

Keywords: Expressway operation; Work safety; Three Foundations construction; Evaluation system

1 Introduction

As the backbone of the modern comprehensive transportation system, the safe and stable operation of expressways plays a crucial role in ensuring economic and social circulation and promoting coordinated regional development. With the continuous expansion of the road network and the increasing complexity of traffic flow, expressway operation enterprises face growing pressure in safety management. Traditional safety management models, which focus on post-incident handling and macro-level systems, are no longer adequate to meet the new requirements of diverse operational risks at the grassroots level and the dynamic changes in on-site management. How to shift the focus of safety management downwards and move risk prevention and control forward has become a key issue in improving the intrinsic safety level of expressway operation enterprises.[1]

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The "Three Foundations" construction for work safety (namely, foundational work, grassroots construction, and basic skills training) originated from high-risk industries in China such as petrochemicals, mining, and electric power. It is a systematic management method formed by enterprises like Daqing Oilfield through long-term work safety practices. This model effectively addresses the "gradual attenuation" problem in the implementation of safety management at the grassroots level by consolidating institutional foundations, standardizing grassroots units, and strengthening personnel competence. It has significantly reduced accident rates and enhanced the resilience of the management system, becoming a widely validated grassroots safety management paradigm in China's industrial sector. [2]

Expressway operation enterprises are characterized by long management chains, dispersed operational sites, complex job types, and strong dynamic risks. The effectiveness of their safety management highly depends on the execution capabilities of frontline units, the completeness of basic systems, and the safety behavior habits of personnel. Therefore, introducing and developing a "Three Foundations" construction and evaluation system suitable for the expressway industry is both an inherent need for the transformation of industry safety management towards systematization, standardization, and normalization, and an important pathway to promote the shift of work safety governance models towards prior prevention, full participation, and continuous improvement.

Taking the work safety "Three Foundations" construction system of an expressway operation enterprise in Sichuan as a practical case, this paper systematically analyzes the connotation and implementation paths of the "Three Foundations" construction for work safety. It summarizes key influencing factors from the three dimensions of foundational work, grassroots construction, and basic skills training, constructs an evaluation indicator system for the "Three Foundations" construction in expressway operation enterprises, and uses the Analytic Hierarchy Process for weighting. The aim is to provide enterprises with an operable evaluation tool and management reference for safety management. [3]

2 Construction of the "Three Foundations" Evaluation System for Work Safety

2.1 Analysis of Evaluation Indicators

Centered on the connotation of the "Three Foundations" construction for work safety, this paper systematically analyzes evaluation elements from the three dimensions of foundational work, grassroots construction, and basic skills training.

Foundational work indicators: Focus on the institutional support and resource guarantee for safety management, including the work safety system, facility and equipment management, safety management organization and personnel, technological innovation and informatization, etc.

Grassroots construction indicators: Focus on the standardization of operational sites and grassroots units, covering safety management standardization, operational site standardization, job safety operation standardization, etc.

Basic skills training indicators: Focus on improving personnel safety literacy and execution capabilities, involving safety culture cultivation, safety training system, safety personnel guarantee mechanism, etc.

2.2 Indicator Screening and System Determination

To enhance the scientific validity and representativeness of the indicators, this paper combines expert experience method and questionnaire survey method for indicator screening. Fifteen experts with over 10 years of experience in expressway safety management were invited to score preliminary indicators using the additive evaluation method (pass scores 1 point, fail scores -1 point), and indicators with low scores were eliminated. Based on this, and in conjunction with industry standards such as the "Detailed Rules for the Evaluation of Work Safety Standardization in Expressway Operation Enterprises," and through a review of the safety management processes and key risk points of expressway operation enterprises, a preliminary evaluation indicator system consisting of 3 first-level indicators, 10 second-level indicators, and 35 third-level indicators was formed (see Table 1).

Table 1. Evaluation Indicator System for the "Three Foundations" Construction of Work Safety in Expressway Operation Enterprises.

First-Level Indicator	Second-Level Indicator	Third-Level Indicator (Examples)
Basic Work	Safety Production System	Safety production responsibility system, dual prevention mechanism, emergency management system, etc.
	Safety Management Organization and Personnel	Organization setup, full-time safety personnel allocation, clear responsibilities, etc.
	Facilities and Equipment Management	Equipment management system, inspection and maintenance records, equipment ledger, etc.
	Technological Innovation and Informatization	Safety management information system, application of technological innovation, etc.
Grassroots Construction	Safety Management Standardization	Objective responsibilities, on-site management, hidden danger investigation, continuous improvement, etc.
	Worksite Standardization	Work area specifications, safety signs and labels, etc.

	Post Safety Operation Standardization	Operation procedures for toll collection, patrol, obstacle clearance, electromechanical, and other posts
Basic Skill Training	Safety Culture	Behavioral safety observation, safety atmosphere creation, etc.
	Safety Training	Training matrix, emergency drills, skill competitions, etc.
	Safety Personnel Support Mechanism	Incentive mechanism, internal trainers, expert database construction, etc.

3 Weighting of Evaluation Indicators Based on AHP

3.1 Method Selection

This paper selects the Analytic Hierarchy Process (AHP) to determine indicator weights. This method constructs judgment matrices and quantifies expert experience, making it suitable for multi-level, multi-indicator system evaluations. It combines qualitative and quantitative analysis under conditions lacking extensive statistical data. [4]

3.2 Weight Calculation Process

A hierarchical structure model with the goal of evaluating the effectiveness of "Three Foundations" construction was established. An expert questionnaire survey form was designed, and the nine-point scale method was used to collect judgments on the relative importance between indicators. A total of 12 valid questionnaires were collected. The eigenvectors of the judgment matrices were calculated to obtain the weight of each indicator (Table 2), and a consistency check was performed ($CR < 0.1$). The results met the logical consistency requirements.

(1) Constructing the hierarchical structure model and judgment matrices

Based on the "Three Foundations" construction evaluation system, a hierarchical structure model was constructed with the construction effectiveness as the goal layer (Y), the three first-level indicators of foundational work, grassroots construction, and basic skills training as the criterion layer (U), and the 10 second-level indicators and 35 third-level indicators as the indicator layer (V). [5]

Construct the judgment matrix UV of the index layer relative to the criterion layer, as well as the judgment matrix YU of the criterion layer relative to the target layer. Perform pairwise comparisons of the same-level index factors to calculate the weights of the same-level indexes. Elements V_{ji} and U_{ji} in the judgment matrix are all greater than 0, and satisfy $V_{ji} = \frac{1}{V_{ij}}, U_{ji} = \frac{1}{U_{ij}}$ To reduce the subjective influence of experts, the nine-point scale method is used for pairwise comparison scoring of evaluation indexes. The final assignment is determined by rounding the average score to the nearest whole number, and the judgment matrix is generated based on the final assignment.

(2) Hierarchical Single Sorting

Calculate the maximum eigenvalue λ_{max} of the judgment matrix at each level and its corresponding eigenvector W_{max}. Normalize the eigenvector to obtain the weight vector $(\omega_1, \omega_2, \ldots, \omega_n)^T$, where $\omega_i (i = 1,2, \ldots, n)$ represents the relative weight of the ii-th indicator factor with respect to the indicator factor of the upper level, so as to sort the importance of indicator factors at the same level. The eigenvector is normalized using the arithmetic average method, and the calculation results are shown in Table 2.

Table 2. Weight Distribution of First-Level Indicators and Partial Second-Level Indicators.

First-level Indicator	Weight	Second-level Indicator	Weight
Basic Work	0.17	Safety Production System	0.334
		Safety Management Organization and Personnel	0.334
		Facility and Equipment Management	0.203
		Technological Innovation and Informatization	0.129
Grassroots Construction	0.387	Safety Management Standardization	0.172
		Worksite Standardization	0.35
		Post Safety Operation Standardization	0.478
Basic Skill Training	0.443	Safety Culture	0.288
		Safety Training	0.448
		Safety Personnel Guarantee Mechanism	0.264

The results show that basic skill training accounts for the highest proportion (0.443), followed by grassroots construction (0.387), reflecting that in expressway operation safety management, improving personnel capabilities and on-site standardized implementation have a more direct impact than basic system construction. [6]

(3) Consistency Test

To ensure the reliability of the analysis results, a consistency test was conducted on the calculation results. Based on the maximum eigenvalue λ_{max} of the judgment matrix and its corresponding eigenvector W_{max}, the consistency index CI, random consistency index IR, and consistency ratio CR were calculated. The calculation process is shown in formulas (1) to (4).

$$\lambda_{max} = \frac{1}{n}\sum_{i=1}^{n}\frac{(X\omega)_i}{\omega_i} = \frac{1}{n}\sum_{i=1}^{n}\frac{\sum_{j=1}^{n} X_{ij}\omega_i}{\omega_i} \tag{1}$$

In the formula, X is the original judgment matrix; ω is the weight vector; i,j=1,2,…,n, Where n is the order of the judgment matrix.

$$CI = \frac{\lambda_{max} - n}{n-1} \tag{2}$$

$$\mathrm{RI} = \frac{\mathrm{CI}_1 + \mathrm{CI}_2 + \cdots + \mathrm{CI}_n}{n} \quad (3)$$

$$\mathrm{CR} = \frac{\mathrm{CI}}{\mathrm{RI}} \quad (4)$$

After verification, the CR values of all judgment matrices are less than 0.1, indicating that the matrices have consistency, and the normalized eigenvectors can be used as index weights.

4 Evaluation Method and Application Standard

4.1 Scoring Model

Based on the index weights and evaluation rules, a weighted deduction scoring model is established:

$$S = 100 - \sum_{i=1}^{n} w_{A_i} w_{B_i} w_{C_i} C_{k_i} \quad (5)$$

Notes:

S—Score for the "Three Basics" construction effect of work safety in expressway operation enterprises;

w_{A_i}—Weight of the first-level index;

w_{B_i}—Weight of the second-level index;

w_{C_i}—Weight of the third-level index;

C_{k_i}—Deduction value corresponding to the third-level index.

4.2 Evaluation Criteria

The "Three Basics" construction effect of work safety in expressway operation enterprises is divided into four grades: Excellent, Good, Qualified, and Unqualified. The value range of each sub-index at all levels in the evaluation system is 0 to 100, and the grade is determined according to the standards in Table 3 below. If the score of any single index is lower than 60 points, the enterprise's "Three Basics" construction of work safety shall be deemed Unqualified. [7]

Table 3. Evaluation Criteria for "Three Basics" Construction of Work Safety in Expressway Operation Enterprises.

Evaluation Grade	Excellent	Good	Qualified	Unqualified
Total Score	≥ 95	< 95, ≥ 85	< 85, ≥ 60	< 60

4.3 Empirical Application and System Verification

Taking the work safety "Three Foundations" construction of an expressway in Sichuan as an example, its current "Three Foundations" construction status was thoroughly investigated. [8] The evaluation system established in this paper was applied to evaluate it, demonstrating that this evaluation system possesses "systematic nature, uniformity, standardization, and completeness." The evaluation results can guide the continuous improvement of the "Three Foundations" construction in expressway operation enterprises. The results show that expressway operation enterprises should adjust the corresponding assessment content within this evaluation system annually based on actual management work. Newly added assessment content should also be classified, analyzed, and its scores recalculated to ensure the evaluation system better aligns with practical work. [9]

5 Application of "Three Fundamentals" Evaluation Results and Continuous Improvement Mechanism

The ultimate purpose of establishing a scientific and systematic evaluation system is to guide and drive substantive improvements in safety management within highway operation enterprises. To ensure that evaluation outcomes transcend mere “portrayal” and “diagnosis” and are transformed into concrete “treatment” and “rehabilitation” actions, this section systematically constructs a long-term operational mechanism integrating data analysis, closed-loop management, and continuous optimization—thereby transitioning the evaluation system from a “management tool” to a “driving engine.”

5.1 Safety Management Decision Optimization Driven by Evaluation Results

The “Three Fundamentals” evaluation results should not serve as the endpoint of management, but rather as a scientific starting point for optimizing decision-making and resource allocation. Managers can conduct multi-level, multi-dimensional analysis of evaluation scores, including the overall rating categories (“Excellent,” “Good,” “Qualified,” or “Unqualified”) and cross-referencing sub-scores across the three dimensions—basic work, grassroots construction, and fundamental skill training—with their respective weight matrices.

For units rated “Excellent” or “Good,” the primary strategic focus should be on “Maintain and Scale” initiatives. This involves identifying successful practices in high-performing dimensions—for instance, outstanding scores in the “Safety Training” indicator under “Fundamental Skill Training”—and institutionalizing these through best-practice extraction, standardization of operational procedures, and internal benchmarking. The goal is to codify core experiences into replicable and transferable management templates, enabling horizontal diffusion of advantages and reducing enterprise-wide exploration costs.

For units rated “Qualified” or nearing “Unqualified,” immediate “Focus and Breakthrough” actions must be initiated. Management must prioritize indicators with high weights but low scores—such as “Standardization of Positional Safety Operations” under “Grassroots Construction” (weight: 0.478), where a low score indicates exceptionally high risk. Sufficient human, financial, and temporal resources must be allocated to rectify these critical gaps. The core of decision optimization lies in leveraging evaluation data to shift from generalized, blanket management to precise, targeted interventions—enhancing resource efficiency and anchoring safety decisions in data rather than experience. Evaluation outcomes must directly inform safety planning, budget allocation, and performance assessment.

5.2 Closed-loop Improvement and Dynamic Feedback Mechanism Based on Identified Gaps

Effective improvement stems from precise root-cause identification and continuous tracking. To enhance the specificity of corrective actions, enterprises must establish a closed-loop management cycle: "Result Analysis → Root Cause Diagnosis → Measure Formulation → Implementation Tracking → Re-evaluation."

For each evaluated unit (e.g., a highway section management center or maintenance work zone), the 35 third-level indicators' deduction items (as defined in Formula 4, <A>) should be analyzed using quality management tools such as fishbone diagrams (cause-and-effect diagrams) and the 5Whys method. This enables deep excavation of underlying systemic deficiencies, inadequate resource allocation, or behavioral patterns behind surface-level issues.

To ensure that improvement measures are tightly aligned with identified evaluation gaps, it is recommended to adopt a Diagnosis–Improvement Mapping Table for dynamic management. Based on this mapping table, management can clearly define the priority level of each improvement task (P1: Immediate action; high weight and large score gap), responsible department, supervisory entity, and expected closure timeline (as illustrated in Table 4). Furthermore, the progress and quality of improvement implementation must be integrated into the next cycle of "Three Fundamentals" evaluation as a monitoring component, establishing a self-validated internal feedback loop. Additionally, the evaluation indicators and their weightings themselves require annual review and dynamic refinement in response to corporate strategic shifts and technological innovations (e.g., smart highway development), ensuring the system continues to guide the optimization of safety management. Through this closed-loop feedback mechanism, the "Evaluation–Improvement" cycle becomes a self-reinforcing, spiral-upward process.

Table 4. Example of Mapping Representation of Closed-loop Improvement Strategies Based on "Three Fundamentals" Evaluation Gaps

Problem Diagnosis (Based on Deductions from Tertiary Indicators)	Corresponding Improvement Strategy	Expected Outcome	Tracking Method / Re-evaluation Indicator
Grassroots Construction / Standardization of Post Safety Operations - Field operation personnel failed to	1. Revise the "Field Operation Safety Regulations" to incorporate risk pre-	Increase the execution rate of risk pre-control before field operations from	1. Records of updated operational procedure documents.

strictly implement the risk pre-control notification process.	control cards (graphic version). 2. Conduct a one-month special training program with on-site simulation assessments. 3. Introduce a pre-shift meeting video spot-check system.	less than 70% to over 95%.	2. Data on training assessment pass rates. 3. Reports on video spot-check qualification rates.
Basic Skills Training / Safety Training - Emergency drills met the frequency requirement but effectiveness evaluation was perfunctory.	1. Establish a "double-blind" mode for emergency drills (no prior notice of time, no preset scenarios). 2. Design a quantitative assessment form based on actual drill records, including response time, coordination efficiency, etc. 3. Mandate a "debriefing workshop" after each drill to form a case library.	Enhance the realism and challenge of drills, allowing for genuine testing and improvement of participants' capabilities.	1. Records and assessment reports of "double-blind" drills. 2. Quantity and quality of the typical emergency case library formed.

5.3 Building a Safety Culture Ecosystem and Long-Term Development Path Led by Evaluation

The ultimate value of the “Three Fundamentals” evaluation system lies in driving the fundamental shaping and sustainable evolution of corporate safety culture. To achieve this goal, the application of evaluation outcomes must transcend technical and procedural levels, penetrating deeply into organizational cognition, attitudes, and behavioral norms. [10]

First, transparent communication of evaluation results should serve as the cornerstone of cultural development. Regularly and positively disseminate evaluation findings to all employees—not only recognizing teams and individuals who excel in the dimensions of basic work, grassroots construction, and fundamental skill training, but also openly addressing shortcomings by clearly articulating their impact on overall safety and personal well-being. This conveys management’s commitment to improvement to every employee, fostering an affirmative atmosphere of “confronting issues head-on and collaboratively devising solutions.”

Second, integrate the evaluation system organically into the organization’s human resources and career development pathways. For instance, employees who consistently achieve high scores in the fundamental skill training dimension should be prioritized as candidates for internal trainers or safety benchmarks; their knowledge-sharing activities should be formally incorporated into their personal performance evaluations and recognition systems. Completion of safety improvement initiatives should serve as a critical criterion in the promotion assessment of frontline team leaders.

Finally, through iterative cycles of evaluation and improvement, employees gradually internalize core safety principles—standard compliance, risk anticipation, and continuous learning—transforming from passive “evaluated subjects” and “managed personnel” into active “standard guardians” and “risk observers.” This cultivates a safety culture ecosystem characterized by universal participation and relentless improvement.

By combining rigid institutional constraints with flexible cultural guidance, this long-term development path truly elevates the “Three Fundamentals” evaluation and enhancement from a mere management initiative into a core corporate competitive advantage.

6 Conclusion and Outlook

This paper introduces the "Three Foundations" management concept, originating from safety management in high-risk industries, into expressway operation enterprises and constructs an evaluation system for its construction effectiveness. This system has a complete structure, covering the three core levels of safety management: foundation, grassroots, and basic skills; its weights are scientific, highlighting the key role of personnel capability and on-site management in expressway safety operation; it is highly operable, providing a complete workflow from scoring to grading. It offers methodological support for self-diagnosis and benchmarking improvement in the work safety "Three Foundations" construction of expressway operation enterprises, helping to promote the transformation of enterprise safety management from passive response to active prevention, and from fragmentation to systematization.

In the next steps, empirical testing across regions and various types of enterprises can be enriched to further optimize the indicator selection and weight calculation of the evaluation system. Exploring integration with smart expressway monitoring systems and big data analysis platforms can be pursued to achieve automatic data collection and dynamic updates for evaluation, enhancing timeliness. Researching the correlation between "Three Foundations" evaluation results and enterprise safety performance can further expand the application value of the researc.

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