Highway Construction Site Safety Status Index Model Construction

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Abstract. In response to the current situation where the assessment of safety status in highway construction sites lacks quantification and dynamism, this paper first analyzes the factors affecting the safety status of highway construction based on the characteristics of highway construction. Based on the Analytic Hierarchy Process (AHP), a safety status index calculation index system is constructed, which includes basic risk indicators, dynamic verification indicators of safety production conditions, procedure execution indicators, and hidden danger investigation indicators. Considering systematization, real-time, dynamism, and quantification, a construction safety status index calculation model is established. Finally, the construction safety status of the Rui-Cang Expressway project in Zhejiang Province was analyzed. The results show the safety state index of each bid section is generally greater than 70 points, and the work point index with higher construction difficulty and risk is less than 60 points. Tunnels, Bridges and other difficult construction sites tend to have lower scores in the basic risk index; The program execution index can better reflect the implementation of site management; The above results show that the safety state index can realize dynamic and quantitative evaluation of highway construction site safety state.

Keywords: Highway; Construction Safety; Status Index; Index System

1 Introduction

With the rapid development of expressway construction in China, construction safety accidents occur frequently [1], and the safety situation is becoming increasingly severe. The fundamental reason lies in the lack of standardized, dynamic and quantifiable safety state evaluation methods in the existing highway construction site safety management, and it is difficult to carry out effective and quantifiable evaluation on the specific safety state of the construction site.

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In the field of assessment of expressway construction safety status, numerous scholars have conducted in-depth research. In terms of the characteristics of highway construction safety risks, Guo et al. [2] (2020) used complex network theory to construct a construction unsafe behavior risk chain accident network, which may be limited in practical application due to strong data dependency and high complexity. Tong et al. [3] (2021) extracted accident factors from four aspects: personnel, objects, environment, and management, and established a highway construction accident causal relationship model. Zhou Jianhui et al. [4] (2020) statistically analyzed the highway construction safety accidents from 2007 to 2017, and analyzed the accident patterns and possible causes, but it may not accurately predict risks. In terms of methods for representing the safety status of highway construction, Lin et al. (2019) [5] proposed a weight coefficient distribution method based on the importance ranking of indicators, but its key indicators need to be updated regularly to adapt to changes. Li Juan et al. (2021) [6] applied the Analytic Hierarchy Process (AHP) to establish a safety index system for the construction of expressway reconstruction and expansion projects, but the AHP, especially when determining the weight of indicators, may be subject to subjective judgment. Yang et al. (2018) [7] quantified the safety risk level of highway bridge construction based on the constructed safety risk factor index system, and its accuracy depends on the quality of the data and the completeness of the index system. Wu Guangyuan et al. (2021) [8] constructed a highway construction safety calculation model based on the ideal solution method - grey correlation based on R-type hierarchical cluster analysis, which may face problems of computational complexity and parameter sensitivity when dealing with large-scale data.

In summary, scholars from both domestic and international backgrounds have identified safety risks in the construction process and constructed comprehensive evaluation models for construction safety risks to represent the safety status of construction. However, the aforementioned research on the evaluation methods for the safety status of expressway construction mainly focuses on the static risk level evaluation of specific stages in the construction process. It fails to propose a dynamic quantitative evaluation method for the safety status of different construction sites within highway projects, which makes it difficult for management personnel to have a real-time and intuitive understanding of the specific safety status of different construction sites.

Based on the above research status, this paper comprehensively considers the influencing factors of the safety status of expressway construction sites, constructs an evaluation index system and index calculation model for the safety status of construction sites, and achieves dynamic quantitative evaluation of the safety status of expressway construction sites.

2 Construction Site Safety Status Index System Construction

2.1 Analysis of Influencing Factors

To comprehensively, objectively, and truthfully reflect and represent the safety status of construction sites, it is necessary to conduct a comprehensive and objective analysis of the influencing factors affecting the safety status of the construction sites from the perspectives of personnel, machinery, materials, methods, and environment. Based on the analysis of the safety status risks in expressway construction, and referring to standards such as the "Highway Engineering Construction Safety Technical Specifications" (JTG F90-2015) and the "Highway Project Safety Evaluation Specifications" (JTG B05-2015), the factors affecting the safety status of expressway construction sites are summarized into four aspects: basic risk indicators, dynamic inspection indicators for safety production conditions, indicators for the execution of procedures, and hidden danger investigation indicators.

(1) Basic Risk Indicators. Based on the construction content and difficulty of the sub-projects, as well as other construction factors, consideration should be given to the risk assessment conclusions made in the project risk assessment report. At the same time, construction workers, as the subjects of related risks, have an increased likelihood of personal injury accidents as the number of workers increases. Construction factors also have a certain impact on the basic risk, and as the risk level increases, the value of the adjustment coefficient also gradually increases. Therefore, the influencing factors of the basic risk indicators are the risk assessment and the number of workers, with the construction factors serving as an adjustment coefficient for the basic risk evaluation indicator.

(2) Dynamic Verification Indicators for Safety Production Conditions. The dynamic inspection index of safety production conditions is an important assessment tool in construction safety management. It ensures construction safety by dynamically inspecting and evaluating the safety production conditions that construction sites should have before and during construction. The scoring of this index is mainly based on the results of the dynamic inspection of safety production conditions, that is, whether the construction unit can effectively inspect the safety production conditions of the construction site according to special construction plans, relevant standards and specifications, policy documents, etc. Therefore, the influencing factors of the dynamic inspection index of safety production conditions are the inspection results.

(3) Procedure Execution Indicators. The index of program execution status is one of the key indicators to measure the effectiveness of the construction unit's safety management system, directly reflecting the quality and efficiency of the implementation of various management procedures in safety management. The index is valued based on the execution status of the management procedures for the construction site issued by the construction unit in the safety management system for that day, and the proportion of program execution results is a direct reflection of the effectiveness of the program execution. The higher the proportion of program execution results, the more in place the construction unit is in the execution of safety management procedures. Therefore, the influencing factor of the program execution status index is the proportion of program execution results.

(4) Hidden Danger Investigation Indicators. The hidden danger investigation index is a key indicator for measuring the level of construction safety management. It assesses the overall safety condition of construction by measuring the construction unit's ability to discover and investigate hidden dangers at the construction site. The construction unit carries out investigations according to the relevant regulations of the state, indus-

try, and the province where the construction site is located, and the findings and investigation of hidden dangers are used as the basis for scoring the index. The influencing factors of the hidden danger investigation index include not only the number of hidden dangers but also their types and severity. The fewer the number of major and minor hidden dangers, the higher the score. Therefore, the influencing factors of the hidden danger investigation index are the situation of hidden danger discovery and investigation.

2.2 Construction of the Index System

Based on the selected evaluation indicators from the previous section, the Analytic Hierarchy Process (AHP) is used to establish the highway construction site safety status index system, as shown in Figure 1. The safety status index system is divided into three levels: (1) the objective level, which is the highway construction site safety status index system; (2) the criterion level, which includes four aspects: basic risk indicators, dynamic verification indicators of safety production conditions, procedure execution indicators, and hidden danger investigation indicators, clarifying the specific content of the construction site safety status index system; (3) the factor level, which refers to the specific influencing factors contained in each element of the criterion level.

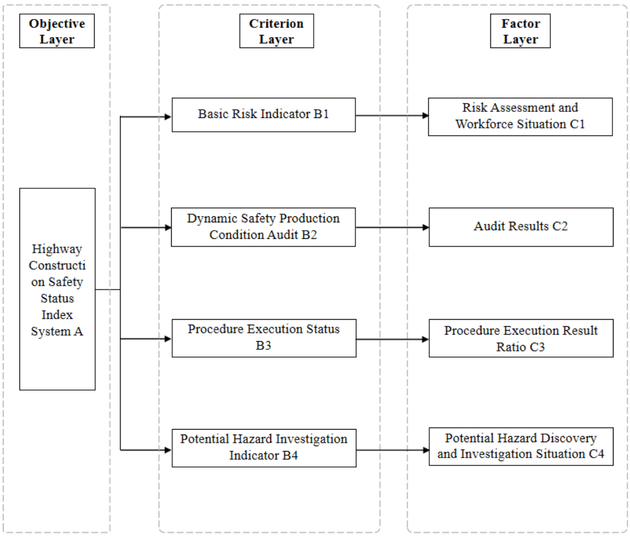


Fig. 1. Index System for Calculating the Safety Status of Highway Construction Sites

2.3 Evaluation Standards for Factor-Level Indicators

To ensure the practicality and wide applicability of the assessment system, it is necessary to comprehensively refer to the construction organization plans and construction safety organization plans of expressways under construction in provinces such as Jiangsu and Zhejiang, as well as industry standards and specifications such as the

"Safety Evaluation Standards for Highway Projects", key elements of the basic risk indicators, dynamic verification indicators of safety production conditions, procedure execution indicators, and hidden danger investigation indicators were selected, thereby clarifying the evaluation content and corresponding scores of the four indicators at the factor level, as shown in Table 1. To ensure the precision of the safety management assessment of highway construction sites, experts in the field score the indicators covered by each element according to the evaluation criteria set in Table 1, and the average score is calculated as the specific score for each indicator.

To further refine and accurately reflect the safety status, this paper uses the Analytic Hierarchy Process (AHP) to calculate and determine the weight distribution of each criterion layer indicator under the evaluation index system relative to the objective layer indicator [7].

Table 1. Evaluation Criteria for the Factor Level of the Safety Status Index System

Factor Layer	Evaluation Content	Score	Explanation
Risk Assessment and Workforce Situation C1	Low risk and the number of personnel is ≤ 20 people	100	①n represents the number of construction workers; ②λ is the adjustment factor, with values of (0.975,1,1.05) corresponding to (low, moderate, high) risk levels, respectively.
	Low risk and the number of personnel is > 20 people, or it is a general risk or significant risk with construction workers present	100-$\lambda \times n \times 0.3$	
	High risk or the number of personnel is > 200 people	40	
Inspection Results C2	The audit procedure is issued, and all dynamic audit requirements for major hazardous projects are fully met	100	①n is the number of unsatisfied general items. m is the number of unsatisfied key items. ②For ordinary construction sites without major hazards, the score is calculated as 100 points.
	The audit procedure is issued, and for each general item not meeting the requirements in the dynamic audit of major hazardous projects, deduct 5 points; for each key item not meeting the requirements, deduct 10 points	100-5×n-10×m	
	The audit procedure is issued, and if the dynamic audit of major hazardous projects finds that the non-compliance rate exceeds 50%, this item scores 0 points	0	
Rocedure Execution	All procedures are legally compliant, and all tasks for the day are completed	100	①n is the proportion of completed tasks.

Result Ratio C3	Tasks have been assigned, with an initial score of 50 points; all procedures are basically legally compliant, and for each 1% of the task volume completed, the score increases by 0.5 points	$50+n\times0.5$	
	There are tasks, but task assignment has not been conducted	0	
Potential Hazard Identification and Investigation Situation C4	No potential hazards were found during the inspection process at the construction site	100	
	The construction site has no significant potential hazards, asterisked potential hazards deduct 5points; non-asterisked potential hazards deduct 1 point	$100\text{-}n\text{-}5\times m$	①n is the number of non-asterisked potential hazards. ②m is the number of asterisked potential hazards.
	The construction site has 1 or more significant potential hazards	0	

3 Safety Status Index Model Construction

3.1 Index Definition

The safety status index for highway construction sites should be developed from multiple perspectives, including the characteristics and safety status of the construction project, hidden danger investigation, safety management procedure execution, and verification of safety production conditions. It should highlight the primary safety responsibility of construction units in site safety management, use mathematical methods, and reflect the current safety status of the construction site at the current moment in a systematic, real-time, dynamic, and quantitative manner, meeting the requirements of refined engineering management.

3.2 Index Calculation Model

Based on the characteristics of the construction site, starting from aspects such as on-site protection, site layout, process management, and external influences, and in conjunction with the daily management mechanisms of construction units, supervision units, and construction units, a safety status index calculation model is proposed. This model enables the dynamic and quantitative representation of the safety status of the site, transforming safety management from static to dynamic. The calculation method of the constructed index calculation model is shown in Equation (1).

$$P = \sum X_i = R_i \cdot \gamma_i \tag{1}$$

In the formula:

P— The overall safety status assessment score.

X_i— The score of the assessment indicator for item, i =1、2、...... n represents the number of items.

R_i— The base score of the assessment indicator.

γ_i— The weight coefficient of the assessment indicator.

In this context, the safety status index is represented on a scale of 0 to 100. A score of 100 is the highest, indicating the best safety status, and a lower score indicates that the safety status needs improvement.

4 Case Analysis

4.1 Case Selection

The Rui Cang Expressway construction project is taken as an example. This project is a key construction project planned during the "14th Five-Year Plan" in Zhejiang Province, with a total length of 52.6 kilometers and a total investment of 15.953 billion yuan. It is built according to the standard of a four-lane expressway, with a designed speed of 100 kilometers per hour. The project has a bridge and tunnel ratio as high as 87%, making it the highest bridge and tunnel ratio among the mountain expressways under construction in Zhejiang Province. The high proportion of bridge and tunnel projects in this project, coupled with the complex on-site construction environment and processes, increases the difficulty of construction safety management. The constructed highway construction site safety status index calculation model is applied to the safety management of the Rui Cang Expressway.

4.2 Effectiveness Analysis

The calculation of the construction safety status index at the construction point mainly selects the four units and four elements in Figure 1 model as the index system for this evaluation. Based on the model and expert experience, the weight coefficients for each unit are given as (C1: 0.2, C2: 0.3, C3: 0.3, C4: 0.2). Combined with Equation (1) index calculation model, calculate the construction safety status index for different construction points in each section of the expressway.

(1) Overall Safety Status Analysis of the Project

Using the established index system and calculation model mentioned earlier, the construction safety status index for the four sections of the project on a certain day is obtained as shown in Figure 2 below. Specifically, the safety status index for each construction site in the section is analyzed as shown in Figure 3 below.

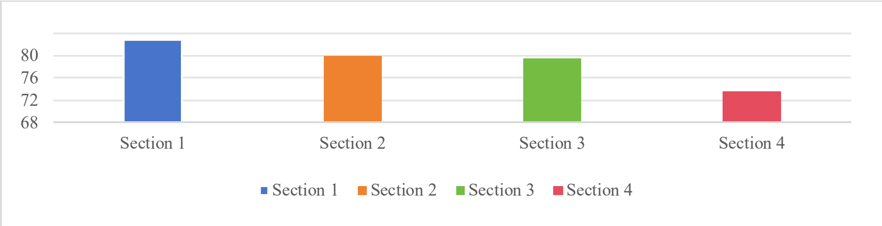
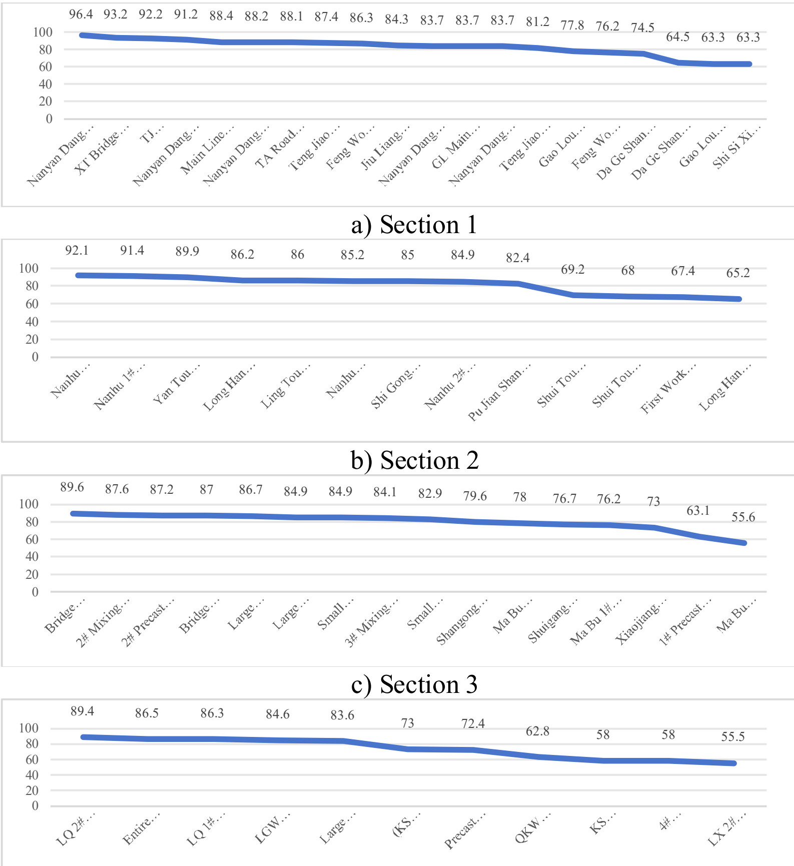


Fig. 2. Safety Status Index of Construction for Sections 1 to 4 of the Rui Cang Expressway



d) Section 4

Fig. 3. Comparison of Safety Status Indices for Construction Sites in Sections 1 to 4 of Rui Cang Expressway

From the analysis results mentioned above, it can be known:

①The construction safety status index has a good degree of discrimination, with significant differences in index scores among the sections, which well reflects the construction safety status of each section of Rui Cang Expressway. As can be seen from the figure, the overall safety status index of each section is greater than 70 points, indicating a generally good safety status.

②The value of the safety status index for each section is related to the safety status indices of all construction sites on that day within the section. Among the four sections of this project, 45% of the construction sites in Section 1 have a safety status index score above 85 points, while in Section 4, only 27% of the construction sites have a safety status index score above 85 points, and there are more construction sites with scores below 60 points. Therefore, the overall safety status index of Section 1 is higher than that of Section 4.

③Specifically, comparing the safety status indices of various construction sites within the section, the construction sites with lower safety status indices are mainly the tunnel exits, bridge pile foundations, and lower structure construction sites, such as the lower structure construction of Kuoshan Bridge and Lingxi No. 2 Bridge in Section 4, where the safety status index is less than 60 points. The main reason is that the construction difficulty and risk of such projects are relatively high. Focus on taking corresponding measures to reduce risks and improve the overall construction safety level for such construction sites with lower indices.

(2) Analysis of Secondary Indicators of Construction Site Safety Status Index

On the basis of the aforementioned index analysis, a further refined analysis of the safety status index scores for each section's construction sites is conducted. The comparative analysis of the secondary indicators of the construction site safety status index for the four sections of the project is shown in the Figure 4.

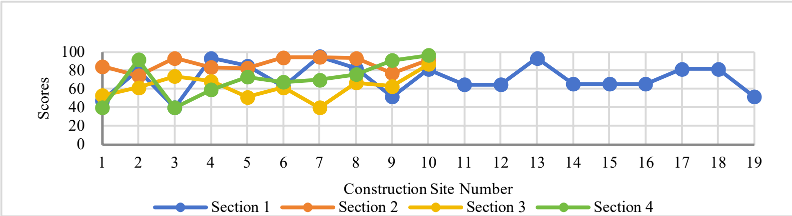
From the analysis results mentioned above, it can be known:

①The Basic Risk Indicator scores effectively reflect the impact of factors such as the number of construction personnel, construction content, and construction difficulty on the basic risk level of the construction site. As shown in Figure 4-a, it can be seen that the construction sites with lower Basic Risk Indicator scores are those with high construction difficulty such as tunnels and bridges. In the safety management of construction sites, lower-scoring sites should be given more attention to on-site safety and personnel management.

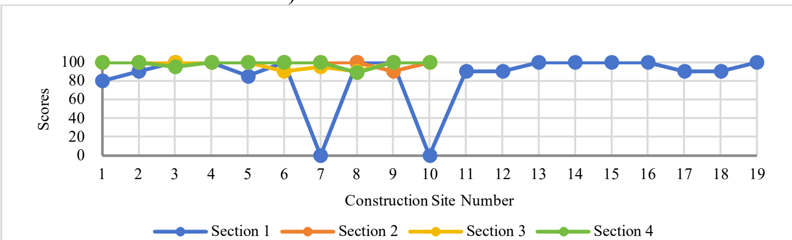
②The Scheme Execution Indicator reflects the dynamic verification results of safety production conditions, serving as a quantitative feedback indicator for the dynamic verification of safety production conditions at the unit engineering sub-item stage. As shown in Figure 4-b, the main line foundation construction of section 1, site 7, and the Tengjiao interchange roadbed construction of site 10 scored 0 points for this item. For sections with lower Scheme Execution Indicators, on-site management should be strengthened, and hidden danger problems found in the verification should be corrected in a timely manner.

③The Procedure Execution Indicator score mainly reflects the execution status of various safety management tasks assigned by the system for that day at the construction site. As shown in Figure 4-c, most construction sites in sections 1 to 4 have good execution, for sections with lower completion rates of procedure execution and Procedure Execution Indicators, on-site management should be strengthened during the management process of construction sites, emphasizing the performance of management personnel on-site and the completion of responsibility solidification.

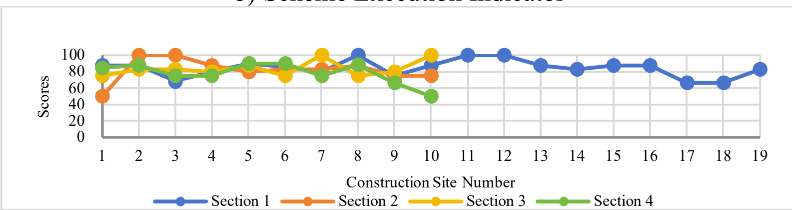
④The Hidden Danger Investigation Indicator reflects the situation of hidden danger investigation and rectification at the construction site. According to Figure 4-d, section 4 had more hidden danger issues, mostly related to the lack or improper placement of protective facilities, and malfunction of alarm facilities. Focus on key safety management for categories with a larger number of hidden dangers to ensure that hidden dangers can be discovered and resolved in a timely manner.



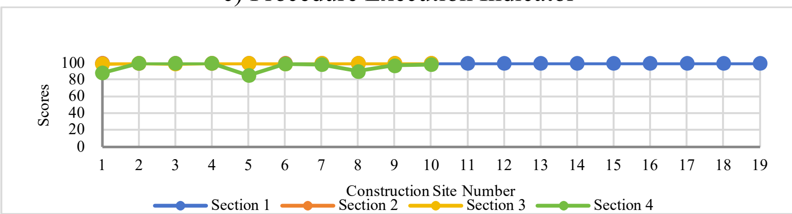
a) Basic Risk Indicator



b) Scheme Execution Indicator



c) Procedure Execution Indicator



d) Potential Hazard Investigation Indicator

Fig. 4. Comparison of Secondary Indicators for the Safety Status Index at Construction Sites

Through the analysis of the scores of the Basic Risk Indicator, Scheme Execution Indicator, Procedure Execution Indicator, and Hidden Danger Investigation Indicator in the safety status index of Sections 1 to 4 of the project, it is possible to reflect the risk level of the construction site, the execution of on-site safety management procedures, and the handling of on-site hidden danger investigations in a real-time and dynamic manner. It objectively and truly presents the safety status of different construction sites during the construction process, confirming the scientific and rational construction of the index system and the index model.

At the same time, the established work site safety state index system and calculation model can also provide reference for work site safety management in construction industry, water conservancy engineering and other related fields. However, it should be seen that the construction, water conservancy and other industries and highway engineering construction are different in safety management rules and regulations, standards and specifications, construction processes and other aspects. Therefore, when introducing and using, we should analyze and study the index system, model weight and application scenario according to the characteristics of the industry, and establish the appropriate index system and model method.

5 Conclusion

This paper has established a safety status index model and its index system in response to the needs of safety management at highway construction sites, and has reached the following conclusions:

(1) Starting from the safety management elements and combining the characteristics of highway engineering construction sites, the calculation index system for the construction safety status index needs to include basic risk indicators, dynamic verification indicators of safety production conditions, procedure execution indicators, and hidden danger investigation indicators, and has clarified the evaluation criteria for each indicator.

(2) Based on the idea of dynamic calculation and quantitative assessment, the definition of the construction site safety status index has been clarified, and the calculation model for the construction site safety status index has been established.

(3) Take the new construction of Ruicang Expressway in Zhejiang Province as an example to verify the validity and applicability of the model. For the work points with low scores, the causes can be analyzed and targeted control strategies can be formulated, which provides an innovative means of safety management for the construction of highway engineering work points.

The next step is to establish a long-term tracking and evaluation mechanism, improve the index system, analyze and verify the effect in other industries, and improve the comprehensiveness and adaptability of the model.

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