A Study on the Safety Assessment for Portal Cranes Based on Analytic Hierarchy Process

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Abstract: This paper introduces the current safety situation of portal crane and the deficiencies of current supervision methods, and proposes the application of new methods for the safety assessment of equipment. The safety assessment method for portal cranes based on the Analytic Hierarchy Process (AHP) is studied, and the safety assessment method applicable to the portal cranes in service is obtained. By defining the equipment safety performance assessment value D, the real-time status and risk level of equipment can be expressed tangibly and clearly.

1. Introduction
Portal crane has been widely applied to shipbuilding bases, inland ports, docks and internal fields in inland river transportation and related industries of Yangtze River Delta as lifting appliances. Such type of crane is usually used for the segmentation and the handling of general cargo and bulk cargo. At present, there are about 200 portal cranes in service in Shanghai. Since the equipment seriously aged (the average service life has reached 15 years) and the operation sites are extremely scattered, it is thus difficult to implement effective safety management. The safety verification for these portal cranes in service is limited to the self-inspection of enterprises and the prescribed national supervision and inspection. These inspections cannot identify and classify the risk levels of the equipment, resulting in a considerable number of equipment operating on huge potential risks. These potential risks easily cause work safety accidents. The high-frequency works safety accidents caused by portal cranes in the Yangtze River Delta region have proven this problem.

Effective safety assessment for the special equipment in service is very popular and applicable at present. Developed countries in the US and Europe have started early in safety assessment, and began to use the safety assessment theory to assess the safety of special equipment in the 1970s. The US Dow's Chemical has contributed the Dow’s fire and explosion assessment method based on the index assessment principle to quantitatively assess the hazard of special equipment in chemical production system[1], and other models such as Banon model[2], Wang and Shah model[3], Park and Angmodel[4] which can be used for the safety assessment of special equipment. British scholars have studied the system safety assessment method represented by probabilistic risk analysis, and assessed the safety of special equipment. In recent years, the numerical analysis method in the safety assessment of special equipment has been widely used. For example, Bayesian network numerical method is mostly used for the safety assessment of special equipment in nuclear power station. With regard to the safety of lifting appliances, Yang Ruigang from Taiyuan University of Technology studied the safety assessment of
bridge cranes\cite{5}, and Huang Hai from Wuhan University of Technology studied the safety assessment of metal structures of port cranes\cite{6}.

The related research data of portal crane safety assessment has not been reported. This paper intends to explore the methodologies which can identify and classify the risk levels of portal cranes in service, in order to prevent and reduce accidents.

2. Selection of safety assessment methods for portal cranes

2.1 Comparison of common safety assessment methods

Several mature methods for the safety assessment of special equipment at present are shown in Table 1:

| Method                   | Basic principle                                                                 | Typical method                          | Main application fields and characteristics                                      |
|--------------------------|---------------------------------------------------------------------------------|-----------------------------------------|----------------------------------------------------------------------------------------|
| Index assessment method  | According to the assessment object, the assessment items are selected, and the scoring range of the assessment items is determined according to specific principles. Professional assessment personnel score each assessment item, and the total score is calculated through exponent arithmetic. | Dow’s method and Mond method            | Mainly applicable to the assessment of energy conversion involved in production       |
| Fault tree analysis      | System safety assessment technology based on probabilistic risk analysis         | Fault tree analysis                     | Mainly used in aerospace industry and newly developed high-tech industries            |
| Bayesian network method   | Based on the numerical analysis method, Bayesian network is introduced into the fault tree model for calculation | Fuzzy analysis method and fuzzy probability method | Applicable to the real-time dynamic assessment of production systems, and require a very high calculation cost |
| Weight assessment method | The necessary safety indexes are obtained by modeling and quantifying the assessment problems | AHP                                     | It is widely used, especially in the absence of necessary statistical data             |

A portal crane is characterized by clear structure, and the relative importance of different components can be qualitatively judged on a simple way. But the quantitative judgment lacks a large number of statistical data as support, so the weight assessment method is chosen as the basic method for the safety assessment of portal cranes.

2.2 Weight assessment based on AHP

Weight assessment based on AHP is contributed by Professor Sarty of Pittsburgh University. In this method, a complex problem can be expressed into a sequential hierarchical chart and specific calculations are implemented to acquire the relative importance of various factors that affect the core problems of the whole process, and finally obtain the assessment value of these problems. The whole problem solving process includes hazard identification and differentiation, importance analysis of different hazards and calculation of equipment safety performance parameters.
The specific steps are as follows: First, the problems to be analyzed are dissolved into different hazard sources (influencing factors), which are combined according to the interrelationships to constitute a multi-level logical structure model of the problems for analysis. The diagram is shown in Figure 1, and the top level T in the figure is called the target level, which refers to the problems to be analyzed. The lowest level (level A) is the bottom level containing various basic factors that cause problems and are inseparable. The middle level between level T and A represents all the intermediate links involved in causing problems. By scoring the mutual importance of each influencing factor constituting the logical structure model by experts according to a certain method and processing the related data, the results of the importance of each influencing factor of the target level T can be obtained. By inspecting the equipment by inspectors, the real-time status of inspection items corresponding to each influencing factor can be obtained, and the real-time status can be expressed as a numerical result. By integrating the results of importance of influences brought by the bottom factors on-target level and the real-time status numerical results of equipment, the assessment value D of equipment safety performance results can be obtained. According to the equipment category, the corresponding safety status and safety measures required by the equipment are known at last.

Figure 1 Hierarchical Structure Model Diagram

3. Study on the safety assessment of portal cranes through weight assessment based on AHP

3.1 Safety assessment model hierarchy for portal cranes

According to the structural characteristics of portal crane, its safety performance can be divided into four levels, among which the first level and the problem we need to solve is the risk assessment value of portal crane. The second level can be further broken down into the mechanism, structure and electrical system of equipment. The factors of the second level fall into crane boom status, slewing table status, pedestal status, A-frame status, main hoist status, luffing mechanism status, slewing mechanism safety, power loop status, control loop status and control system status. At the fourth level, the factors of the third level are subdivided into 49 irreducible bottom-level influencing factors. For example, the luffing mechanism status can be subdivided into luffing motor status, brake status, reducer status, coupling status, steel rope status, pulley status and shaft, key and pin status (the schematic diagram of portal crane safety assessment structure is shown in Figure 2).
3.2 Acquisition of relative importance of all influencing factors towards the target level $T$

3.2.1 Establish a comparison matrix to obtain the maximum eigenvector

After the safety assessment structure model is established, the degree of influence brought by each factor on the directly related factors of the previous level can be obtained by solving the eigenvector of comparison matrix among the influencing factors. Through a great number of study and analysis of portal crane by professionals, we have a deep understanding towards the main types and frequency of faults occurring during equipment operation. Based on the above outcomes, relevant professionals have expressed the relative importance of each component of portal crane with reference to 1-9 quantitative scales (as shown in Table 2).

| Scale | Definition |
|-------|------------|
| 1     | Two factors are equally important after comparison |
| 3     | The former factor is more important after the comparison between two factors |
| 5     | The former factor is obviously important after the comparison between two factors |
| 7     | The former factor is remarkably important after the comparison between two factors |
| 9     | The former factor is extremely important after the comparison between two factors |
| 2,4,6,8 | The intermediate value in the above comparisons |
The relative importance of each factor in the second level in the assessment structure diagram relative to the factor T in the first level can be expressed as a matrix shown in Table 3 according to 1-9 quantitative scales. The matrix shown in Table 3 is also called comparison matrix because it represents the importance of factors of a certain level to the directly related factors of the previous level. The maximum eigenvector of matrix T can be calculated by ANC (Asymptotic Normalization Coefficient) method, and the importance coefficient \( \omega = (0.566, 0.242, 0.192) \) of the second level to the target level T can be obtained accordingly.

In the same way, the comparison matrix of the third-level factors directly related to the second-level factors and the fourth-level factors directly related to the third-level factors can also be obtained. After calculation, the eigenvectors of each comparison matrix are known. The maximum eigenvectors of the third-level factors directly related to the second-level comparison matrix are \( \omega_1 = (0.386, 0.204, 0.213, 0.197) \); \( \omega_2 = (0.174, 0.723, 0.103) \); \( \omega_3 = (0.106, 0.260, 0.634) \) respectively.

### Table 3 Comparison Matrix of Factors on the Second Level to the Target Level T for Portal Cranes

|   | A1 | A2 | A3 |
|---|----|----|----|
| A1 | 1  | 4  | 2  |
| A2 | 1/3| 1  | 2  |
| A3 | 3/5| 1/2| 1  |

#### 3.2.2 Comparison matrix consistency verification

After obtaining the maximum eigenvector of each comparison matrix, it needs to verify the consistency of each comparison matrix to ensure that the relative importance of each component expressed by professionals according to the 1-9 quantitative scales are reliable. AHP suggests that the consistency of comparison matrix has passed the verification when the consistency ratio (CR) of each comparison matrix is lower than 0.10.

Where, the maximum characteristic root \( \lambda_{\text{max}} \) can be obtained as per Formula 1:

\[
\lambda_{\text{max}} = \sum_{i} \left( \frac{A \omega}{n \omega} \right) (i = 1,2,\ldots,n)
\]

The consistency index (CI) of comparison index is shown in Formula 2:

\[
CI = \frac{\lambda_{\text{max}} - n}{n - 1}
\]

The average random index (RI) of comparison index can be found from RI Order List. The CR of matrix can be expressed as follows:

\[
CR = \frac{CI}{RI}
\]

According to the calculation, the maximum characteristic root \( \lambda_{\text{max}} \) of matrix T is 3.024 and CI is 0.012, and the RI of the third-order matrix is 0.58, then CR can be calculated as being more than 0.02 and less than 0.1, so the matrix T passes the consistency verification.

In the same way, the consistency of the comparison matrix of the third level to the second level, and the fourth level to the third level is verified respectively. Through calculation, all CR values of the comparison matrix are less than 0.10. Therefore, AHP safety assessment method based on expertise and data statistics is available for portal cranes.
3.3 Safety performance result assessment value $D$ and range definition

All coefficients of the safety assessment method based on AHP for portal cranes are determined by calculating the maximum eigenvector of each comparison matrix. After inspecting the specific equipment, the inspectors score the factors shown in the safety assessment structure diagram of portal cranes according to the inspection results (each status is expressed according to the hundred mark system) and the best status will be given 100), and normalize each score to obtain the real-time status score $I$ corresponding to each assessment index. Then the evaluation value $D$ of the safety performance result of the equipment can be calculated according to Formula 4. The real-time safety and risk status of the equipment can be obtained according to the value $D$.

$$D = \sum_{i=1}^{n} \omega_i \times I_i (i = 1, 2... 49, 0 \leq D \leq 1)$$ (4)

According to the specific characteristics of portal crane, relevant professionals define the safety status and corrective actions corresponding to different ranges of the value $D$. See Table 4 for details:

| Range of value $D$ | Safety status  | Necessary measure                                      |
|-------------------|----------------|--------------------------------------------------------|
| $> 0.8$           | Slight risk    | The equipment risk is negligible                       |
| $0.6 \leq D < 0.8$| Low risk       | The equipment is in good status but should be actively monitored |
| $0.4 \leq D < 0.6$| Moderate risk  | The equipment can work normally but it needs to repair the equipment or replace corresponding parts to ensure the operation safety |
| $0.2 \leq D < 0.4$| High risk      | The equipment can work normally but it needs to repair the equipment or replace corresponding parts to ensure the operation safety |
| $< 0.2$           | Extreme risk   | Perform an overhaul to the equipment and control the risk in a reasonable and tolerable scope |

4. Practical engineering applications of safety assessment through weights based on AHP

In a port in Shanghai, a portal crane in service (as shown in Figure 3) has undergone safety assessment using AHP. After comprehensive inspection to the crane, the inspectors score all factors of the fourth level shown in the assessment structures model diagram (as shown in Figure 2). After normalizing the data, the safety performance assessment value $D$ of this equipment is 0.782 according to Formula 4.

Figure 3 Portal Crane for Test
According to related information in Table 4, the equipment is at low risk in real time, indicating that the overall safety performance of the equipment is good. Under such circumstance, it only needs to actively monitor the equipment during operation.

Table 5 Scores of Safety Performance Assessment for Portal Cranes

| Item                  | Score | Item                  | Score |
|-----------------------|-------|-----------------------|-------|
| Steel rope status     | 75    | Pulley status         | 76    |
| Luffing motor status  | 80    | Shaft, key and pin status | 71    |
| Brake status          | 83    | Coupling status       | 60    |

5. Conclusion
This paper introduces the current safety situation of portal cranes in service, and proposes a new portal crane safety assessment method. After specific researches, we have drawn the conclusion below:

1) Due to the characteristics and incomplete supervision system of portal cranes, it is necessary to perform safety assessments with risk level identification and division.

2) Through the research on safety assessment for portal cranes based on AHP, a method applicable to the safety assessment for portal cranes in service is explored. This method can express the real-time status and risk level of equipment tangibly and clearly through safety assessment index D, and provide an effective and simple solution for equipment supervisions.

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