Safety risk analysis and control of tower crane

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Abstract. Tower crane is one of the vertical transport machinery widely used in the construction at present. Due to its own structure and safety management defects, accidents often occur and have serious consequences [1]. Therefore, it is of great significance to study the safety accidents of tower crane. In this paper, through a large number of accident statistical analysis and expert interviews, from the analysis of the entire process of tower crane installation, use and disassembly stage, the accident tree with the tower crane safety incident as the top event is established. Through the qualitative analysis of the accident tree, the minimum cut (diameter) set is obtained, on this basis, the structural importance of all basic events is sorted, the main factors affecting the safety accident of the tower crane are determined, and the corresponding management and control are proposed, and provide a basis for preventing tower crane accidents and controlling tower crane risks.

1. Preface

With the development of our country's economy, the progress of urbanization has been continuously strengthened. Tower cranes have been widely used as the main horizontal and vertical transportation vehicles on the construction site. However, during the operation of tower cranes, tower crane-related accidents are frequent and have serious consequences. Therefore, in order to improve the safety management level of tower cranes in the construction, it is necessary to study the influencing factors of safety risks of tower cranes [2].

At present, many scholars at home and abroad have conducted research on the influencing factors of tower crane safety. Xiaoqin Zhang[3] analyzed the influencing factors of tower crane safety from the perspectives of human, machine, environment and management, and used AHP and fuzzy comprehensive evaluation method to construct a tower crane safety assessment model. Shin [4] investigated the safety influencing factors of accidents during the installation and dismantling phase of tower cranes in South Korea, and analyzed that the illegal operation of workers was the main factor causing the safety accidents of tower cranes. Tingsheng Zhao et al. [5] analyzed the factors affecting the safety of the tower crane during the use phase, and based on the Bayesian modeling method, constructed a safety risk assessment model for the tower crane during the use phase, and realized the quantitative assessment of the safety risk during the tower crane's use phase. Ding et al. [6] adopted a modified model of the source of loss, established a tower crane construction risk classification through statistical analysis of multiple engineering cases, and used fishbone diagrams to summarize and analyze various risk factors.

Based on the above research, it is found that the existing research on the influencing factors of tower crane's safety risk has important guiding significance for tower crane's safety management, but most of them are limited to the research of the tower crane at a certain working stage, and the system is not analyzed comprehensively from the whole process of installation, use and disassembly of tower crane. According to the 162 cases collected by the statistical study of tower crane's accidents, the most frequent
phase of tower crane accidents is the use phase, followed by the disassembly and installation phase [7]. Due to the long operation cycle and complicated operations in the use phase, the frequency of accidents is the highest. However, the installation and disassembly phases are short and relatively simple tasks, and the frequency of accidents is also relatively high. This shows that the safety management of the tower crane installation and disassembly phases should not be underestimated. As an effective method for reliability analysis and evaluation of engineering systems [8], the accident tree analysis method provides an effective means for analyzing tower crane safety accidents. Based on the accident cause theory, and following the principle of "incident causes unfolding layer by layer" [9], this paper analyzes tower crane safety accidents from the four major factors of human-machine-environment-management, and sorts out the direct and indirect causes that affect tower crane safety layer by layer, establishes the tower crane safety accident tree, and determines the important influencing factors according to the structural importance of each safety risk influencing factor, so as to take targeted control measures to provide a basis for the safety management of the tower crane.

2. Build a tower crane safety accident tree

2.1. Summary and Classification of Factors of Tower Crane Safety Accidents
According to the accident cause theory, the occurrence of a tower crane safety accident is a complex process of a long accident chain, which constitutes the "unsafe state" of the human-machine-environment-management and other factors of the system. It is the hidden cause of the "dynamic disturbance" or even failure change of the structure, function and state of the safety event chain of the tower crane system. Therefore, in the analysis of the direct and indirect causes of tower crane safety accidents, the most direct causes are ultimately attributed to the four important influencing factors of human, machine, environment, and management.

(1) Analysis of human factors
The human factor specifically refers to the "human unsafe behavior" during the operation of the tower crane, and is the most direct factor that causes the safety risk accident of the tower crane, mainly including fatigue work, illegal operation, inadequate supervision and inspection, improper promotion, wrong command and no personal protection.

(2) Analysis of machinery (tower crane) factors
The mechanical factor mainly refers to the "unsafe state of things (tower cranes)", mainly including fatigue cracks on the chord, overloaded lifting, failure of lifting components, inadequate maintenance and other factors.

(3) Analysis of environmental factors
The environmental factor analysis mainly refers to two aspects of the operating environment and natural environment. Operating environment factors mainly include failure of foundation bearing capacity, collision of tower cranes and collision with obstacles; Natural environmental factors mainly include low visibility, high temperature and high wind speed during operations.

(4) Analysis of management factors
Tower crane accidents are often the result of a combination of multiple factors, most of which are inextricably linked to management factors, mainly including imperfect management staff, unlicensed employment, imperfect supervision system, no special construction plan and other factors.

2.2. Build a tower crane safety accident tree
Through the statistical analysis of the tower crane accidents, the types of tower crane high accidents are mainly overturning (collapse) accidents, broken and folding arm accidents, falling object accidents and collision accidents. Therefore, the overhead incident is designated as the tower crane safety accident, and the overturning (collapse) accident, broken and folding arm accident, falling object accident and collision accident are taken as the four intermediate events of the tower crane safety accident, and the tower crane safety accident tree is drawn, as shown in Figure 1 below.
3. Qualitative analysis of tower crane safety accidents

According to the maximum number difference method of the minimum cut (diameter) set, the minimum diameter set of this accident tree is large, and the minimum cut set is 9, so the minimum cut set should be used for analysis.

(1) Minimum cut set analysis

The minimum cut set is the set of the minimum basic events of the top event occurs. According to the definition of the minimum cut set, each minimum cut set represents a possibility of the occurrence of the top event. There are several minimum cut sets in the accident tree, and there are several possibilities for the occurrence of the top event. The more the minimum cut sets, the more likely the accident will occur, and the more dangerous the system will be.

Use the Boolean algebra method to find the minimum cut set:

\[ T = M_1 + M_2 + M_3 + M_4 = X_1 + X_2 + M_5 + M_6 + M_7 + X_3 + M_8 + M_9 + M_{10} = X_1 + X_2 + X_4X_5X_6 + X_7X_8 + \]

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Table 1. List of basic events.

| Event number | Event name                                      | Event number | Event name                                      |
|--------------|-------------------------------------------------|--------------|-------------------------------------------------|
| T            | Tower crane safety accident                     | X5           | Oblique hanging                                 |
| M1           | Overturning (collapse) accident                 | X6           | Improper operating procedures                   |
| M2           | Broken and folding arm accident                 | X7           | Existing fatigue cracks on chord                |
| M3           | Falling accident                                | X8           | Failure of connection between components        |
| M4           | Collision accident                              | X9           | Insufficient maintenance                        |
| M5           | Improper lifting operation                      | X10          | Imperfect supervision system                    |
| M6           | Tower arm structure resistance failure          | X11          | Imperfect management staffing                   |
| M7           | Poor management                                 | X12          | Safety devices such as lifting limiters fail    |
| M8           | Failure of lifting components                   | X13          | Hook problem                                    |
| M9           | Tower cranes collide with each other            | X14          | Wire rope break                                 |
| M10          | Collide with obstacles                          | X15          | Command error                                   |
| X1           | Basic bearing capacity failure                  | X16          | Small working space                             |
| X2           | Tower structure resistance failure              | X17          | Failure of monitoring equipment                 |
| X3           | Improper lashing or lifting operation overload  | X18          | Organizational coordination is not in place     |
| X4           | Overload                                         | X19          | Existing a blind spot in the lifting operation  |
The minimum cut set is:
\[ E_1 = \{X_1\}, \quad E_2 = \{X_2\}, \quad E_3 = \{X_4, X_5, X_6\}, \quad E_4 = \{X_7, X_8\}, \quad E_5 = \{X_9, X_{10}, X_{11}\}, \quad E_6 = \{X_3\} , \]
\[ E_7 = \{X_{12}, X_{13}, X_{14}\}, \quad E_8 = \{X_{15}, X_{16}, X_{17}, X_{18}\}, \quad E_9 = \{X_{17}, X_{19}\} \]

Through intuitive judgment, it can be seen that the tower crane safety accident tree has 9 minimum cut sets, which shows that there are many ways of tower crane safety accidents, so the frequency of tower crane safety accidents is high. In addition, the minimum cut set can intuitively compare the risk of accidents, so as to choose the best plan for controlling accidents. The minimum cut sets with fewer basic events are more likely to cause accidents than the minimum cut sets with more basic events. In order to improve the reliability and safety of the system, measures to increase the basic events can be taken for the minimum cut sets with few basic events. The three basic events of \(X_1\) "failure of foundation bearing capacity", \(X_2\) "failure of resistance of tower body structure", and \(X_3\) "improper lashing or lifting operation" can be controlled in the safety accident of tower crane to reduce the probability of accident.

2. Structural importance analysis

Structural importance reflects the degree of impact of the occurrence of basic events on the occurrence of overhead events. Structural importance analysis does not consider the probability of the occurrence of basic events, and only analyzes from the structure of the accident tree, so it is called the structural importance coefficient [10].

There are two types of structural importance analysis methods. One is to calculate the structural important coefficients of each basic event, and the coefficients are arranged in order of importance. The second is to use the minimum cut set and the minimum diameter set. Approximately determine the size of the structural important coefficients of each basic event and arrange the order. This paper uses the second method to analyze the safety accidents of the tower crane. The principle of sorting is: (1) When the number of basic events in the minimum cut (diameter) set is equal, the more basic events that appear repeatedly in the minimum cut (diameter) set, the greater the structural importance; (2) When the number of basic events in the minimum cut (diameter) set is not equal, the events in the cut (diameter) set with fewer basic events are more important than the basic events in the cut (path) set with more basic events; (3) In the minimum cut (diameter) set with few basic events, the event with fewer occurrences is compared with the one with more occurrences in the minimum cut set (diameter) with more basic events, and the former is generally larger than the latter. There are 9 minimum cut sets of the tower crane safety accident tree, and the order of structural importance of each basic event is:

\[ I(X_1) = I(X_2) = I(X_3) > I(X_7) > I(X_{19}) > I(X_8) > I(X_4) = I(X_5) = I(X_6) \]
\[ = I(X_9) = I(X_{10}) = I(X_{11}) = I(X_{12}) = I(X_{13}) = I(X_{14}) > I(X_{15}) = I(X_{16}) = I(X_{18}) \]

4. Tower crane safety risk management

According to the analysis results of the minimum cut set and structural importance of the tower crane accident tree, it can be seen that in order to prevent the safety accident of the tower crane, it should be started from the aspects of preventing overturning (collapse) accident, broken arm folding arm accident, falling object accident and collision accident. And it is necessary to control the occurrence of each bottom event, especially the bottom event with a large structural importance factor, such as "failure of foundation bearing capacity", "failure of tower structure resistance", "improper operation of lashing or lifting", "failure of monitoring equipment", "There are blind spots in hoisting operations", "fatigue cracks on chords" and "failure of connection between components". In response to these 7 important factors, the relevant management and control measures are proposed as follows:

1. Failure of foundation bearing capacity

In addition to its own gravity, the tower crane also has to bear the pressure brought by heavy objects when lifting. Therefore, insufficient foundation bearing capacity is an important reason for the tower crane's overturning. For this reason, the strength of the concrete used for the foundation must reach the standard, and avoid the rain erosion of the tower crane foundation at the same time to ensure the foundation bearing capacity. In addition, the fixed tower crane mostly fixes the foundation section or foundation of the tower crane with embedded legs or bolts. This embedded part can only be used once.
When replacing it, the same model components must be purchased from the same manufacturer, otherwise the connection may occur breaking, causing the tower crane to overturn.

2) The resistance of the tower body structure fails

There are two main reasons leading to the failure of the resistance of the tower body structure. One is that the strength of the tower body itself is insufficient, and the other is the failure of the connecting parts. To this end, the quality of the main components of the tower crane must be ensured before leaving the factory. Regular maintenance should be carried out during use. And the tower crane should be avoided from working on the construction site for a long time, otherwise the structure and connections of the tower body are prone to fatigue damage, causing the tower to break.

3) Improper binding or lifting operations

During the hoisting process, due to the lack of danger awareness and professional skills, the workers caused improper binding or lifting operations, which resulted in the accident of falling objects in the tower crane. Therefore, it is necessary to strengthen safety education for workers and organize regularly professional technical training and professional skills examinations. In addition, virtual simulation technology can be introduced. By simulating the construction environment, not only can workers learn standard operating procedures, but they can also truly experience the consequences of accidents caused by illegal operations without being injured.

4) Failure of monitoring equipment

In order to ensure the normal operation of the monitoring equipment, it is necessary to arrange professionals to regularly check and maintain the equipment to ensure the performance of the monitoring equipment and make it sensitive and reliable.

5) There is a blind spot in the lifting operation

Although there are currently tower crane monitoring equipment, there is still a problem of visual blind spots during the operation of the tower crane driver. The traditional solution is to complete the operation based on experience and the signal-bearer command on the ground. This leads to an increase in the driver's work intensity, and a little carelessness will cause a safety accident. Under the current research background of smart construction sites, a new type of intelligent tower crane video surveillance system can be designed to circumvent this problem.

6) Existing fatigue cracks on the chord

The tower crane has been working on the construction site for a long time and the task is heavy, resulting in cracking of the connecting weld, structural fatigue damage, and cracking. Therefore, it is necessary to strengthen the safety inspection, find cracks in the tower arm in time, and avoiding the operation of the tower crane with disease, buried hidden dangers for the tower crane safety.

7) Failure of connection between components

The connection method between tower crane components is mainly bolt connection, and high-strength bolts are mainly used, and repeated use is prohibited. However, due to the large amount of high-strength bolts used in the tower crane and the high cost, most units are used illegally. In addition, the tower crane has been working on the construction site for a long time and has a lot of work content. It is easy to cause fatigue damage to the connection members and the connection parts will also be loose. Therefore, regular maintenance and inspection of the connection members and the connection structure are required.

5. Conclusion

(1) Through a large number of statistical analysis of tower crane safety accident cases, the impact factors of tower crane safety risk are summarized from the whole process of the tower crane of installation-use-dismantlement.

(2) Combining the accident cause theory, dig layer by layer from the human-machine-environment-management to the middle event and the bottom event leading to the top event, thus establishing a tower crane accident tree model.

(3) Through a qualitative analysis of the risk of tower crane safety accidents, the minimum cut set of the tower crane safety accident tree is calculated, and a total of 9 paths that affect the occurrence of top
events are obtained. It can be seen that there are many ways of tower crane safety accidents and the safety management is more complicated.

(4) According to the analysis of the minimum cut set, the structural importance of the 19 basic events is ranked, and then the factors that have a greater impact on the top event are the failure of the basic bearing capacity, the failure of the tower structure resistance, the improper binding or lifting operation, monitoring equipment failure, dead zone in hoisting operation, existing fatigue cracks on chords, and failure of connection between components. Based on this, it can provide an effective basis for the safety management of tower cranes.

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References
[1] Ren, L.L. (2018) Research on the dynamic evolution of safety risk in the whole process of building construction crane. Huazhong University of Science and Technology.
[2] Zhao, T.S., Zhou, W., Xu, K., He, L.Y. (2019) Analysis of influencing factors of tower crane safety in construction engineering. Industrial Safety and Environmental Protection., 45(02): 17-22.
[3] Zhang, X.Q. (2012) Research on safety evaluation of tower crane based on analytic hierarchy process. Journal of Fujian Institute of Technology., 10(03): 302-306.
[4] Shin, I.J. Factors that affect safety of tower crane installation/dismantling in construction industry[J]. Safety Science, 2015, 72:379-390.
[5] Zhao, T.S., Zhou, W., Xu, K., He, L.Y. (2019) Safety risk analysis and Bayesian model of tower crane in use stage. Science and Technology and Engineering., 19(11): 350-356.
[6] Ding, K., Hu, H., Gao, Z.F. (2010) Identification and analysis of accident safety risk factors of tower cranes. Construction Technology., 39(11): 110-112.
[7] Yu, Q.Z., Sun, B.W., Luo, H.B., Zhou, R., Li, Y.W. (2015) Statistical analysis of tower crane accidents. Construction Safety., 30(11): 10-13.
[8] Li, W.Z., Li, J.F., Wang, Y., Song, W.H. (2020) Research on the leakage risk of petrochemical enterprises based on Bayes-accident tree. Journal of Nankai University (Natural Science Edition.), 53(01): 12-16.
[9] Yang, Y.L., Ren, W., Li, X., Shi, J.R. (2012) Accident tree analysis of campus trampling incident. Safety and Environmental Engineering., 19(02): 125-127+131.
[10] Xin, J.Q., Xia, Z.K., Gao, Y.L., Shi, T., Zhang, Y., Zhai, Y.G. (2014) Analysis of the causes of power theft losses based on the accident tree. Journal of Electric Power System and Automation., 26(03): 47-51.