Cause analysis of bridge erecting machine tipping accident based on fault tree and the corresponding countermeasures

LI Xiangyang*, ZHAN Jing, JIANG Fuliang, WANG Shuyun
School of Environment Protection and Safety Engineering, University of South China, Hengyang 421001, Hunan, China

Abstract

Bridge erecting machine has been widely used nowadays with its efficiency, while just as a coin has two sides, it also brings problem. If a rollover happens, it will lead to equipment damage, casualties or other disastrous accidents. How could technicians take measures to prevent accidents as efficiently as possible? Question remains unsaved. Based on the analysis of “10.26” bridge erecting machine tipping accident, this paper gives a qualitative analysis on the accident by using fault tree analysis. Firstly, fault tree diagram for the bridge erecting machine tipping, namely the causal and generalization relation between events is formulated. All the basic events that influence the way and the degree of the accident are identified, and these can be ascribed to the following three aspects: manufacturing defect, personnel operating error and management oversight. In terms of management oversight, the responsibility of construction unit, safety supervision department and supervision unit are of great importance. Secondly, combining the minimal path set with the structure importance, we conduct a qualitative analysis on the personnel casualties resulted from the accident, thus seek critical approaches to accident prevention. Finally corresponding safety control measures are put forward. It is noteworthy that the approach can be applied in the similar accidents entirely.

Keywords: bridge erecting machine tipping; fault tree analysis; minimal path set; structural importance; countermeasure

1. Introduction

Reportedly, the rate for Chinese special equipment accident remains high all the time, which is still 5–6 times higher than industrialized countries. The situation is still grim [1]. Bridge erecting machine has been extensively used in bridge engineering owe to its high efficiency. In recent years, though the accident number and deaths in ten thousand units decreased continuously, the absolute number of deaths increased at varying degrees, compared with the same period, for the increasingly use of special equipment. It belongs to the large equipment of bridge construction, which generally mounted on the surface of narrow construction site, this will result in tipping more easily. It not only brings huge property loss, but also threatens life safety. Therefore, it is of great significance to identify the root reasons of tripping in the process of construction.

On the basis of the situation about the “10.26” bridge erecting machine tipping accident in a highway, we make a FTA (fault tree analysis) to search for the main causes and potential factors of the accident, and to represent logical dependency of these basic causes in leading to the event [2]. These have certain value to enhance the safety during the design stages, make safety technical measures and take security management measures. Additionally, these are also useful to prevent the similar accidents.

* Corresponding author. Tel.: +86-13786480277.
E-mail address: lcczclxy@126.com

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2. Accident overview and investigation results

2.1. Accident overview

On October 26, 2011, a bridge erecting machine tipped on a highway bridge girder construction site, the accident resulted in one dead and two wounded, moreover, one QJ30–100 type bridge erecting machine was damaged. The bridge erecting machine was produced by a lifting equipment company in August, 2010, and the construction unit made a second installation in August, 2011, what’s more, it passed the qualified test of special equipment inspection institution.

2.2. Results investigation

(1) Lifting mechanism, girder and the front supports capsized on the south of 3–4th pier. Fig.1 is the scene of the accident.

(2) The 4th joint of walking beam (4×6 m) fractured and fell on the 4th pier, supporting sleepers damaged, the fixed front leg hoist rope fractured. Fig.2 is the fractured front leg of the bridge erecting machine.

3. Fault tree analyses

3.1. Fault tree analysis principle

Accident tree analysis which is a deductive system safety analysis method is also named fault tree analysis. This method has expressed the logical relationship between the possibility of certain accident and the causes of undesired events or accidents in fault tree diagram [3]. On the ground of the fault tree qualitative and quantitative analysis, the root causes of the accident can be reached, at the same time, these can also provide a reliable basis to make safety countermeasures.

![Fig.1. Scene of the accident.](image1)

![Fig.2. Fractured front leg of bridge erecting machine.](image2)

3.2. Fault tree diagram

The fault tree analysis about “10.26” bridge erecting machine tipping accident is followed FTA principle. By means of the FTA, the reasons for the accident are actually quite obvious. The top event number is $T_0$, the intermediate events are numbered from $M_1$ to $M_5$. The basic events are numbered from $X_1$ to $X_{17}$, which have considered the person, machine and management factors [4]. The fault tree diagram is shown in Fig.3 and the meaning of each sign in Fig.3 is shown in Table 1.

3.3. Calculating minimal path set

According to the discrimination method of the maximum number of minimal path set, this tree has more “or gate” and less “and gate”, then, it is more convenient to apply the minimal path set to qualitative analysis. The success tree about the fault tree is made in compliance with the De Morgan laws of Boolean algebra [3]. The function of its success tree minimal cut set gotten by Boolean algebraic simplification method is as follows.

Success tree structure function expression:

$$T_0' = M_1' + M_2'$$

$$= X_1'X_2' + X_3'X_4'X_5' + X_6'X_7'X_8' + X_9'X_{10}'X_{11}'X_{12}'X_{13}'X_{14}'X_{15}'X_{16}'X_{17}'$$

$$P_1 = \{X_1, X_2\}, P_2 = \{X_3, X_4, X_5\}, P_3 = \{X_6, X_7, X_8\}, P_4 = \{X_9, X_{10}, X_{11}, X_{12}, X_{13}, X_{14}, X_{15}, X_{16}, X_{17}\}$$

The fault tree minimal path sets:

$$P_1 = \{X_1, X_2\}, P_2 = \{X_3, X_4, X_5\}, P_3 = \{X_6, X_7, X_8\}$$

$$P_4 = \{X_9, X_{10}, X_{11}, X_{12}, X_{13}, X_{14}, X_{15}, X_{16}, X_{17}\}$$
Table 1. Meanings of each sign in Fig.3

| Sign | Meaning                                      | Sign | Meaning                                      |
|------|----------------------------------------------|------|----------------------------------------------|
| $T_0$ | Bridge erecting machine tipping casualties   | $M_1$ | Personnel at the scene                       |
| $M_2$ | Bridge erecting machine tipping              | $M_3$ | Manufacturing defect                         |
| $M_4$ | Personnel operating error                    | $M_5$ | Management oversight                         |
| $M_6$ | Construction unit management oversight       | $M_7$ | Safety supervision departments management oversight |
| $M_8$ | Supervision unit supervision negligence      | $X_1$ | Lacking of safety knowledge and experience   |
| $X_2$ | Thin safety awareness                        | $X_3$ | Welding process unqualified                  |
| $X_4$ | The factory equipments detection inadvertent |       |                                              |
| $X_5$ | Not trial lifting                            | $X_7$ | Without permission of hoisting               |
| $X_6$ | Not wearing seat belts                       | $X_9$ | Personnel safety training, education is not enough |
| $X_{10}$ | Deficiency of safety inspection              | $X_{11}$ | Deficiency of site safety management        |
| $X_{12}$ | Deficiency of equipment repair and maintenance | $X_{13}$ | Non-strict examination about the operators |
| $X_{14}$ | Inspection testing institution inadequate supervision | $X_{15}$ | Quality inspection departments lacking of regulation |
| $X_{16}$ | Site supervision personnel dereliction of duty | $X_{17}$ | Supervision system imperfection              |

$T_0$ —intermediate events; $X$ —basic events; $\square$ —and gate; $\bigcirc$ —or gate

Fig. 3. Fault tree diagram.

3.4. Structure importance analysis

Generally, the minimal cut set and minimal path set in fault tree are used to judge the basic events structure importance. Sometimes it is difficult to have an accurate estimation of the failure rate of individual event or the probability of occurrence of undesired events due to a lack of sufficient data. Besides, the basic events in the most sets are not repeated; we can suppose the occurrence probabilities of basic events are the same [5]. Owning to the structure importance of general guidelines, the structure importance of basic events can be judged approximately as following [6–7]:

$$I_{\Phi}(1) = I_{\Phi}(2) > I_{\Phi}(3) = I_{\Phi}(4) = I_{\Phi}(5) = I_{\Phi}(7) = I_{\Phi}(8) > I_{\Phi}(9) = I_{\Phi}(10) = I_{\Phi}(11) = I_{\Phi}(12) = I_{\Phi}(13) = I_{\Phi}(14) = I_{\Phi}(15) = I_{\Phi}(16) = I_{\Phi}(17)$$

3.5. FTA results and prevention

(1) From the fault tree logic gates, numbers of and gate more than the number of or gate. Therefore, the system’s risk is relatively large from the proportion of logic gate number [8].
(2) From the aspect of basic events. There are total 17 basic events causing the accidents. To be more specific, among them only “the unqualified equipment welding process” is related to the devices, while human unsafe behaviour and the oversight management accounts for the majority. Compared to factors, human factors show a lower reliability. So we should take the people, machine, management factors into account to prevent the accidents, especially focus on strengthening the safety management.

(3) From the minimal path set, there are four minimal path sets. As long as the basic events in \( P_i \) do not happen, the accident will not happen, besides, it also provides four efficient ways to prevent the accident \([7]\).

(4) From the consideration of structure importance, different event of the system has different structure importance. The basic event \( X_1, X_2 \) have the biggest structure importance, which have the greatest impact on its top event, meaning that it is the most favourable control approach, followed by \( X_3, X_4, X_5, X_6, X_7, X_8 \), once again \( X_9, X_{10}, X_{11}, X_{12}, X_{13}, X_{14}, X_{15}, X_{16}, X_{17} \).

4. Countermeasures

(1) Some measures such as strengthening the safety management, setting the safety warning signs or prohibiting persons into the dangerous zone should be put in to practice to prevent workers from staying at the scene unconsciously.

(2) Construction unit can ameliorate safety production responsibility system, by enhancing staff’s safety and responsibility consciousness, reinforcing the safety education and training to staff. We can also improve staff’s capacity of emergency and escape by conducting regular emergency drills \([6]\).

(3) Production unit should constantly improve the quality management system. Product performance, specifications and others should be consistent with existing national standards and design requirements. Construction units should be strictly in accordance with the requirements of equipment instruction and inspection.

(4) Safety supervision departments should strengthen safety supervision work, strengthening not only the supervision of illegal behaviour, but also the equipments supervision and inspection. It must be also strict to the examination and review of operators’ qualification certificates. The safety supervision responsibilities about the special equipments during seven processes of manufacturing, installation, renovation, repair, use, inspection and scrapped are jointed seamlessly.

(5) The special equipment installation should be strictly consistent with the requirements of GB 26469—2011 Bridge erecting machine safety regulations. It has to test and inspect equipments after installation and before lifting every time. At the same time, strengthen regular maintenance and inspection about the equipments.

5. Conclusions

(1) In this paper, we first briefly adopt FTA to analyze the bridge erecting machine tripping accident. An effective method is provided to analyze the other similar accidents. The fault tree, utilizing the logic gate, provides a complete cause–consequence analysis diagram of the accident. It has certain reference value to prevent similar accidents.

(2) Accidents are always resulted from potential safety hazards, including unsafe conditions of equipments and person unsafe behaviours. Therefore, we can efficiently prevent accidents from the person, equipments and management factors. Especially safety supervision, the safety supervision responsibilities of seven processes about special equipments must be jointed seamlessly.

(3) Worthy of mentioning, the probabilities of the basic events are not sure, the qualitative analysis of this paper based on hypothesis that the occurrence probability of basic events are the same, and the quantitative analysis need to be further discussed.

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