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ANALYSIS OF CONSTRUCTION ACCIDENTS USING FAULT TREES

Arocho, Ingrid[1, 3] and Yang, Rebecca[2]
[1] Oregon State University, USA
[2] Oregon State University, USA
[3] Ingrid.Arocho@oregonstate.edu

Abstract: Construction is one of the most hazardous industries in the United States, accounting for 20% of all labor related deaths in the country. Heavy civil construction, including transportation infrastructure projects, account for 20% of the fatalities in the construction industry. The objective for this study is to identify the most frequent causes for accidents in transportation infrastructure projects using fault tree analysis. This methodology will allow the study of the causes for each accident and the interaction between causes. The data used was collected from OSHA's Integrated Management Information System that includes Fatality and Catastrophe Investigation Summaries. The summaries were collected from transportation construction projects located in Oregon, Idaho, Alaska, and Washington. The methodology used included the creation of a fault tree using causes identified from the summaries and performing root cause analysis. The results from this study show that the most frequent type of accident is struck by/against. The most common causes of accidents for struck by/against accidents were misjudgment and inappropriate procedures. The results from this study could support construction professionals on transportation infrastructure projects to improve safety on the construction site. A better understanding of the most common accident types and the events that caused them can offer safety managers the opportunity to prioritize their efforts.

1 INTRODUCTION

The construction industry is seen as one of the most dangerous industries in the United States. The statistics from 2015 show that 937 people died of work related injuries in construction (BLS 2017). This number represents 19% of all work related fatalities in the country, placing construction as the industry with more total fatalities. Taking this statistics into consideration, it is imperative to reduce the number of fatalities and to improve conditions for construction workers.

The current study focusses on accidents that resulted in severe injuries and fatalities during transportation infrastructure projects. Transportation projects present characteristics that could result on unsafe construction environments such as multiple equipment and machinery working on a small site, night shift work, and construction zones that could be invaded by incoming traffic.

The Occupational Safety and Health Administration (OSHA) has developed regulations and programs to ensure a safer environment for all workers. Employers need to report fatalities and serious accidents to OSHA as part of the regulations. An OSHA officer will visit the site of the accident, investigate what happened, and determine the citations relevant to the situation. The accident summaries completed by OSHA inspectors will be used on this study as the principal source of information about each case. OSHA categorizes accidents based on the primary cause of the accident. There are four categories of accidents that account for 64% of all the fatalities in the construction industry (OSHA 2017). These are called the "fatal four" and include falls, struck by/against, electrocution, and caught in/between.

The first objective of this research is to identify the causes of struck by/against accidents. The causes for each accident were identified by carefully reading and interpreting the accident summaries completed by OSHA inspectors. The study will focus on struck by/against accidents because they represented the majority of the accidents that were present on the data collected. Studying the causes for struck by/against accidents could help to significantly reduce the number of fatalities in the construction industry. Transportation infrastructure projects located in Region 10 that includes the states of Washington, Oregon, Idaho, and Alaska were selected for this study.

The second objective of this study is to understand the relationship between the causes using fault tree analysis and minimal cut analysis. Fault trees can be used to identify the order in which the events happened before accidents. The analysis will also show which causes happened by themselves and which ones need to happened in relation with other events.

Previous work has shown the benefit of using fault tree analysis to study accidents on different industries. The methodology presented here shows how fault tree analysis can be applied to transportation infrastructure projects. The study is different from some of the work presented before by using information from OSHA accident investigations to identify the causes of the incidents. The results from this study could be used by construction professionals to improve conditions on the worksite. Having knowledge of the most common causes of accidents and how this causes are related can help to develop programs to reduce accidents and fatalities. A better understanding of the most common causes that are directly related with an accident would allow safety professionals to prioritize their work.

2 LITERATURE REVIEW

The current study uses two methods to identify and analyze the causes of accidents. The first method is to identify the root cause for each accident. Root cause analysis is the study of the cause that starts the chain of events resulting on a problem in a process (ASQ 2017). Root cause analysis can be completed in four major steps. The first step is to collect all the data relevant to the event that is been studied and identify the causes. The second step is to develop a chart that includes all the causes identified on the previous step. The third step is to identify the root causes for the event. The fourth step is to generate recommendations based on the findings. The objective of this process is to understand the main event and how it happened but also to identify why it happened (Rooney and Vanden Heuvel 2004).

Research has been done in the past to study construction accidents using root cause analysis. Abdelhamid and Everett (2000) developed the Accident Root Cause Tracing Model (ARCTM) based on the idea that there are three basic causes for accidents: failure to identify unsafe conditions, workers response to unsafe conditions, and workers' unsafe acts. The authors used this model to study accident reports from the Michigan Department of Transportation. The study presented here uses the root cause analysis method to identify all the causes for the accidents.

The second method used is fault tree analysis. The use of fault trees will help to understand the relationship between the all the causes. Fault tree analysis was developed for the US Air force to analyze the reliability of missiles. The tree starts with a main event on the top and branches are added to represent intermediate and root causes. The root causes of an event will be found at the bottom of the tree (NASA 2002). The causes are related using Boolean algebra AND and OR gates. Causes connected by an AND need to occur together to result on the event. An OR connection means that at least one of the causes presented needs to occur to result on the event.

Previous work has been completed to apply Fault Tree Analysis to construction operations. A fault tree expert system was developed by Hadiprioni (1992) to study falls from elevator floor openings during the construction process. The causes used for this study were determined by the author based on previous work but do not correspond to any particular accident. The author divided the causes of the accidents in four categories: worker's enabling causes, worker's triggering causes, naturally induced impacts, and worker's support related causes. Chi et al (2014) collected information for 411 fatalities due to falls in Taiwan construction project between 2001 and 2005. The data was collected from accident reports from

the Labor Safety and Health Inspection agencies in Taiwan. The results from this study showed that the most common causes for accidents were unsafe behavior, unsafe machinery and tools, and unsafe environment.

The fault tree will also be analyzed by identifying minimal cut sets. Cut sets are defined as the combination of events that will cause the main event. Minimal cut set is the smallest set of events that is needed to cause the main event (Fard 1997). Minimal cut sets are important during the qualitative analysis of fault trees because it allows to identify the minimum number of events that need to happen together to result on failure of the system, in this case, a fatal accident (Tang and Dugan 2004).

Previous work has been done to identify the root causes of safety accidents and to use fault trees to understand how these causes affect each other. The contribution of the present study is to apply fault tree analysis to transportation construction projects. The identification of the causes was completed using accident summaries and not from theoretical or simulated information.

3 METHODOLOGY

The first step of this research was to collect the information from the accident summaries. All the cases selected were from OSHA's Region 10 that includes the states of Oregon, Washington, Idaho, and Alaska in the United States. The projects selected were the ones classified as highway, street, and bridge construction (NAICS 237300) by the North American Industry Classification System.

The information was collected from the Integrated Management Information System that includes the Fatality and Catastrophe Investigation Summaries. The summaries were completed by OSHA inspectors and included an accident synopsis report, categories of causes, and OSHA findings. A total of 105 accident summaries were collected from the OSHA office at Salem, Oregon. From these, 41 cases were struck by/against accidents.

The summary for each accident was carefully read and studied to identify all the causes. The primary cause was identified using the OSHA classification of accidents. The intermediate causes were identified by continuously asking why the previous event occurred. The root causes were identified as the first event that caused the chain reaction. For example, the primary cause for an accident was identified by OSHA to be struck by/against. The next step was to ask why the employee was struck by the object. The next cause could be because the construction site had poor layout. The process will continue asking why until there is no additional information on the accident summary. The causes were recorded using the phrases used by the OSHA inspectors. When a cause identified was not well explained by OSHA phrases the authors added additional phrases.

A fault tree was developed for struck by/ against accidents and the probability of each root cause was determined using frequency. Probabilities were calculated by dividing the number of cases that included a particular cause by the total number of cases. The limited information available would not allow to calculate probability using exposure or severity. The summaries do not provide information on the number of workers exposed to the hazard or the victim's pain compared to other accidents

A minimal cut set analysis was performed to identify the groups of intermediate and root causes that need to be present for an accident to occur. Each tree has different minimal cut sets based on the relationship between causes. Small cut sets are more dangerous because fewer events need to happen before an accident occurs. Studying the minimal cut sets can help to identify critical causes that result on more accidents.

4 RESULTS

The resulting fault tree for the struck by/against accidents is presented on Figure 1. The solid lines represent an OR relationship. The dashed lines represent an AND relationship between the adjacent causes. For example, misjudgment and miscommunication should happen together and result on

squeeze point action. The boxes also show the probability based on frequency for each cause based on the 41 cases for struck by/against accidents. The probabilities for causes connected by an AND relationship are divided between the causes. For example, four accidents were causes by squeezed point action. The probability for the root cause is 4/41, however, because of the AND relationship, the two causes need to happen together to cause the main event and the productivity is divided between them, resulting in 4/82 for each.

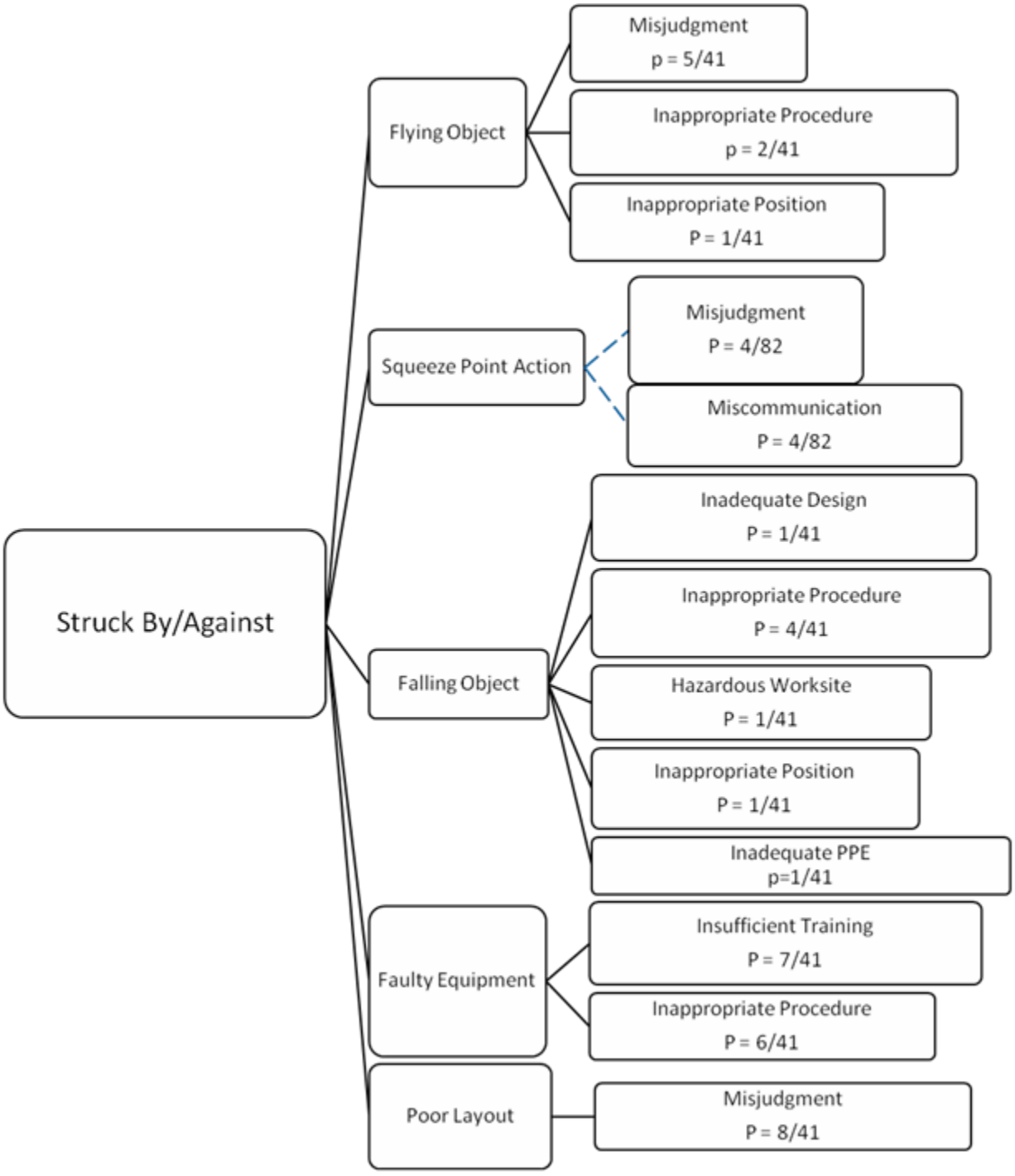

Figure 1 Fault tree for struck by/against accidents

Table 1 presents all the root causes that were identified for struck by/against accidents. The table also classifies each cause as basic or conditional. Basic causes are behavioral causes that can be improve or avoided directly by the workers. Conditional causes result from environmental conditions or from poor design of the construction site. Conditional causes cannot be easily fixed by workers and will require additional managerial decisions. The majority of the causes presented on Table 1 are basic including misjudgement or inappropriate position. Inadequate design and hazardous worksite are the only two conditional causes for these accidents. The most frequent root cause for accidents was misjudgment that occurred on 17 of the accidents followed by inappropriate procedure that occurred on 12 of the accidents.

Table 1 Possible root causes for struck by/against accidents

Type	Description	Probability
Basic	Insufficient Training	7/41
Basic	Inappropriate Position	2/41
Basic	Inadequate PPE	1/41
Conditional	Hazardous Worksite	1/41
Basic	Misjudgment	15/41
Basic	Inappropriate Procedure	12/41
Basic	Miscommunication	2/41
Conditional	Inadequate Design	1/41

Table 2 presents the result for the minimal cut set analysis for struck by/against accidents. The analysis resulted on 11 sets that included only two causes. There were also three sets with three causes. Longer sets represent safer systems where many events need to happen before a severe accident occurs. Table 2 shows that the majority of sets for this type of accidents are small. Misjudgment was included in 3 of the 14 minimal cut sets.

Table 2 Cut sets for struck by/against accidents

Two-Causes	• Flying Object, Misjudgment • Flying Object, Inappropriate Procedure • Flying Object, Inappropriate Position • Falling Object, Inadequate Design • Falling Object, Inappropriate Procedure • Falling Object, Hazardous Worksite • Falling Object, Inappropriate Position • Falling Object, Inadequate PPE • Faulty Equipment, Insufficient Training • Faulty Equipment, Inappropriate Procedure • Poor Layout, Misjudgment
Three-Cause	• Pinch Point, Inappropriate Equipment Use, Insufficient Training • Pinch Point, Inappropriate Equipment Use, Inappropriate Procedure • Squeeze Point, Misjudgment, Miscommunication

The fault tree model was validated using 18 safety accident cases that were not included on the original database. These cases were collected from the National Institute of Occupational Safety and Health (NIOSH) database that includes summaries from numerous cases from different regions of the United States. The fault tree developed was used to describe the causes for the NIOSH cases and the result showed that the trees were compatible. The minimal cut sets developed were sufficient to explain the additional cases. This result is an indication that, even when the model was created using cases from the Pacific Northwest, the results could be used to study accidents from other areas.

5 CONCLUSIONS

The conclusions for this research are directly related to the objective presented above. The first objective was to identify the causes of struck by/against accidents. The cases of severe accidents were studied to determine the primary, intermediate, and root causes for each one. Eight root causes were identified with misjudgement and inappropriate procedures as the most common causes.

The second objective was to understand the relationship between the causes using fault tree analysis and minimal cut sets analysis. The fault tree was created using all the causes identified. The majority of the root causes had an OR relationship with other root causes. The exception are four cases that had misjudgment and miscommunication as root causes with an AND relationship.

The results show that the majority of the root causes are basic causes that could be reduced by helping workers to make better decisions during operations. Misjudgment and inappropriate procedures are events that could be prevented by properly training employees. The training program should include retraining after certain amount of time or as needed because of accidents or changes on the activities performed by each employee. The results from the minimal cut set analysis show that only two or three events need to happen together to result on accidents. Efforts to reduce the two more frequent root cause could result on a reduction of more than half of the accidents presented on the study. For example, even when misjudgment was part of only four of the cut sets, it was a root cause for 15 of the accidents. This information could be used to focus resources on eliminating the most frequent causes and combination of causes to result on greater improvement of safety on site.

The results of this study could be used by construction professionals to improve the safety programs for transportation construction projects. It is valuable to understand that the majority of the accidents studied were caused by workers making the wrong decision when confronted with unsafe situations. Training activities can be improved to increase emphasis on the most common types of accidents and the root causes for them.

The cases presented here were struck by/against accidents on transportation infrastructure projects in the Pacific Northwest of the United States. Future work should be done to study other types of accidents in different geographical areas. The validation work completed suggests that the fault tree analysis could be generalized to other regions, however the number of cases are limited and additional research would be needed.

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References

Abdelhamid, T. and Everett, J. 2000. "Identifying Root Causes of Construction Accidents." *Journal of Construction Engineering and Management*, American Society of Civil Engineering, Volume 126(1), Pages 52-60.

American Society for Quality (ASQ). 2016. “What is Root Cause Analysis (RCS)?” Milwaukee, WI. Accessed February 2017. http://asq.org/learn-about-quality/root-cause-analysis/overview/overview.html

Bureau of Labor Statistics (BLS) 2017. “2015 Census of Fatal Occupational Injuries.” United States Department of Labor, Washington, D.C. Accessed February 2017. http://www.bls.gov/iif/oshwc/cfoi/cfch0013.pdf

Chi, C., Lin, S., and Dewi, R. 2014. "Graphical Fault Tree Analysis for Fatal Falls in the Construction Industry." *Accident Analysis and Prevention*, Volume 72, Pages 359-369.

Fard, N.S. 1997. “Determination of Minimal Cut Set of a Complex Fault Tree.” *Computer and Industrial Engineering*, Volume 33 (1-2), Pages 59-62.

Hadiprioni, F. 1992. “Expert System for Construction Safety I: Fault-Tree Models.” *Journal of Performance of Constructed Facilities*, Volume 6(4), Pages 246- 260.

National Aeronautics and Space Administration (NASA) 2002. “Fault Tree Handbook with Aerospace Applications.” NASA Office of Safety and Mission Assurance, NASA Headquarters, Washington, DC.

Occupational Safety and Health Administration (OSHA). 2017. “Commonly Used Statistics.” United State Department of Labor, Washington, D.C. Accessed February, 2017 https://www.osha.gov/oshstats/commonstats.html

Rooney, J.J. and Vander Hauvel, L.N. 2004. “Root Cause Analysis for Beginners.” *Quality Progress*, American Society for Quality, Volume 37(7), Pages45-53.

Tang, Z. and Dugan, J.B. 2004. “Minimal Cut Set/Sequence Generation for Dynamic Fault Trees.” Proceedings of Annual Symposium Reliability and Maintainability - RAMS, Pages 207-2013, Alexandria, VA, USA.