FAULT TREE ANALYSIS FOR ACCIDENT PREVENTION IN TRANSPORTATION INFRASTRUCTURE PROJECTS

FINAL PROJECT REPORT

by

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16. Abstract Heavy civil construction projects, including transportation construction, account for 20 percent of the fatalities in the construction industry, which is one of the most hazardous industries in the United States. To improve the safety performance of the industry, the objectives of this research are (1) to identify the most frequent types of accidents during transportation infrastructure projects, (2) to identify the root and intermediate causes for those accidents, and (3) to analyze the causes of accidents to identify the relationship between causes. OSHA's Fatality and Catastrophe Investigation Summaries were used to identify accident types and causes for accidents on the Pacific Northwest region. Fault tree analysis was then used to determine the intermediate and root causes for each case. Lastly, cause analysis and minimal cut set analysis were performed to identify the most frequent causes and the relationship between them. Results showed that the most frequent types of accidents were struck by/against an object, caught in/between objects, falls, and electric shock, while the most common causes of accidents were misjudgment, inappropriate procedures, insufficient training, and miscommunication. The minimal cut set analysis indicated that each accident required between two and four causes to happen together to result in a fatality or serious injury. The results from this study are expected to support construction professionals in improving safety in the field, removing common causes of accidents leading to fatalities and serious injuries, and improving safety training procedures.			
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Executive Summary

The construction industry is one of the most hazardous industries in the United States accounting for 20 percent of all labor related deaths in the country. Heavy civil construction, including transportation infrastructure projects, account for 20 percent of the fatalities in the construction industry (BLS, 2013).

To improve the safety performance of the industry, this research targeted (1) identifying the most frequent types of accidents during transportation infrastructure projects, (2) identifying the root and intermediate causes for those accidents, and (3) analyzing the causes of accidents to identify the relationship between causes.

OSHA's Fatality and Catastrophe Investigation Summaries were used to identify accident types and causes for accidents. All the accidents cases were from transportation construction projects on the Pacific Northwest region. Fault tree analysis was used to determine the intermediate and root causes for each case. Cause analysis and minimal cut set analysis were also performed to identify the most frequent causes and the relationships between them.

Results showed that the most frequent types of accidents were struck by/against an object, caught in/between objects, falls, and electric shock. These types of accidents correspond with the Fatal Five identified by OSHA as the most frequent accidents in the construction industry. It was also found that the most common causes of accidents were misjudgment, inappropriate procedures, insufficient training, and miscommunication. The minimal cut set analysis indicated that each accident required between two and four causes to happen together to result in a fatality or serious injury.

The results from this study are expected to support construction professionals on transportation infrastructure projects in improving safety on the construction site because

identifying and removing common causes of accidents can help prevent fatalities and serious injuries. In addition, safety managers and supervisors are expected to use the most frequent causes identified in this study for their safety training programs in order to improve the overall safety performance of their projects.

Chapter 1 Introduction

Construction is one of the most hazardous industries in the United States. The construction industry was responsible for 18.6 percent of all fatal work injuries in 2014, making it the industry with most total fatalities in the country (BLS 2016). The heavy civil section of construction accounts for 20 percent of the total injuries in the industry and employs 985,000 workers (BLS 2013). Heavy civil projects include the construction of bridges, water treatment plants, highways, roads, and other large public infrastructure projects.

Studying the causes of fatalities and serious accidents in construction can help to reduce the number of accidents and to improve safety on construction sites. The most important reason to reduce serious accident and fatalities in the construction industry is to ensure that workers are safe and can go back to their families at the end of the day. In addition to the obvious benefits to safety, reducing accidents and fatalities can help construction companies and the entire industry to reduce costs and increase productivity. Accidents have a direct cost related to them, such as medical costs and worker compensation claims. There are also indirect costs related to an accident that are more difficult to quantify. The additional costs include costs due to reduced productivity, fees related to an extended schedule on a project, and the cost of training new employees.

The present study focuses on accidents that occur in heavy civil construction projects, a major sector in the industry, particularly those related to transportation infrastructure projects. Information was collected from summaries developed by Occupational Safety and Health Administration (OSHA) officials during the investigation of fatalities and severe injury accidents. All of the cases used for the analysis were located in the Pacific Northwest region.

This study had three objectives. The first objective was to determine frequent and severe accidents in transportation infrastructure projects. The second objective was to identify the causes of the accidents. The third objective was to use fault tree analysis to study the relationships among the causes that were identified. Root cause analysis was also used to determine the relationships between different causes and the risks associated with them. Lastly, minimal cut set analysis was performed to determine the different combinations of causes that can result in a severe accident.

The results from this study can be used by construction professionals to reduce the number of accidents during heavy civil construction projects. Information about the most common causes of accidents can be used by project managers and safety managers to prioritize their work. Causes that are related to the largest numbers of accidents can be identified and mitigated to contribute to accident prevention.

Chapter 2 Literature Review

This section presents an extensive literature review that was performed at the start of the study. The section is divided into the different topics that were researched to ensure a thorough review.

2.1 Heavy Civil Construction

Heavy civil construction is a term that includes the construction of infrastructure including bridges, roads, canals, and airports. Transportation infrastructure projects are a major part of heavy civil construction projects. Safety on roads and highway construction projects is very important. It is known that some heavy civil construction is done during the night to reduce the impact to traffic, resulting in added complications to the safety aspect of the work. Between 2003 and 2010 there were 962 fatalities on transportation infrastructure projects (Pegula 2013).

2.2 Occupational Safety and Health Administration

The Occupational Safety and Health Administration (OSHA) was created in 1970 to enforce safety regulations and establish safety standards that need to be followed by industry in the United States. During the decades since OSHA's foundation, work place fatalities were reduced by 62 percent and injuries by 42 percent (Hinze 2011). OSHA has officers that are responsible for visiting workplaces and making sure that all the regulations are followed. However, the number of officials available is not enough to visit every single work location. OSHA officers need to prioritize their work and normally focus on reporting imminent danger, investigating fatalities, addressing employees' complaints, responding to agencies referrals, and targeting inspections.

When an accident occurs, OSHA officers will visit the site, write an accident narrative explaining what happened and the immediate causes of the accident, and classify the accident based on OSHA categories. Firms are required to report severe accidents in the OSHA 300 log. From 1996 to 2014, firms were required to report any fatality or hospitalization of three or more employees within eight hours of the accident. In 2015 the requirement was changed to prescribe that accidents that resulted in hospitalization of one or more employee, amputation, or loss of an eye needed to be reported within 24 hours of the accident. Fatalities need to be reported within eight hours (OSHA 2016b). All the accidents used in this study occurred before 2015, during the period when the old reporting regulation was in place. OSHA uses the Integrated Management Information System (IMIS) to store information from fatalities and serious injuries reported by industry. The accidents summaries used in this study were collected directly from IMIS.

OSHA has identified falls, electrocution, struck by or against an object, and caught-in/between objects as the leading causes of death in construction, resulting in a combined 57.6 percent of construction fatalities (OSHA 2016a). Fall accidents include falls from elevations as well as falls at the same level. Electric shock accidents are caused by getting in contact with electric lines or live circuits as well as lightning strikes. Struck by/against object accidents include being struck by a flying or falling object as well as a swinging or rolling object. Caught in/between objects accidents can be caused by cave-ins, machinery, or employees crushed between objects.

2.3 Root Cause Analysis

The American Society for Quality defines “root cause” as the cause that starts the chain of events that creates a problem in a process. The root cause of a problem should be eliminated by process improvements (ASQ 2016). There are many studies that have focused on accident causation using root cause in recent years. Abdelhamid and Everett (2000) studied accident causation and human error theories. They developed the Accident Root Cause Tracing Model (ARCTM) to study the causes of safety accidents. The model is based on the idea that accidents are caused by failure to identify unsafe conditions, workers' response to unsafe conditions, or workers' unsafe acts. They used ARCTM to study three accident reports from the Michigan Department of Transportation. The investigation model can help to answer why accidents occur and how to prevent them in the future.

Burke et al. (2006) studied the effectiveness of different intervention methods to reduce accidents. The methods were classified by the level of worker engagement. The results showed that more engaging training resulted in safer performance from the workers. Less engaging methods such as lectures, pamphlets, and videos were less effective. Engaging training methods included behavior modeling, programmed instruction, and feedback.

Cooper and Philips (2004) performed a study that looked at the perception of safety hazards at manufacturing plants. They surveyed workers' perception of workplace hazards, safety hazards and self-compliance, and safety participation. The results showed that changing unsafe environments and unsafe behaviors was a better approach than changing attitudes and beliefs about safety.

Chi et al. (2005) studied the causes for 9,358 accidents in construction in the United States from 2002 to 2011. The results showed that the most frequent root causes for construction accidents were unsafe worker acts and unsafe working conditions. Unsafe worker acts included misjudgment and inappropriate operations. Unsafe working conditions included characteristics of the construction site such as unsafe work surfaces as well as other factors such as inclement weather.

2.4 Fault Trees Analysis

Fault tree analysis (FTA) is s method of deduction developed for the US Air Force by Bell Telephone Laboratories for missile reliability analysis. The FTA is often used to increase safety and reliability and for accident investigation. The trees start with a main event on the top. From there, branches are added that lead to intermediate causes and root causes that are at the bottom of the tree. Fault trees can be used to prioritize the causes of an accidents and to optimize the safety of systems (NASA 2002).

The causes on a fault tree are connected by Boolean algebra AND and OR gates. An AND gate means that an event will occur if all the causes connected occur. An OR gate means that the event will occur if any of the causes connected occur. An example of a fault tree is presented on figure 2.1. This tree shows that there are two paths that result in a break fail. The first path is caused by the brake pads failing. The second one is if all the sensors, controllers, and actuators fail together.

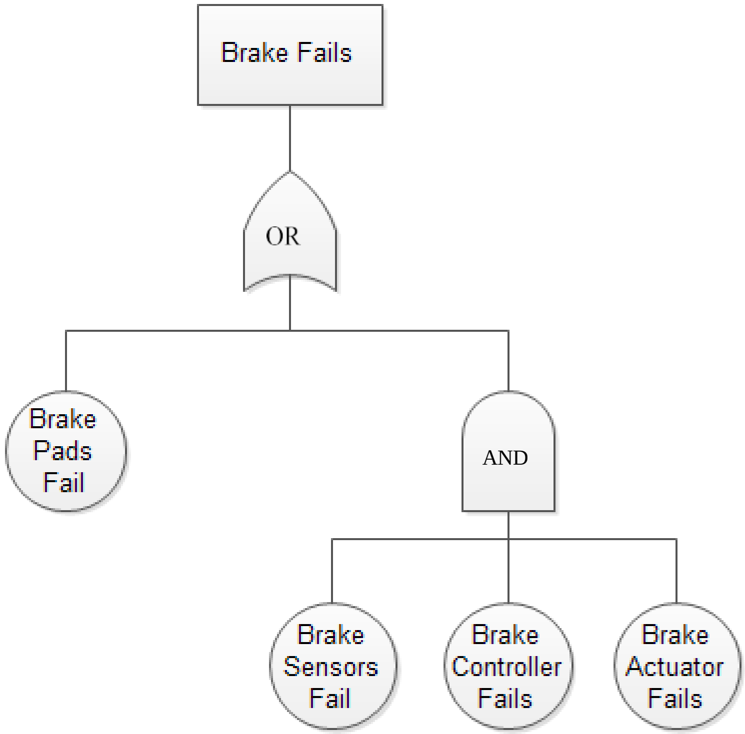

Figure 2.1 Fault tree structure (Image from CET 2016)

Hadiprioni (1992) used a fault trees expert system to study falls from elevator floor openings during construction projects. The study showed that the accident causes can be divided in four categories. The first category is workers' enabling causes, including attitude, health, and skill-related issues. The second category is workers' triggering causes, which includes human-induced impacts with equipment, materials, or other workers. The third category is naturally induced impacts, for example, impacts caused by strong winds. The last category is workers' support-related causes, including failure of structures and components.

Chi et al. (2014) used fault trees analysis to study 411 fatal construction falls in Taiwan from 2001 to 2005. The study results showed that unsafe behavior, unsafe machinery and tools, and unsafe environment were the most common causes for the fall accidents.

Even though fault tree analysis has been used in many different studies, it has not been applied to the construction of transportation infrastructure projects before. Previous research has been completed using theoretical or simulated information. The study presented here will use actual information from serious accidents reported to OSHA.

Chapter 3 Methodology

The study presented here was completed by following three research tasks: data collection, fault tree analysis, and minimal cut sets analysis.

3.1 Data Collection

The data collection task consisted of the identification and analysis of severe accidents that occurred on transportation construction sites in the Pacific Northwest region. All the cases selected were in Region 10 based on OSHA's divisions, which includes the states of Oregon, Washington, Idaho, and Alaska. The North American Industry Classification System (NAICS) was used to select projects in Highway, Street, and Bridge Construction - NAICS 237300. NAICS was developed by the US Economic Classification Policy Committee, Statistics Canada, and the Instituto Nacional de Estatística y Geografía of Mexico. The NAICS sectors are used to classify businesses all across North America (USCB 2016). The study presented here focused on the most serious cases that included fatalities or multiple hospitalizations.

The cases were collected from the OSHA office in Salem, Oregon. The information was collected from the Integrated Management Information System (IMIS) that includes Fatality and Catastrophe Investigation Summaries. The summaries included an accident synopsis report, categories of causes, and OSHA findings pertinent to the accident. The summaries were completed by an OSHA inspector during the investigation that occurred after the accidents were reported. The summaries also included investigation findings, citations, and other actions that the employer needed to take after the investigation. A total of 105 summaries were collected and used for this study.

3.2 Fault Tree Creation

The summary for each case was carefully studied to understand the accident and the causes that resulted in a severe injury. The primary cause for each case was identified as the direct cause of the accident. The intermediate causes were identified by figuring out why the previous cause occurred based on the primary cause. The process was continued until no more causes were present on the summary. The final cause for each accident was identified as the root cause. Intermediate and root causes were reported using the root phrases that OSHA inspectors provide on the report. Table 3.1 shows the root phrases with their definition. Additional phrases were used when needed to improve understanding and close gaps where the OSHA root phrases were not enough to explain the details presented on the accident summaries.

Table 3.1 OSHA root phrase definitions

Phrase	**Definition**
Hazardous Worksite	working conditions and environment present hazards to workers
Inadequate Design	design does not follow guidelines and leads to unstable structure
Inadequate PPE	not wearing the minimally required amount of personal protective equipment
Inappropriate Position	not using the correct position for a task
Inappropriate Procedure	not following the correct procedure for a task
Insufficient Training	not having adequate training for a task
Lack of Engineering Controls	not having appropriate design or enclosures to reduce or eliminate hazards to workers
Miscommunication	not communicating effectively with other workers
Misjudgment	not utilizing correct judgment
No Spotter	not having a safety observer designated for watching out for electrical hazards
Poor Layout	ineffectively arranging a worksite

Accidents with the same first cause were grouped to create fault trees. The first causes that were used to create fault trees were caught in/between objects, fall (from elevation), struck by/against an object, and electric shock. The trees included all the intermediate and root causes identified from the case summaries.

Fault trees also show probability for each root cause. There are three different methodologies typically used to calculate probabilities for safety accidents in construction: exposure, severity, and frequency. Calculating probabilities based on exposure requires information on how many workers were exposed to the same type of accident or how many times that victim was exposed to the hazard. However, the case summaries only provide information on accidents that resulted in injuries or fatalities, and so the information was not sufficient to determine the frequency of exposure. Probabilities based on severity are related to the intensity of the victims' pain, and they need to be compared with the severity of other accidents. However, the case summaries do not offer enough detailed information on the medical condition of the victims or other victims of the same type of accident. Therefore, the lack of detailed information made it impossible to calculate probabilities using exposure or severity. As a result, the probability for each root cause was calculated only by using frequency. The number of cases that were caused by a particular root cause was divided by the total number of cases used for that particular fault tree.

3.3 Minimal Cut Sets Analysis

A minimal cut sets (MCS) analysis was performed to all the fault trees. MCS analysis is a methodology that uses the "branches" of the fault trees to identify the different paths that can result in a severe accident. The results of the analysis are groups of intermediate and root causes that need to be present for an accident to occur. Each fault tree has multiple MCS depending on the number of “branches” on each tree and the relationship between causes. Smaller MCSs that have fewer causes could be more dangerous because fewer causes need to happen for a serious injury. MCSs with more causes show a more robust system that requires more events to happen to result in a system failure, which in this case is a severe accident. Studying the MCS for each fault tree can help to identify critical causes that result in more accidents or are present on smaller MCSs.

Chapter 4 Results

This section presents the results for the fault tree analysis and the minimal cut sets analysis. Figures 4.1 to 4.4 show the fault trees that were developed for the four accidents types that were identified in the accident summaries. The solid lines represent the OR relationship. The dashed lines connected to adjoining boxes represent the AND relationship. For example, in Figure 4.1, misjudgment and miscommunication happen together with an AND relationship and resulted in pinch point action.

The boxes for the root causes (the boxes on the far right) show the probability calculated for each root cause. The probability for the root causes connected with an AND relationship is equally distributed between the two causes. The probabilities are calculated using the frequency of a particular root cause on all the cases used for that fault tree. For example, in figure 4.1 the probabilities for the root causes were calculated based on the 27 cases of caught in/between objects accidents. For more detail, please refer to Yang (2016).

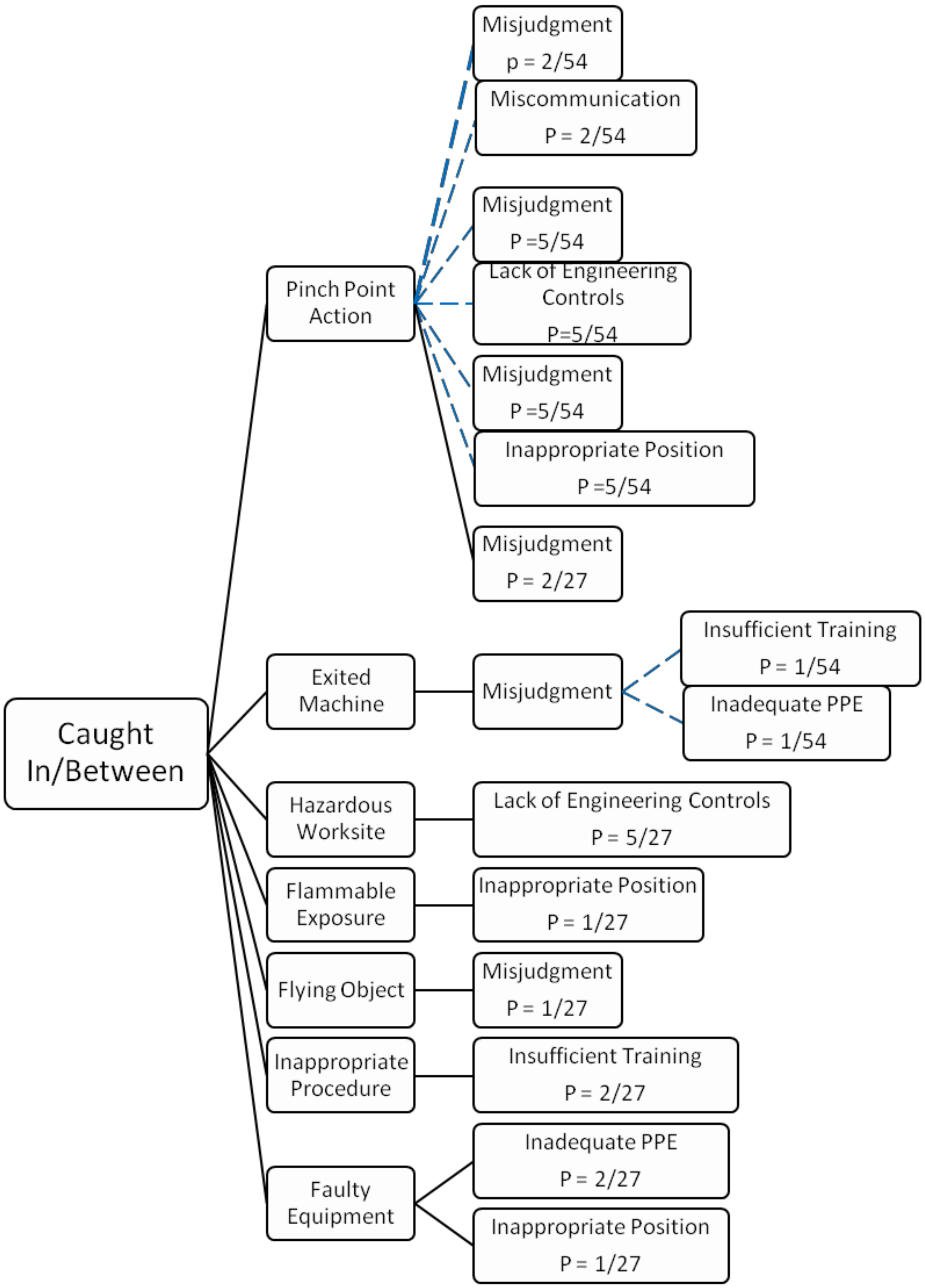

Figure 4.1 Fault tree for caught in/between objects accidents

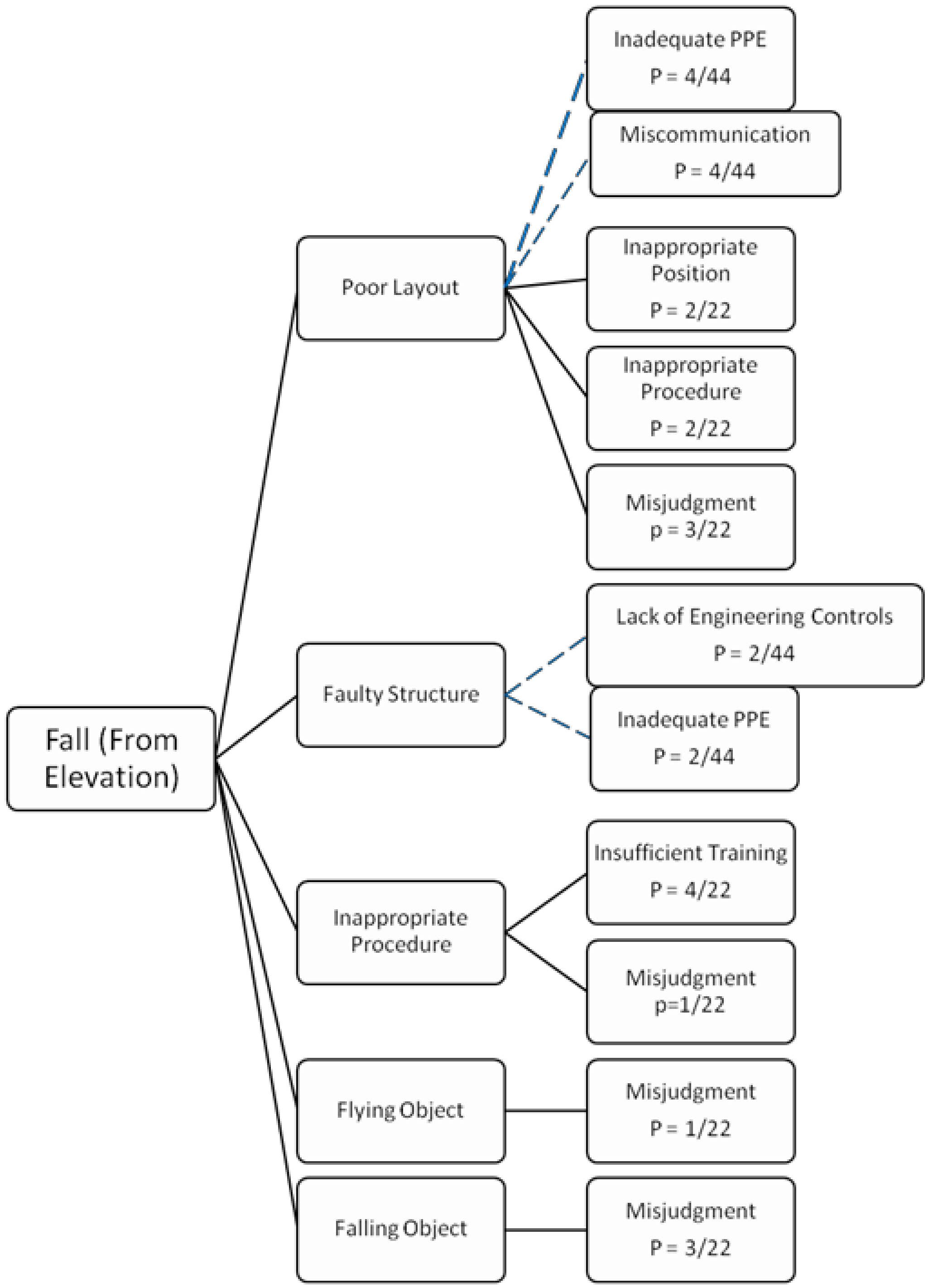

Figure 4.2 Fault tree for fall (from elevation) accidents

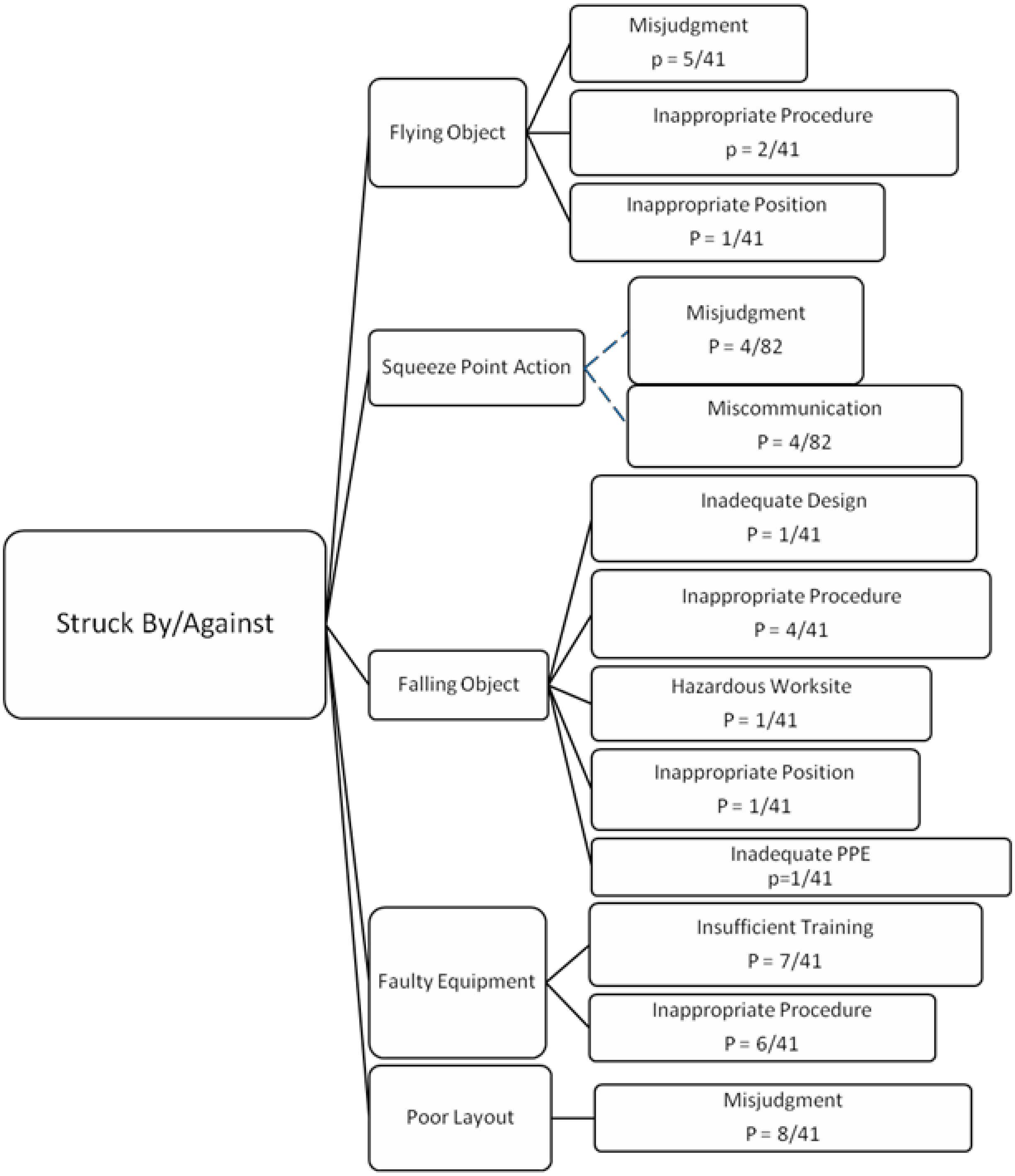

Figure 4.3 Fault tree for struck by/against an object accidents

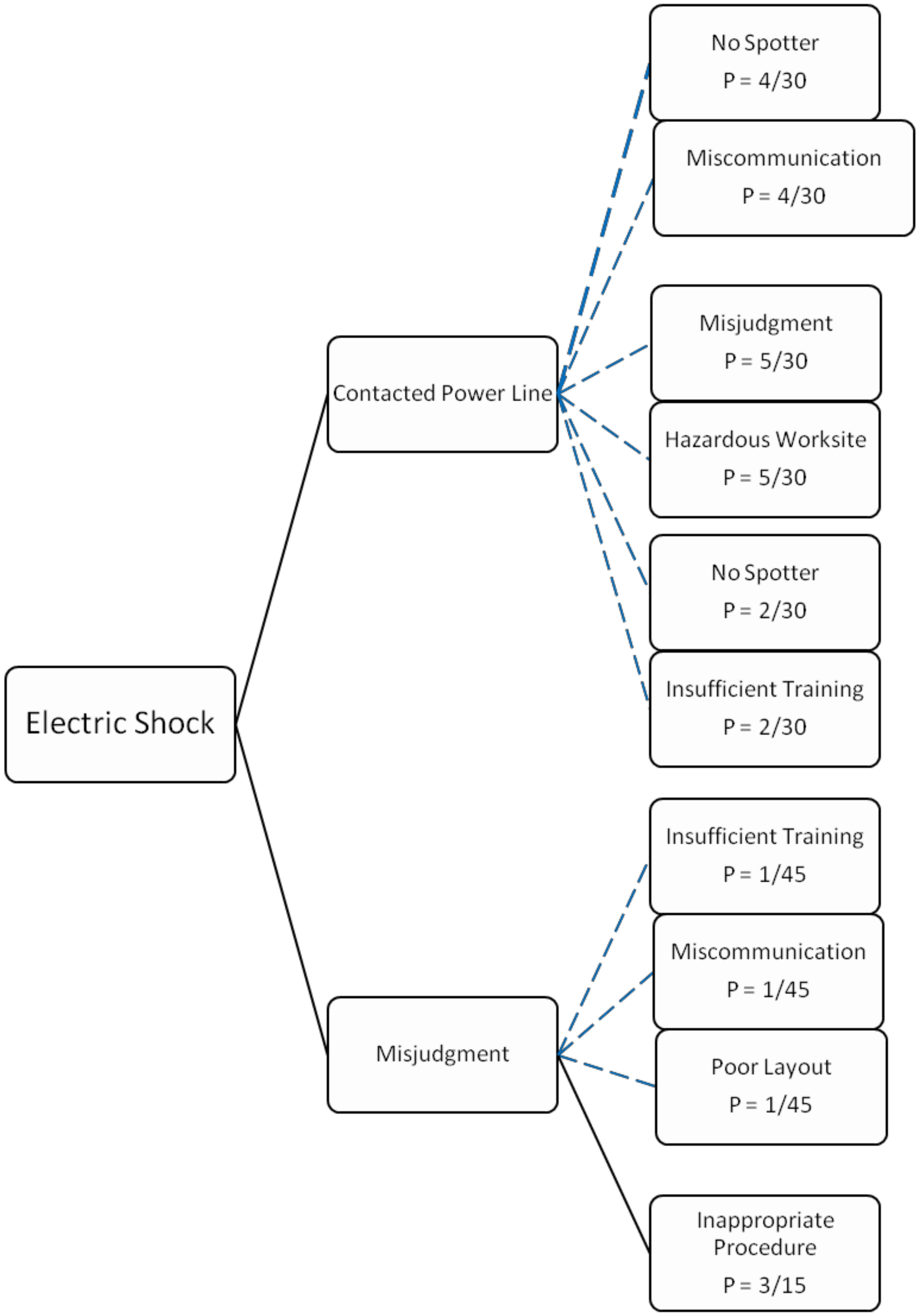

Figure 4.4 Fault tree for electric shock accidents

The results for the minimal cut sets are presented in tables 4.1 to 4.8. The tables present the root causes for each type of accident and the different MCSs that were identified for each tree.

Table 4.1 presents the root causes for caught in/between objects accidents according to the cases presented. The most frequent root cause was misjudgment, with 18 of the 54 cases. Root causes are categorized as basic or conditional. Basic root causes are behavioral and can be avoided when workers change their actions or change the way they react to the environment. Conditional root causes are environmental conditions often caused by poor design. Conditional causes cannot be easily fixed by the worker and require better planning and management of the construction activities. Lack of engineering controls was the only conditional root cause. The other five causes were basic causes.

Table 4.1 Root causes for caught in/between objects accidents

Type	Description	Frequency
Basic	Misjudgment	18/54
Basic	Miscommunication	2/54
Conditional	Lack of Engineering Controls	15/54
Basic	Inappropriate Position	9/54
Basic	Insufficient Training	5/54
Basic	Inadequate PPE	5/54

Table 4.2 shows the MCS that resulted for caught in/between objects accidents. The table shows that seven of the sets had two causes, four sets had three causes, and one set had four causes. The majority of the MCS were short, indicating that only a few events needed to happen to result in a severe caught in/between objects accident.

Table 4.2 Minimal cut sets for caught in/between objects accidents

Two-Causes	• Pinch Point, Misjudgment • Hazardous Worksite, Lack of Engineering Controls • Flammable Exposure, Inappropriate Position • Flying Object, Misjudgment • Inappropriate Procedure, Insufficient Training • Faulty Equipment, Inadequate PPE • Faulty Equipment, Inappropriate Position
Three-Cause	• Pinch Point, Misjudgment, Miscommunication • Pinch Point, Misjudgment, Lack of Engineering Controls • Pinch Point, Misjudgment, Inappropriate Position
Four-Cause	• Exited Machine, Misjudgment, Insufficient Training, Inadequate PPE

Table 4.3 presents the root causes for fall accidents. The most frequent cause was misjudgment, in 16 of the 44 cases. Lack of engineering controls was the only conditional cause, and the other six causes were basic.

Table 4.3 Root causes for fall accidents

Type	Description	Frequency
Basic	Inadequate PPE	6/44
Basic	Miscommunication	4/44
Basic	Inappropriate Position	4/44
Basic	Inappropriate Procedure	4/44
Conditional	Lack of Engineering Controls	2/44
Basic	Insufficient Training	8/44
Basic	Misjudgment	16/44

Table 4.4 shows the MCS for fall accidents. The table shows seven MCSs with two causes and two sets with three causes. Fall accidents require very few events to happen together to result in a severe accident.

Table 4.4 Minimal cut sets for fall accidents

Two-Causes	• Poor Layout, Inappropriate Position • Poor Layout, Inappropriate Procedure • Poor Layout, Misjudgment • Inappropriate Procedure, Insufficient Training • Inappropriate Procedure, Misjudgment • Flying Object, Misjudgment • Falling Object, Misjudgment
Three-Cause	• Poor Layout, Inadequate PPE, Miscommunication • Faulty Structure, Lack of Engineering Controls, Inadequate PPE

Table 4.5 shows the root causes for the struck by/against an object accidents. The most frequent cause was misjudgment, in 15 of the 41 cases. This is the same finding as the previous two accident types. In this case, there were two conditional causes: hazardous worksite and inadequate design. The other six causes were basic.

Table 4.5 Root causes for struck by/against an object accidents

Type	Description	Frequency
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 4.6 shows the MCSs for struck by/against an object accidents. Eleven sets had two causes and three sets had three causes.

Table 4.6 Minimal cut sets for struck by/against an object 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

Table 4.7 presents the root causes for electric shock accidents. The most frequent causes were not having a spotter and inappropriate procedures, in 18 of the 90 cases. Not having a spotter is a unique root cause that is not relevant to the other accident types. Two of the causes were conditional (hazardous worksite and poor layout) and the other five were basic.

Table 4.7 Root causes for electric shock accidents

Type	Description	Frequency
Basic	No Spotter	18/90
Basic	Miscommunication	14/90
Basic	Misjudgment	15/90
Conditional	Hazardous Worksite	15/90
Basic	Insufficient Training	8/90
Conditional	Poor Layout	2/90
Basic	Inappropriate Procedure	18/90

Table 4.8 shows the MCSs for electric shock accidents. Four of the sets had two causes and one set had four causes. There were fewer MCSs that resulted in severe electric shock accidents, and the majority of them were very small.

Table 4.8 Minimal cut sets for electric shock accidents

Two-Causes	• Power Line, No Spotter, Miscommunication • Power Line, Misjudgment, Hazardous Worksite • Power Line, No Spotter, Insufficient Training • Misjudgment, Inappropriate Procedure
Four-Cause	• Misjudgment, Insufficient Training, Miscommunication, Poor Layout

Chapter 5 Discussion and Analysis

The results from the fault tree and the MCS analyses showed that there were a number of root causes that were common to many of the accident types, including miscommunication, misjudgment, and insufficient training. Misjudgment was the most frequent cause for three of the accidents types and the third most frequent cause for the other type. The most frequent root causes were basic, which means that they were directly related to workers' actions and their response to hazards. For caught in/between objects accidents, misjudgment was related to more than half of the accidents, followed by lack of engineering controls, and inappropriate position. Eliminating these three root causes could reduce the occurrence of a large number of accidents. One of the methods to reduce the occurrence of basic root causes is to ensure that workers are trained in the proper procedures to complete their tasks and how to react to safety hazards.

5.1 Model Validation

The fault trees were developed using OSHA accidents reports from the Pacific Northwest region. The model was validated using additional data to assess the generalizability of the fault trees. The first validation method was to compare the results to other findings from literature.

Chi et al. (2005) studied the causes for fall accidents. The authors showed that the causes for fall accidents are ungraded openings, inappropriate protection, protection removal, bodily actions, improper PPE, tools, defective scaffolding, overexertion, unsafe equipment, and poor work practices. The root causes found on that research can be correlated to the root causes that were found on the study presented herein. Inappropriate protection, protection removal, and improper PPE can be related to inadequate PPE. Unguarded openings, defective scaffolding, and unsafe equipment can be related to lack of engineering controls. Poor work practices can be related to insufficient training. The differences in term selection can be explained by the use of the OSHA root phrases for the study presented here, whereas Chi et al. (2005) used other terms.

Chi et al. (2009) studied electrical accident fatalities. The root causes presented included different forms of contact with power lines and defective equipment. The fault trees also included contact with power lines as an intermediate cause for the accidents. The selection of additional root causes resulted in a more detailed fault tree.

The second method to validate the fault trees was to collect information on additional severe accidents and determine whether they could be explained using the fault trees developed for the OSHA cases. Data wee collected for 42 accidents cases from the National Institute of Occupational Safety and Health (NIOSH). The 42 cases included 18 struck by/against an object accidents, 13 fall accidents, six caught in /between objects accidents, and five electric shock accidents. The accidents occurred on projects located in different areas of the United States. The fault trees were used to analyze each accident corresponding to the accident type. The results showed that the intermediate and root causes for the NIOSH cases were a good fit for the fault tree already created. These results indicate that the analysis presented in this study can be used to analyze other accidents in other regions of the country.

Chapter 6 Solutions and Applications

The previous sections present the results for the fault tree and root cause analyses for serious accidents during transportation construction projects. After studying the causes for the accidents, the next step is to determine how to use the results to reduce accidents on construction sites. One of the methodologies used to reduce accidents on construction sites is to apply the hierarchy of safety control during the planning phase. The hierarchy includes five different actions that can be taken to minimize the effects of a hazardous condition on the construction site: eliminate the hazard, substitute the hazard, engineer controls that will reduce the hazard, use administrative controls to reduce the exposure to the hazard, and use PPE that can protect a worker from the hazard. If the actions are to be listed in order of effectiveness, the best way to protect workers from hazard is to eliminate the situation completely. The least effective way to protect the employees is to rely on PPE, and it should be the last resource after all the other methods are evaluated.

As part of its regulating function, OSHA provides employers with rules and advice on how to maintain safe construction sites, particularly for the Fatal Four accidents. Fall prevention, including guardrails and covering openings, as well as safety nets and harness systems, are some of the ways to prevent falls. Paying particular attention to safety during excavations and confined spaces work can reduce the frequency of caught in/between objects accidents. Routinely checking and maintaining equipment and taking special considerations for moving objects can reduce the frequency of struck by/against an object accidents. OSHA regulations also include rules to determine the distance from power lines for any construction work and the particular considerations needed to reduce the frequency of electric shock accidents. In addition to all the precautions mentioned before, PPE can be used to supplement any of these engineering and administrative measures to increase visibility and further protect workers.

The current study presented the most frequent causes for accidents on transportation infrastructure projects. These results can be used to identify specific methods to reduce accidents for this sector of the industry. A study by Jorgenson (2016), which also looked at the intermediate and root causes for safety accidents, reported that the intermediate causes were related to unsafe conditions, unsafe acts, or chance, while root causes were related to inexperience and lack of training. The study's suggestion on how to reduce accidents was to observe the employee, evaluate whether more training is needed, and act to add training and instruction as needed. These results are in line with the results from the present study because misjudgment was found as a root cause on all four fault trees.

The fault trees and minimal cut set analyses can be used to identify possible actions to reduce accidents. The caught in/between minimal cut sets show that misjudgment is the most frequent root cause. The presence of a pinch point is one of the frequent intermediate causes for these accidents. Improving training addresses both of these causes. A better trained employee should be able to identify safety hazards, such as pinch points, and make decisions that will keep the employee safe. Another intermediate cause presented is faulty equipment. This cause can be effectively minimized by inspecting and maintaining the equipment, which will correspond to a higher level of the hierarchy of controls. The use of PPE can always be emphasized as a last resource to protect employees from the equipment.

The analysis of fall accidents showed that poor layout was an intermediate cause for half of the accidents studied. Safety managers should pay particular attention to the layout of the construction site and rearrange it when necessary to ensure that hazards are eliminated. A faulty structure is an intermediate cause that should be addressed by ensuring that the design of all the structural elements is done properly. Reviewing the structural design before starting construction is a good practice to ensure that the structure will be safe while it is being erected as well as during operations. The elimination of hazards before construction starts is the highest level on the hierarchy of controls. Another cause presented for fall accidents was inappropriate procedures. Safety managers should make sure that all workers are trained properly and that they know how to safely complete all their activities and tasks.

One of the most important causes for struck by/against an object accidents was falling and flying equipment. Construction sites often include construction equipment that has moving parts and can move throughout the site. It is important to ensure that equipment is well maintained to minimize the possibility of an injury due to faulty operations. Poor layout can also be an important cause for struck by/against an object accidents. The layout of the construction site should be designed and managed to ensure that accidents are prevented. For example, workers should be at an appropriate distance from moving equipment.

The most common intermediate cause for electric shock accidents was the lack of a spotter. The majority of fatalities caused by electric shock are due to machinery getting in contact with live electric lines. Having a spotter who can alert the worker or the machine operator of the proximity to electric lines can prevent accidents. Given that numerous regulations are in place to ensure that construction workers are safe from live electrical lines, many accidents appear to happen because of inappropriate procedures followed by managers and workers.

The hierarchy of control provides a guideline as to where to start if a company wants to reduce the number of accidents and fatalities. The minimal cut sets analysis should provide a more detailed idea of the intermediate and root causes that result in accidents. In general, the study results are expected to support construction professionals in taking direct and specific actions that will improve safety for workers on the site.

Chapter 7 Conclusions and Recommendations

This section presents the conclusions from the current study following the study's objectives. Recommendations for future research are presented at the end.

The first objective of this study was to identify the most common accidents in transportation infrastructure construction projects. The results showed that the most common types of accidents during the transportation construction projects considered here are falls, caught in/ between objects, struck by/against an object, and electric shock. These four accident types are identical to the "fatal four" identified by OSHA as the most frequent accidents in construction. Out of the 105 accidents studied, 41 were struck by/against an object accidents, 27 caught in/between objects, 22 falls, and 15 electric shocks.

The second objective was to identify the causes responsible for the most frequent and fatal accidents. Information from fatalities and severe injury cases was analyzed to identify the factors that were involved with each accident. The causes were identified using the terminology used by OSHA as well as other factors determined from the accident summaries. The analysis showed that the causes that were responsible for the majority of the accidents were misjudgment and inappropriate procedures. Other common root causes were lack of engineering controls, inappropriate positioning, lack of a spotter, miscommunication, and hazardous worksite.

The third objective was to develop a fault tree model to analyze the causes identified in the previous steps of this study. The fault trees were created to identify the root causes for the accidents and their relationship among different causes. A minimal cut sets analysis was performed to determine the minimum cause paths that would result in an accident. The results from this analysis showed that there are numerous two-cause sets, which are the most critical because only two events need to occur to result in a severe accident.

The work presented here is based on transportation construction projects on the Pacific Northwest region. The fault trees were validated by using previous studies and additional cases from other states. However, additional research can be done to include cases from different geographical areas to expand the applicability of the study results. Additional steps can also be completed to add accidents that occurred on other types of construction projects, such as commercial and residential construction. Such additions could result in fault trees that can be used more widely in the construction industry.

Additional work can also be performed to develop a methodology to use the information from the fault trees during the construction and planning process. Given that the information used for this study was collected after the accidents had already happened, using the fault trees to minimize accidents and reduce the number of fatalities during the construction phase would be ideal.

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