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Fault tree analysis and risk mitigation strategies for mine hoists

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ABSTRACT

Mine hoist are an essential part of an underground mine. In addition to extracting the ore from the mine, this machine transports the miners from the surface to the various underground levels of the mine. The two main hazards to which minors in the cage are exposed to are rope severance and loss of control of the hoisting machine. In both cases, the risk is the crashing of the cage at one end of the shaft. Hoisting accident and fatalities are rare but still happen despite the use of safety catches to retain the cage in the event of rope severance. The objective of this article is to improve mine hoist safety and to prevent the crash of a cage (of more generally any conveyance) at the shaft boundaries. Fault Trees (FT) are used to analyze the accidents scenarios of a cage crash in a shaft. Two generic fault trees are presented: one based on rope severance and the other based on loss-of-control of the conveyance. Results of the study indicate that, in the case of a rope severance, most of the root causes are based on secondary failure of the safety catches. In the case of a loss-of-control of the conveyance, most of the root causes are based on command failures that prevent the cage from stopping before reaching the shaft boundaries. This article suggests general mitigation measures and recommends the use of machinery safety standards in order to improve the reliability of hoisting machines.

1. Introduction

Mines in general, and coal mines in particular, have always been dangerous workplaces. Leigh et al. (2004) mention that in the United-States, lignite and bituminous coal mining stood second for the average cost of injury and illness per worker in 1993, at US$8600. Kecojevic et al. (2007) note that coal mines had an accident rate 69% higher than metal and non-metal mines between 1978 and 2005. However, the difference was less obvious for worker fatalities, with only 13% more for coal mines. Since the 1990s the difference between coal mines and metal/non-metal mines has declined. Moreover, a significant improvement in mine safety has been seen in every country over the last few decades.

1.1. Accident and fatality statistics in the mining industry

Saleh (2011) mentions that the average number of fatalities in the mining industry in the U.S. during the 1970s was roughly 270 per year. Kecojevic et al. (2007) indicate that this average had fallen to 110 by the late 1980s, and stood at around 60 per year in the first decade of the 2000s. The number of workers in the mining industry increased and decreased over the last 15 years (Table 1), while the number of fatal accidents has been decreasing (Table 1) (MSHA, 2018a, 2018b). As shown in Fig. 1, the fatality rate has been declining over the last four decades, with some annual variations. In particular, it can be seen that the fatality rate per thousand workers has been cut by two thirds since 2000 (0.244, compared to 0.079 in 2016) (MHSA, 2018a).

Chen et al. (2012) note that in China the number of fatalities dropped from 6200 per year in 2000 to 2800 per year at the end of the decade.

Fatalities in the U.S. mining industry are caused by a variety of hazards. From 1995 to 2005, the three most frequent causes of occupational fatalities were powered haulage (33%), machinery (18%), and fall of roof, back, or brow (10%) (Kecojevic et al., 2007). From 2009 to 2016, the three most frequent causes were powered haulage (26.4%), machinery (17.6%), and ignition/explosion of gas/dust (10.9%) (MSHA, 2018a). More specifically, the three types of machines which were involved in most fatalities from 1995 to 2015 were haul trucks (20.84%), conveyors (8.8%), and loaders (7.98%) (MSHA, 2018a). They are the same as those mentioned by Zhang et al. (2014). Hoisting accidents represented 1.8% of all fatalities over that period.

According to the Mine Safety and Health Administration (MSHA) database, since 2000 only seven accidents, involving eight fatalities, have been related to hoisting. They are listed in Table 2.

Of these seven accidents, four occurred in coal mines, resulting in five fatalities, while the other three occurred in metal or non-metal

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Table 1
Number of workers/number of fatalities by mine type from 2000 to 2015.

	2000	2005	2010	2015
Coal	102,291/38	110,920/23	129,358/48	98,505/12
Metal/Non-metal	210,432/47	200,207/35	197,846/24	218,864/17

mines, and caused three fatalities. Some of the accidents were caused by a hoist rope failure, but in most of them, the hoist rope was still intact. The total number of fatalities is relatively low, however, considering the maximum number of workers in a cage (40 in the cage for the 2014 accident). It would therefore seem reasonable to take whatever precautions are necessary to prevent such accidents. Furthermore, the hoisting machine does not discriminate among workers based on age, experience, or physical shape, contrary to many other accident causes, as Kecojevic et al. (2007) have shown.

In Canada, there is no federal mining fatality database. However, several hoisting accidents and incidents have occurred in the province of Quebec in recent years. In 2009, three workers died when the cage was lowered to a flooded level of the mine. In 2011, during maintenance of a hoisting machine's brakes, the cage finished its descent at the bottom of the shaft. Last, in 2013, a skip crashed at the shaft bottom due to a bug in the software of the Programmable Electronic System (PES). Fortunately, in the 2011 and 2013 incidents, there were no fatalities. Still, since the software problem could have affected a fully loaded cage with around 50 workers, the consequences could have been disastrous. It should be noted that none of these accidents was caused by the failure of the hoist rope. However, though less frequent than in the 1950s and 1960s, some hoist rope failures have happened in the last few decades.

Mine hoists are the main link between the surface and the below ground levels of an underground mining operation. They are used to transport workers and to bring ore to the surface. A hoist can operate in either a vertical shaft or on an inclined ramp (which is more common for coal mines). For deep metal mines, the most common hoists in use nowadays are drum hoists (Leonida, 2013). In 2004, in Canada, there were 300 drum hoists and 43 friction hoists (also called Keope hoists) (Udd, 2004). In Quebec, in 2016, there were 28 drum hoists (18 double drum hoists and 10 single drum hoists), 3 friction hoists, and 1 Blair hoist (Giraud et al., 2017). This means that the vast majority of cages are hoisted by a single hoist rope. To prevent the cage from falling down the shaft in the event of hoist rope severance, safety catches, also called safety dogs, are mandatory in all provinces of Canada whenever a single hoist rope is used to move the cage.

1.2. Fault tree analysis

Fault Tree Analysis (FTA) is one of many symbolic logic analytical techniques. It was first used in the aerospace industry, but is now used in many different industries, including the nuclear industry since 1979, as well as the offshore (Lavasani et al., 2011), chemical (Dong and Yu, 2005), and mining (Zhang et al., 2014) industries. It is a systems analysis technique for determining the root causes and the probability of occurrence of a specified undesired event. Many authors or organizations have described the technique in the literature (Harms-Ringdahl, 2013; Oakley, 2012; IEC 61025, 2006; Ericson, 2005; NASA, 2002).

NASA (2002) suggests the following eight steps for an FTA:

1. Identify the objective for the FTA
2. Define the top event of the fault tree (FT)
3. Define the scope of the FTA
4. Define the resolution of the FTA
5. Define ground rules for the FTA
6. Construct the FT
7. Evaluate the FT
8. Interpret and present the results

The first five steps involve the problem formulation for an FTA. The remaining steps involve the construction of the FT, its evaluation, and finally the interpretation of its results. While most of the steps are performed sequentially, steps 3 to 5 can proceed concurrently. The "resolution" (step 4) and the "ground rules" (step 5) can be modified during steps 6 and 7.

Ericson (2005) suggests using three main concepts to determine the type of gate to be used and the gate inputs:

1. The I – N – S concept, which is also used in the IEC 61025 standard
2. The "State-of-the-system" (SS) – "State-of-the-component" (SC) concept
3. The P – S – C concept, which is only used with a component-based event: "What are the primary (P), secondary (S), and command (C) causes of the event?"

"A primary failure is the inherent failure of a system element (e.g., a resistor fails open). […] A secondary failure is the result of external forces on the component (e.g., a resistor fails open due to excessive external heat exposure). […] A command failure is an expected, or intended, event that occurs at an undesired time due to specific failure." (Ericson, 2005) If a failure in the missile arm and fire functions launches the missile prematurely, it is a command failure.

1.3. Objectives

As the statistics and past accident reports show, hoisting accidents and fatalities are rare, but still happen despite the technical progress made in recent decades on hoist ropes and hoisting machines. Nevertheless, considering the number of people that can be carried in a mine cage at the same time, and the almost round-the-clock operation of underground mines, it is absolutely vital to devote considerable effort to preventing mine cage crashes, caused either by severance of the hoist rope or by loss of control of the hoisting machine.

This article proposes to use fault trees and fault tree analysis to determine root causes of the crash of a cage (or, more generally, any conveyance) at the bottom, or top, of a shaft or inclined ramp. First, a short section presents risk mitigation measures that can be taken to prevent hoist rope severance and loss-of-control of the conveyance. Then, the fault trees are presented. Two different hazardous events are considered: the case of a wire rope severance, and the case of the loss of control of the conveyance without any hoist rope severance. The fault trees were developed on the basis of past accident and incident reports. Last, drawing on the fault trees presented, the article proposes some risk mitigation measures that can be taken to prevent cage crashes and assesses their effectiveness in regard to the fault tree branches.

2. Mine conveyance safety

When travelling up or down a mine shaft, miners are exposed to certain risks, including the risk that the cage could plummet down the shaft as a result of hoist rope severance or an out-of-control hoisting machine (Fig. 2). In underground mines, workers are frequently exposed to such risks.

There are two schools of thought regarding mine conveyance safety (Young, 1947; Larsen et al., 1972):

- The best safety system is to use a reliable hoist rope (which is the dominant school of thought in South Africa): conventional safety catches are not effective if the problem is related to the hoisting machine, and they are not foolproof if the hoist rope breaks at a great distance from the attachment point;
- Hoist rope failures will always occur, whatever the precautions taken during the process of hoist rope selection, inspection, and