1. INTRODUCTION

The comprehension of slope failures or slope deformation behaviour in mines remains limited. Mining affects the surrounding rockmass, and excavation instability is when stress exceeds rock strength (Kayesa, 2006a). Rapid opencast mining and improved automation have led to deeper opencast mines with better production rates. The amount of waste mined and dumped will rise, increasing the risk of highwall slope and dump collapses. With stricter environmental rules and a lack of alternative land for forestation, the threats are multifaceted, with deep excavations and rising dumps impacting stress concentration. These situations endanger employees and machinery. Several opencast mining accidents have been caused by slope and dump failures. In India 23 accidents have resulted in a total of 143 fatalities due to slope failures.

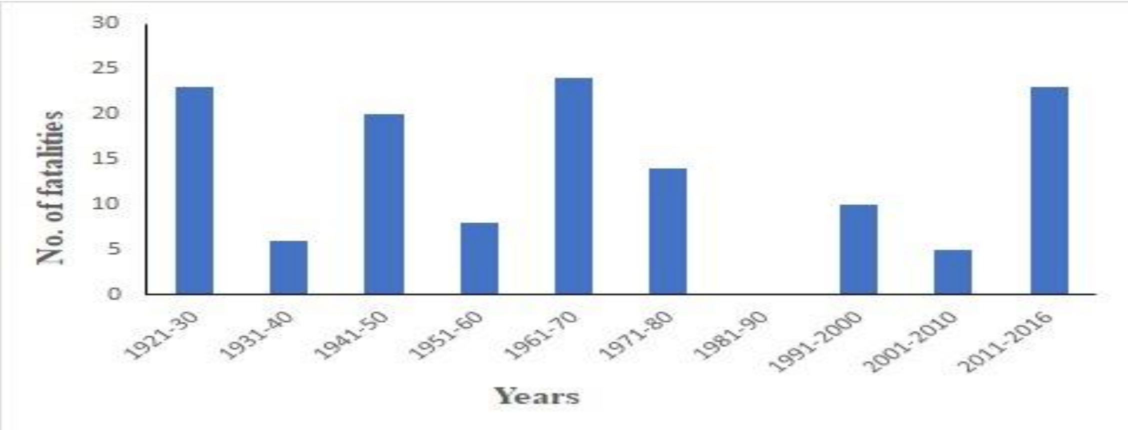

Figure 1. 1 : Loss of lives due to slope failure from 1921 to 2016 in India (23 accidents causing 143 fatalities) (Dash, 2019)

Flatter slopes are stable but lock up tremendous mineral resources, whereas steeper slopes are riskier. Maintaining scientific equilibrium ensures the benches' longevity. Monitoring mine slopes for signs of imminent collapse is the most effective way to protect miners. Lack of proper slope design, monitoring and forecasting contributes to mining accidents. In mining, monitoring is used to control residual design risk. Unknown constructions, unexpected weather patterns, or seismic stress may cause slope collapse (Girard & McHugh, 2000). Even professionally engineered slopes may collapse due to geology, weather, seismic rocks, and other factors like poor drainage, proximity to inhabited areas, and difficulty segregating topsoil after excavation. Bench design may avoid slope collapses and increase geotechnical safety, but geology, weather, and earthquakes may collapse even conservatively designed slopes (Girard, 2001a). Rock movement may interrupt mining operations, raise safety risks, cause serious injuries, and cost lives and money (Girard, 2001b). Monitoring uses reference points to identify deformation and slope deformation warnings safeguard employees and machinery preventing or reducing losses. Therefore, increasing the need of a good slope monitoring system and improved forecast of impending slope movements. Keeping track of the stability of the rocks that make up a slope is defined as slope stability monitoring (Kayesa, 2006a). A slope monitoring program is the most critical slope stability system.

1.1 Background

The safety of the mineworkers is of foremost importance. Slope movement could be dangerous to mining operations and the mineworkers. Predicting how rocks will behave is critical to ensure that mining slopes are safe for workers, machines, and infrastructure. Many studies have tried to predict the collapse of mine slopes, but there is no single model that experts agree on. Even with the best computer tools and the most up-to-date slope design methods, there are still unexpected slope failures. Monitoring slope movements in surface mines has become common to help with slope design issues. Fortunately, if a slope problem is found early enough, it may be possible to avoid it. Understanding how mine slopes move can help reduce the risk of them collapsing. The search for better ways to manage the slopes in mines led to the development of many different systems to keep an eye on the slopes in terms of more accuracy and precision of the monitoring the slope movements by adopting a balanced and informed approach that integrates technology with human expertise and thorough analysis. Figure 1. 2 shows an image of slope failure of Bingham Canyon Mine, USA.

Figure 1. 2 : Slope failure. Bingham Canyon Mine. Utah / USA (Source: http://www.mining.com)

GroundProbe (Pty) Ltd. installed the Slope Stability Radar (SSR) in June 2003, and since then, progress has been made in slope monitoring with the help of remote sensing technologies. The development of ground-based slope stability radar technology has made it easier to keep track of surface changes of slopes. Radar operators can look at images made from line-of-sight data to see how the slope of the pit wall changes. Ground-based radar has many advantages over conventional slope monitoring and can cover a wide area and get readings a long way away without prism reflectors. Operators can set up multiple alarms inside the ground-based radar scan zone to alert safety personnel in charge if there are changes in slope behaviour.

1.2 Problem Statement

Using ground-based radar data for real-time response and failure time prediction when a slope deformation alert is triggered or an accelerated trend is observed is the most effective way to deal with forecasting problems of slope failures. Conventional failure time analysis methods, such as the inverse-velocity approach, are often employed in practice, but the accuracy is low, and also, they work with many assumptions. Uncertainty and hesitancy in instructing mineworkers in a dangerous location might occur when there is no predetermined protocol to follow in an impending slope failure is a massive problem for the mining industry. Ground-based radars used by mines to monitor a dangerously unstable slope may not have a real-time failure time analysis approach that may make the most of their radar monitoring investment. Therefore, it is essential to have a system that can accurately forecast slope failures. Our work focuses on this by developing a model to predict slope failures in surface mines.

Many surface mines in India and around the world now utilise radar slope monitoring, such as the SSR. Nevertheless, the efficacy of this radar in alerting mine workers to an approaching slope breakdown is not completely appreciated.

This difficulty can only be solved if you have a thorough grasp of the radar system and the data it collects. By analysing mine slope behaviour and including time/displacement data from radar monitoring, the proposed study hopes to create a model to predict when the slope would fail.

Despite decades of research, mine slope failure prediction remains challenging.

Traditional failure forecasting is manual. The lack of automation has led to inefficient real-time evaluation. Non-automated procedures produce some results but aren't suited for emergency warnings or speedy responses. The main reason for RADAR not being used commonly is the lack of innovative research and understanding in this area resulting to the inaccuracy of the mine slope failure predictions. Mine personnel, in general, the mining industry has not realized the effectiveness of this radar in notifying them of an impending slope failure.

1.3 Research Questions

- How effective is the RADAR in monitoring slope behaviour?
- How can the safety of a mine be increased using RADAR techniques of slope monitoring?
- How effective have existing conventional and moder-day slope failure prediction techniques been?
- How can we identify slope thresholds like threshold velocity?
- How can slope behaviour, and time to failure, be effectively predicted using the displacement/time data from a RADAR monitoring system?

1.4 Objectives of the research

The aim was to use the ground-based radar displacement data to develop a model to predict slope failures in surface mines. Data from the South Eastern Coalfields Limited (SECL) Kusmunda, Gevra, and Dipka mines was used and in addition to the data from other surface mines from the literature to achieve this goal of constructing a model to anticipate mine slope collapses. Our proposed model should increase the reliability and performance of findings when monitoring time-dependent rock mass behaviour and time of breakdown investigations.

The objectives of this work are listed below;

- Analysis of slope movements with the help of SSR Data
- Finding the Onset of Failure/Onset of Acceleration
- To develop an understanding of slope velocity and acceleration threshold limits

- Developing a Slope Failure Prediction Model for Surface Mines (SFPMSM)
- Making an automated model to ensure a user-friendly experience

1.5 Structure of the Thesis

After the introduction as the **1st chapter**, it is in the **2nd chapter** of literature review that the fundamental concepts used in this thesis are discussed. The chapter begins with the review of rock slope deformation processes followed by an in-depth examination of traditional and modern-day slope monitoring approaches. We review the Slope Stability Radar (SSR), the Movement and Surveying Radar (MSR), the Work Area Monitoring (WAM), and the IBIS-M slope monitoring radar systems, additionally discussing the drawbacks of specific commonly implemented strategies. Furthermore, an overview of many current approaches for forecasting the failure time of mine slopes is discussed. Fukuzono's Inverse Velocity Method (IVM) is the main focus as it has been the most widely accepted technique to forecast slope failures.

Chapter 3 discusses the construction of the SFPMSM to estimate the time of failure for slopes in surface mines. In this chapter of methodology, the progress of work and development of the algorithm and the model is discussed. In the course of methodology development and refinement, we started with testing the Inverse Velocity Method (IVM) utilizing Microsoft Excel across diverse datasets. The IVM exhibited its efficiency predominantly in scenarios where the slope deformations displayed rapid movements. However, when applied to datasets characterizing a more gradual and slow deformation of the slope, the IVM generated highly inaccurate estimations for the time of failure. Recognizing this limitation, a pivotal shift in approach was imperative.

Subsequently, we decided to devise an algorithm that could aptly forecast the time of slope failure, transcending these limitations. This algorithm was meticulously conceptualized and fine-tuned to enhance accuracy and applicability across varying deformation patterns. One of the critical steps in this evolution was the strategic implementation of the algorithm through the versatile computational framework of MATLAB to craft a more nuanced and accurate approach to predicting slope failures.

The results of the proposed model are discussed in **Chapter 4** along with validation. To ensure a proper understanding of results some of the data input and the output for that particular code has been discussed in the chapter. The model was validated and shown to be functional using case studies. **Chapter 5** concludes the study and suggests important inputs for further research in the field of mine slope monitoring and prediction of slope failures.