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SLOPE STABILITY AND ROCKFALL HAZARD ANALYSIS IN OPEN PIT ZINC MINE

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ABSTRACT

Rockfalls are a major safety hazard in open cut mines, particularly in large-scale deep pits. The geotechnical design relies on in-situ, site-specific, rock slope data to predict the trajectories and velocities of rockfalls that present a residual hazard in the mines. This paper presents slope stability analyses using both static general limit equilibrium methods and finite element stress analyses to estimate unstable areas and slope displacements in the mid-west slope at Glencore Zinc's Handlebar Hill Open Cut mine at Mt. Isa, Queensland, Australia. A conventional program -RocFall- was used for the slope rockfall risk assessment. Results indicate the possible slope benches involved in the initiation of rockfalls, and the maximum run-out distance, which could be defined as the pit's hazardous zone. A rockfall restraining system to absorb the impact energy of boulders and prevent them further falling was also modelled.

Keywords: Factor of Safety, Continuum Modeling, Shear Strength Reduction, RocFall, Rockfall Hazard Barrier

1. INTRODUCTION

Rockfalls are a major risk in open cut mining as they often involve the unexpected detachment of rocks from a slope and their rapid movement by rolling or bouncing deeper into the pit. The rock fragments could come to rest on the lower benches or on the pit floor, generating high risk to workers, mine assets and the mine environment. The impacts depend on the size of the rockfalls, slope geometry, momentum of the rocks, the presence of obstacles and the site risk management.

Rockfall dynamics are largely a function of the mechanical properties of the rock and rock mass, location of detachment and downslope profile [1]. Falls have two successive mechanisms: the failure (i.e. rock detachment) and its propagation down the slope [2]. Once the potentially unstable areas have been identified, the potential run-out of the rockfalls can be evaluated using propagation models.

This paper presents analyses aimed at better understanding the rockfall hazard in the Handlebar Hill Open Cut (HHOC) zinc mine, approximately 20km north of Mount Isa in northern Australia (Fig 1). The study focuses on the slope stability of the mid-west pit, which is characterised by four geological domains with major discontinuities such as faults and shear surfaces dipping 60º - 70º to the west.

Standard models from the Rocscience suite of programs [3] were utilised to undertake the analyses. The main objective of the analyses was to identify the potential rockfall initiation areas and failure mechanisms, predict the sensitivity of the slope to different triggering mechanisms and provide simulations that may inform the design of optimal slope geometry and restraint mechanisms.

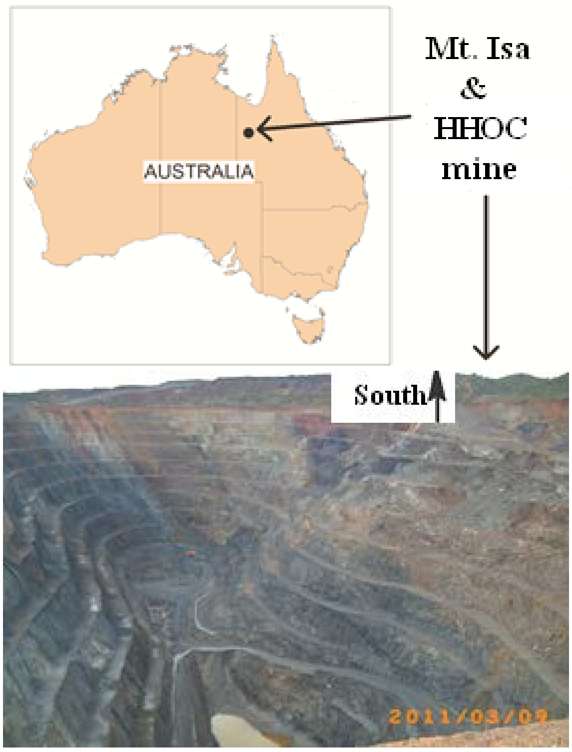

Fig. 1 The HHOC mine pit location and view looking south. This study focuses on the western wall, which is on the right hand side of the image.

2. ROCK SLOPE STABILITY ANALYSES

Two software packages - Slide 6.0 and Phase^2 - were used to undertake a limit equilibrium analysis and construct finite element stress models of the pit slopes. The purpose of these analyses was to identify the most likely areas where rockfalls would be initiated. This information was then used as input into the rockfall simulation models.

The geometry of the slope, the different material domains and three major geological structures are shown in Fig.2 using Slide 6.0 model. The input parameters used to characterise the rock mass strength are listed in table 1.

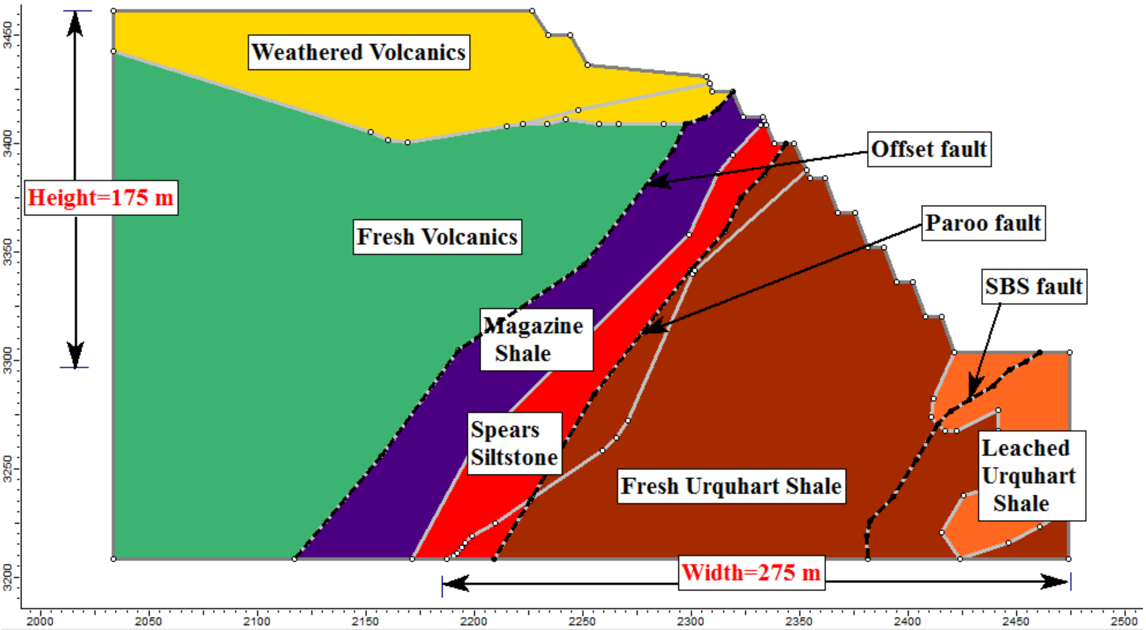

Fig. 2 Slide model of the Handlebar Hill west slope

Table 1 Handlebar Hill rock mass parameters

Domain	(γ) KN/m^3	Cohesion (c) KPa	φ (º)	σ_{ci} (Mpa)	σ_{rm} (MPa)	E_i (GPa)	GSI	m_i	D
Weathered Volcanics	27.4	350	23	36.4	1346.68	39.03	36.16	4	0.7
Fresh Volcanics	28.3	800	32	55.5	2293.59	52.53	43.08	4.07	0.7
Magazine Shale	26.5	410	25	31.8	1784.92	40.88	43.08	4	0.7
Fresh Spears Siltstone	27.2	990	35	111.1	2800.47	60.80	44.46	4	0.7
Leached Urquhart Shale	26.9	300	22	32.7	1141.03	33.06	36.16	4	0.7
Fresh Urquhart Shale	31.1	1250	44	107.9	3342.02	70.56	45.16	9.59	0.7

2.1 Limiting Equilibrium Analysis

Limit equilibrium analysis of the overall slope at the HHOC pit was analysed using Slide 6.0. Modern limit equilibrium software (such as Slide) is making it possible to handle ever-increasing complexity in the analysis. It is now possible to deal with complex stratigraphy, highly irregular pore-water pressure conditions, various linear and nonlinear shear strength models, almost any kind of slip surface shape, concentrated loads, and structural reinforcement [4]. All methods used in limit equilibrium analysis are based on a comparison of forces (moments or stresses) resisting instability of the mass with those that cause instability (disturbing forces).

In slope stability analysis, the Factor of Safety (FOS) is considered as the ratio of resisting shear strength to the disturbing shear stresses at initial failure [5], with a typical FOS for open pit slope design ranging between 1.1 and 1.5. The potential failure surface is assumed to be directed by the linear Mohr-Coulomb relationship between rock shear strength and the normal stress applied on the slope failure surface.

The results of the general limit equilibrium analysis for the HHOC pit slope is shown in Fig.3. The critical surface specifies a minimum FOS of 1.21 for slope instability generated by the general limit equilibrium analysis.

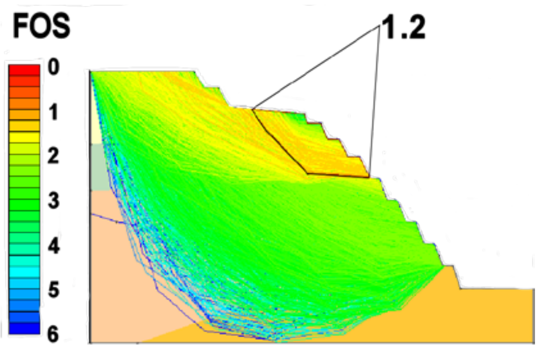

Fig. 3 FOS using limiting equilibrium analysis. (the critical surface shown has FOS = 1.21).

2.2 Finite Element Analysis

For many decades, limiting equilibrium has dominated over any other method of analysis for soil/rock slope stability practitioners. Uncertainty is a key factor in slope design as an increase of one degree in excavated slope angle might make the slope unstable. Conventional slope practice is often based on a FOS which can not explicitly address the uncertainty, which ultimately led to the development of probabilistic finite element slope stability analysis [6]. In addition, the advantage of finite element methods for slope stability analysis over traditional limit equilibrium methods is that no assumptions needed to be made pre-analysis about the shape and location of the failure surface and geometry, such as the failure slice side forces and directions.

To reduce the limitations of conventional methods, the finite element shear strength reduction method was used in which the explicit material deformation and failure progression can be modelled. The strength reduction factor of the mid-west slope was modelled using the numerical method of the Phase^2 software. The results are shown in Fig.4.

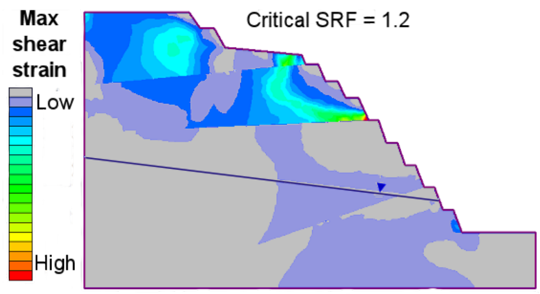

Fig. 4 Modelled strength reduction factor for the mid-west slope.

The resulting critical strength reduction factor (SRF) is 1.2 at maximum total displacement 0.026m.

3. ROCKFALL MECHANISMS

The movement of a numerical-continuum body is a continuous time sequence of displacements. The rock material will occupy different configurations of size and shape at different times so that a particle occupies a series of points in space which describe a path line.

The displacement vectors and contours illustrated in Fig.5, shows that the most of rock displacements are close to the major discontinuities at the upper part of the slope surface. The slope is most likely influenced by the reduction in the strength (mechanical) properties of the rock masses in these zones.

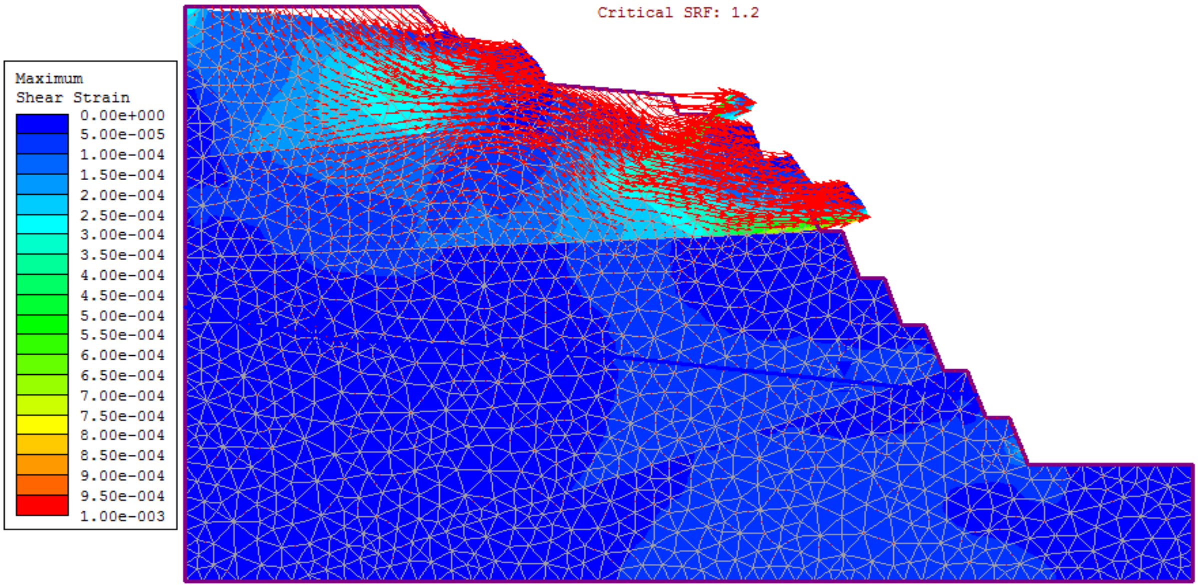

Fig. 5 Modelled displacement vectors of deformation showing the possible directions of block rotation and sliding modes.

Continuum modelling was used to determine the total displacements in the slopes and the locations of yielded elements in the rock mass shows critical state conditions as illustrated in Fig.6.

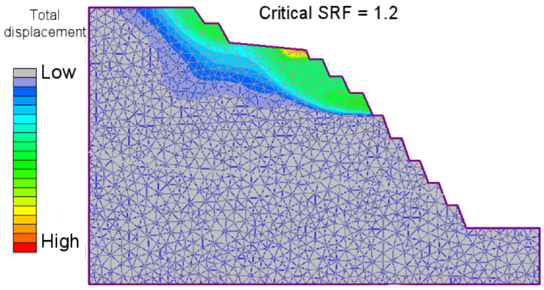

Fig. 6 The total displacement in the slope. The most critical displacement for the slope surface on which the proposed rocks could be detached, is located in the bottom of the ramp and nearby the upper benches around the haulage road.

Generally, rockfalls could be initiated by specific climatic conditions, which may create some changes to the forces acting on the slope. This is especially the case in tropical zones (e.g. the HHOC mine location), which experience a season of heavy rains. Rainfall events may rapidly increase pore pressures due to infiltration through the rock mass. At such times, the potential of rockfall initiation will probably be higher than during drier seasons.

For that reason, it is necessary to analyse the potential for rockfalls in high rainfall events. In addition investigating the causes of historical rockfalls (and mine accidents) can help planning to avoid future rockfalls.

4. ROCKFALL SIMULATIONS

An assessment of rockfalls was undertaken to identify the potential fate of blocks that may detached from unstable pit slope faces and therefore, to improve the safety at the mine. The analysis was completed using RocFall, a program that simulates the trajectories of rocks falling from the slope. The trajectory is modelled as a two dimensional rockfall simulation largely based on the slope geometry. Using statistical analyses, the method calculates the probable trajectories, energy, velocity and bounce height envelopes for individual rock blocks. The entire slope can be modelled by the program, so that the ultimate resting locations of rockfalls can be determined, and the results are graphed with comprehensive statistics automatically calculated [3]. Besides the slope geometry, the program requires input data such as the slope roughness, restitutions of normal and tangential rock energy, coefficient of rolling friction and rock mechanical parameters.

To account for the uncertainty in the definition of the input parameters, stochastic variability is used. The determination of selected standard deviations for input parameters of detached boulders is required.

The potential rockfalls in the HHOC pit were initially modelled using a starting point located at the top slope vertex (0, 0). In this simulation, the source of the rockfalls is the Volcanics formation rock mass and their falling paths are illustrated in Fig.7 using the model inputs listed in Table 2. A number of 50 detached rocks was used, each of 300 Kg weight and 28 Kn/m^3 density. The simulation calculated that all rockfalls would end on the ramp.

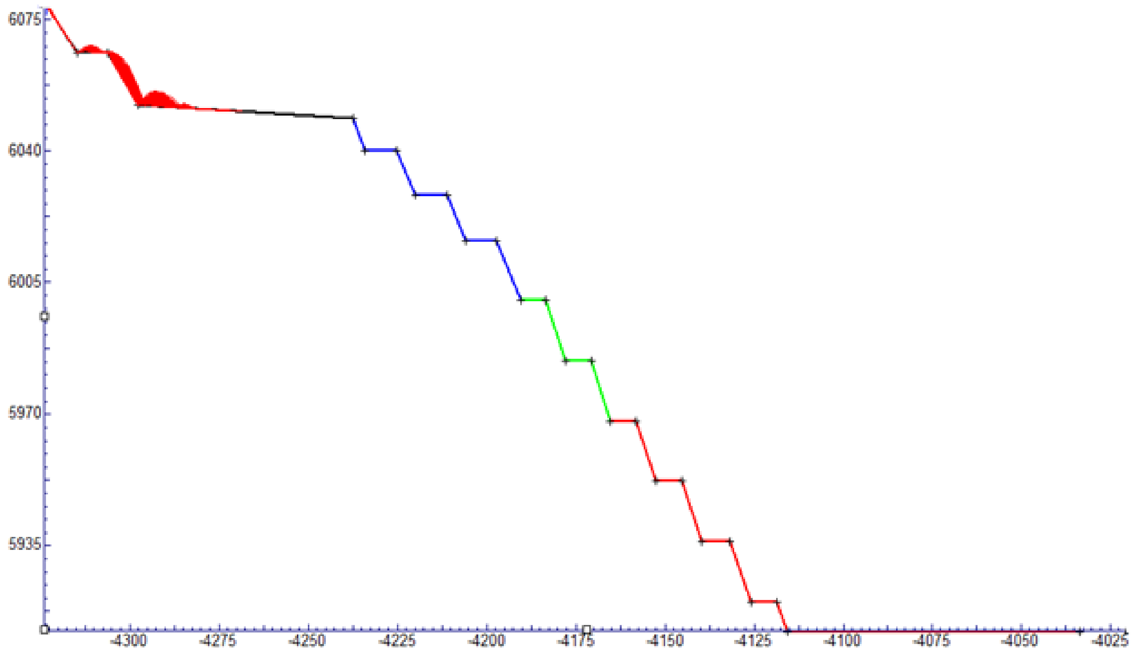

Fig. 7 Results of the simulation of a number of possible rockfalls from the top crest source area.

Table 2 The input parameters of rock mass materials used in the rockfall simulation

Rock mass material	Rn (mean | std)	Rt (mean | std)	Phi (mean | std)	Roughness (std)	**Colour**
Volcanics	0.44 | 0.04	0.87 | 0.04	150 | 0	0	Black
Magazine Shale	0.46 | 0.04	0.89 | 0.04	160 | 0	0	Blue
Spears Siltstone	0.47 | 0.04	0.91 | 0.04	360 | 0	0	Green
Urquhart Shale	0.48 | 0.04	0.93 | 0.04	350 | 0	0	Red

A second sumulation was run using a starting vertex in the Magazine Shale, which is from the lower bench following the the ramp on the slope surface. This area is regarded as a probable source for rock detatchments based on the results of the modelled displacement vectors (Fig.5).

The rockfalls source point and their paths are illustrated in Fig.8 (A). The same number of 50 detached rocks were used, 300 Kg weight and 26.5 Kn/m^3 density for each falling block. The simulation predicts that many rockfalls would end on the pit floor and away from the toe of the slope.

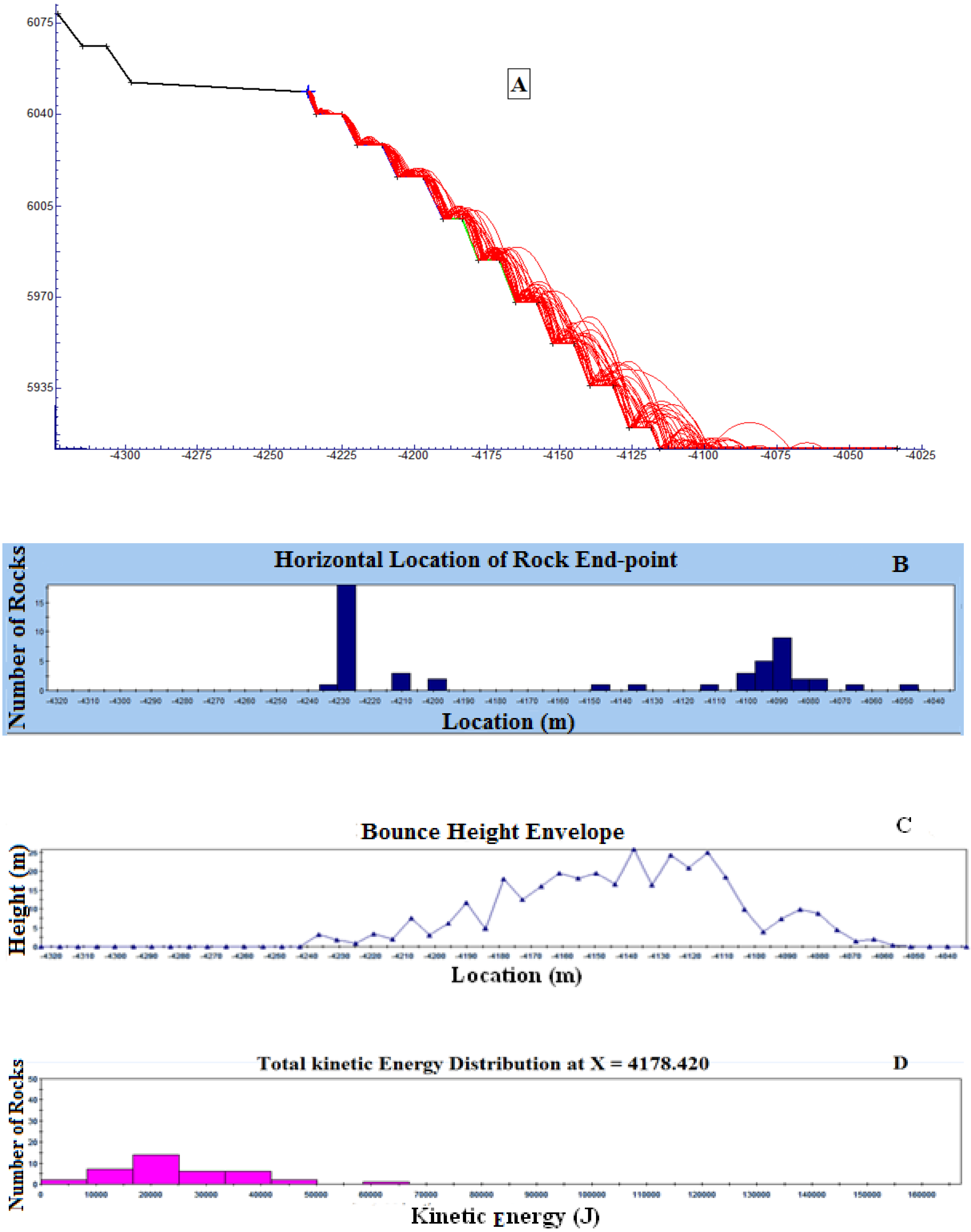

Fig. 8 The results of the RocFall simulations for the rockfalls sourced from the Magazine Shale on the top bench face. (A) red lines show rockfall trajectories and the horizontal distances of rock ends points. (B) the bar chart shows the distances and numbers of rockfalls from the source area. The majority of rockfalls travelled horizontally to a stop point, indicating that a probable hazard exists and that the installation of an effective protective system was required. (C) shows the distributions of rockfall bounce heights above the ground level. (D) shows the total kinetic energy distributed on the slope and the numbers of fallen rocks; the final impact energy on the ground is important for a safety design of the protective barrier fence or windrow.

6. ROCKFALL SURVEY

Many investigations were undertaken at the mine by geotechnical staff in order to better understand the maximum trajectories of rockfalls, stability of geological units of the highwall and to collect data about rock fall measurements. Most of the rockfalls are broken debris perched on the lower bench next to the source of the failure. These fallen rock masses are composed of small loose rocks and stones that can move along the slope. Boulder rockfalls usually generate faster movement and longer run out distances. The weight and dimensions of rock blocks were collected. No significant rockfall event was reported after 2010. A boulder of around 0.9m3 and 2.3t weight was recorded to have fallen from the potential unstable slope blocks and travelled away from the toe for 22.4m as a maximum rockfall end-point in 2011. Fig.9 shows only the blocks that have travelled in maximum trajectories at the west slope.

Fig. 9 Shows blocks travelled in maximum trajectories on the west pit floor, looking south.

7 MODELING A PHYSICAL BARRIER FOR ROCKFALLS

Assuming that rockfalls will be inevitable, then rockfall restraint must be considered.

A number of protective measures have been identified for the prevention of impacts on people and assets from rockfalls in open pit mines [7]. These include flexible rockfall barriers, identifying effective berm widths, bunds constructed on production berms and using draped mesh.

Windrows and catch barriers could be positioned to stop rockfalls from moving further down slope. Barriers and collectors can be modelled in RocFall as a line segment that can be positioned anywhere along a slope, so as to intercept the paths of the rocks as they fall down the slope surface. The analysis includes the kinetic energy of the falling rocks and their impact energy could determine the location and capacity of the rockfall barrier. The proposed barrier protection structure at the HHOC mine was modelled as perfectly inelastic; therefore rockfalls that reach the barrier will finally stop. The rocks will not bounce back and just will fall straight down-wall to the foot of the barrier. The horizontal locations for maximum trajectories of falling blocks are shown in Fig.10.

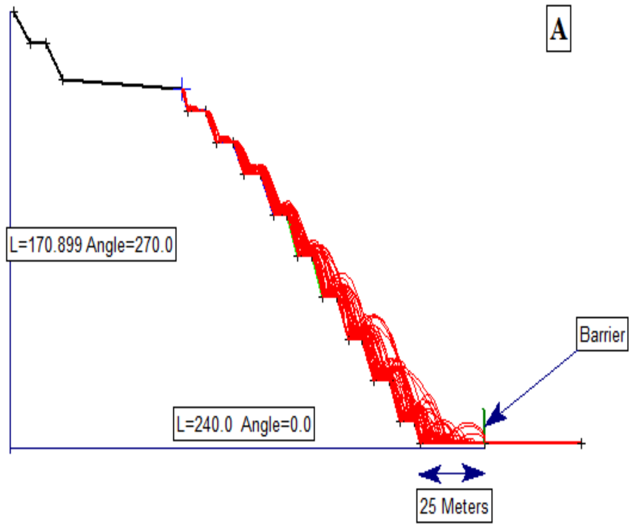

Fig. 10 Simulated horizontal location of rockfall end-points utilising a perfectly inelastic barrier located 25 meters from the slope toe.

8 CONCLUSION

Rockfalls are considered as a significant hazard in open cut mines. Blocks falling from high up on a slope can easily travel into the pit floor may destroy mining infrastructure and present a serious safety hazard for mine personnel. At the mid-west slope of the HHOC mine, the results of a general limiting equilibrium analysis indicate stable slopes with a FOS = 1.21. This deterministic analysis was verified through a finite element analysis using the shear strength reduction method. Modelled displacement vectors illustrated the potential areas for slope instability and the potential areas of failures were contoured.

Rockfalls simulations confirmed the potential for individual rocks dislodged from the Volcanic rock formation at the slope crest to travel down slope and come to rest on the haulage ramp. By contrast, blocks falling from the top bench of the Magazine Shale rock mass, can possibly travel beyond the slope toe and onto the pit floor, presenting a hazardous zone. The models show that a barrier located at the foot of the slope on the pit floor, would be required to safely prevent the falling rocks reaching the mining operation zone.

The installation of a protective structure may partially control the rockfalls from the slope but the hazard cannot be fully eliminated.

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