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TOWARDS SAFER MINING: THE ROLE OF MODELLING SOFTWARE TO FIND MISSING PERSONS AFTER A MINE COLLAPSE

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ABSTRACT

Purpose. The purpose of the study is to apply science and technology to determine the most likely location of a container in which three miners were trapped after the Lily mine disaster. Following the collapse of the Crown Pillar at Lily Mine in South Africa on the 5th of February 2016, there was a national outcry to find the three miners who were trapped in a surface container lamp room that disappeared in the sinkhole that formed during the surface col-lapse.

Methods. At a visit to Lily Mine on the 9th of March, the Witwatersrand Mining Institute suggested a two-way strategy going forward to find the container in which the miners are trapped and buried. The first approach, which is the subject of this paper, is to test temporal 3D modeling software technology to locate the container, and second, to use scientific measurement and testing technologies. The overall methodology used was to first, request academia and research entities within the University to supply the WMI with ideas, which ideas list was compiled as responses came in. These were scrutinized and literature gathered for a conceptual study on which these ideas are likely to work. The software screening and preliminary testing of such software are discussed in this article.

Findings. The findings are that software modeling is likely to locate the present position of the container, but accurate data and a combination of different advanced software packages will be required, but at tremendous cost.

Originality. This paper presents original work on how software technology can be used to locate missing miners.

Practical implications. The two approaches were not likely to recover the miners alive because of the considerable time interval, but will alert the rescue team and mine workers when they come in close proximity to them.

Keywords: *safer mining, missing miners, software modelling, caving phase, software, underground mining*

1. INTRODUCTION

The purpose of the study is to apply science and technology to determine the most likely location of a container in which three miners were trapped after the Lily mine disaster. The WMI became involved 20 days[1] after the container disappeared in the sinkhole and started a migration route into the underground workings of the mine, along with backfill debris, broken rock and other (mostly metallic) surface infrastructure objects. The objective of this article is to investigate which technologies can locate the container[2]. Normally, the first step is to determine whether there were communicating devices (e.g. cell phones and portable radios) in the container, but considering the time lapse it was highly likely that the battery power of these devices were down to zero. The Lily mine disaster has several lessons for future mine search and rescue operations and it is therefore critical to learn from the event. Although such lessons will be too late for this disaster, the mining sector must be better prepared for disasters like these. This study is of interest to the families of the miners who are missing following a disaster, the mining industry, government and mine rescue teams. Technologies for physical testing are expensive and mostly unproven in complex and harsh mining environments with many different scenarios. As a result, the study is mostly conceptual with minimal testing, but

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[1] It is important to understand that the initial aim was not to rescue the miners while they were still alive. There is no evidence that the miners had food and water with them at the time of the disaster. It is unlikely that they could survive without water, especially when it is likely that they were injured as a result of the steel container tumbling down the sinkhole. However, there is evidence that there was at least one survivor because an underground geophone recorded tapping sounds in the first week following the collapse.

[2] It was not possible to start searching from surface because of the risks associated with highly unstable sidewall slopes and several significant cracks at the surface of the mine and at the high wall

the methodology followed resulted in identification, evaluation and systematic exclusion of technologies to arrive at a point where expenses could be minimised through targeting technologies with a high probability of success. Considering the significance of the event, there were some volunteer companies[3] with probable solutions who tested new technologies at the mine, in addition to the efforts of the mine, government and the rescue team. Apart from the geophone that detected "tapping" during the first few days after the collapse, no reliable technologies were found despite the effort. It is hoped that it will contribute to first, a better understanding of what happened at Lily mine; second, the national imperative of achieving zero harm; and third, the development of a pool of knowledge that can be consulted during mine disaster and rescue management. The next section gives an overview of the mine, the event and the broad technology approaches, where after the role of software in analysing mine disasters is discussed. This is followed by a conceptual screening and elimination exercise with a view to propose software for testing. For budgetary reasons, only limited testing was done before a recommending a strategy on the role of modelling software to detect the container in which the miners were trapped is proposed. The major finding is that 3D software and digital data can be used to model the movement of the container.

2. OVERVIEW OF THE MINE, THE EVENT AND THE BROAD TECHNOLOGY APPROACHES

Lily Mine is about 38 km south-east of Nelspruit and 25 km north-east of Barberton in the Mpumalanga Province of South Africa. It is a gold mine owned and operated by Vantage Goldfields. The mine workings are situated along the east west-trending Lily Fault. Barberton's varied geology gives rise to a steeply incised mountainous terrain that stretches from the Lochiel Plateau in the south to the Nelspruit-Komatipoort area in the north and straddles the Swaziland border (Lowe, Byerly, & Kyte, 2014). It includes part of the Komati river catchment in the south-west, the de Kaap catchment in the north and Mahlambanyathi and Crocodile Rivers in the north-east (Kröner, 1984). The hills are rocky, with moist grassy uplands and forested valleys and the altitude ranges from 600 to 1800 metres above mean sea level (Hofmann & Harris, 2008; Lowe, Byerly, & Kyte, 2014). The study area is shown in Figure 1.

Underground mining remains a high risk activity prone to mining accidents and sometimes mine disasters. The costs associated with an accident can be so substantial that mining operations could become infeasible following the event. One such an accident occurred at the Lily Mine on the 5th February 2016, when the crown pillar protecting the underground and surface workings collapsed. The lamp room was housed in a container and it fell down into the sinkhole along with three miners trapped inside. Two 550 KVA transformers, one generator and two steel water tanks were also lost due to the abrupt and unexpected accident. The reasons for the collapse are still under investigation.

On the 25th of February the MHSC requested the WMI[4] to assist with ideas to locate the lost container. A promising and quick response was received from all over the University. The ideas received included using an unmanned aerial vehicle (UAV) with mounted magnetometer and digital camera, detecting the underground cavity with ground penetrating radar (GPR), using acoustic equipment like geophones to detect sound (try to hear something), electric resistivity tomography, thermal imaging, through-the-earth communication systems, electric conductivity meter and simulating the movement of the container using 3D simulation software. These solution-based ideas were then divided into two distinct groups. First, locating the container through technological equipment and second, simulating the movement of the container through 3D fluid flow software – similarly to those used to find trapped persons after an avalanche in mountainous areas. At a visit to Lily Mine on the 9th of March, the WMI team suggested a two-way strategy going forward:

– a temporal 3D modelling approach using software technology;

– a scientific measurement and testing approach.

The two approaches were not likely to recover the miners alive but will alert the rescue and mine workers when they are in close proximity to them. There is no doubt that it is necessary to develop an approach to finding missing persons in mining. Lily Mine is not the first mine to have this problem and it will certainly not be the last time we need to find missing miners trapped underground. For the sake of such missing persons, their families, government and the mining industry we need to find them quickly before the window of opportunity to find them alive, closes – as is the case now with Lily Mine. For now, we must learn. The costs of not learning, will be counted in more future lives.

3. THE ROLE OF SOFTWARE IN ANALYSING MINE DISASTERS

This and the next section document the thought process applied to reduce the many technological and software options that can be applied to the problem. This discussion concentrates on the 3D mass movement simulations to model the movement of a solid object on and underneath the surface of the earth.

Although the application of GIS for the extraction industries increased in recent years, its utilization to ensure underground mining safety is rare (Salap, Karslıoglu, &

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[3] These include the CSIR, Schaunenburg (a camera system capable of picking up Lithium concentrations), and Metal Detector SA (MD SA).

[4] The WMI is a new research entity at the University of the Witwatersrand. It is doing research on 21st century mining practices, which research includes digital mining systems. The WMI is also the Coordinator of the Wits Digital Mining Project hosted by the School of Mining Engineering. Mr Dube, CEO of the MHSC, contacted Wits with a request to assist the team at Lily mine by identifying suitable technologies to locate the three miners who were trapped underground after a surface lamp room disappeared into a sinkhole when the crown pillar collapsed. The Wits request came after the mine, volunteer vendors of untested technologies and the CSIR could not successfully locate the container. At the time it was established that the batteries of the cap lamps contain lithium ion and it was hoped that this element could be quickly traced. Since the initial request, the Wits team took on a pro-bono advisory role to the MHSC, channeling ideas and recommendations to the Department of Mineral Resources, the Mine and the Rescue team.

Demirel, 2009). Luo (2013) developed the Underground Mining Safety Production Management System based on GIS technology. His work included a safety status assessment and accident early warning indicator hierarchy in underground mines. GIS based modelling in underground monitoring and safety management systems have been developed to provide hazard monitoring for underground mining. However GIS and 3D modelling is an emerging field for underground rescue operation monitoring. The capabilities of GIS to visualize 3D in real time make it appropriate for hazard assessment and rescue operations. Moridi et al. (2015) developed an Automated Underground Mine Monitoring and Communication System based on the integration of new technologies to promote health and safety, operational management and cost-effectiveness. The system integrated Wireless Sensor Network (WSN) with GIS to monitor and control underground mining applications from surface. Based on the capabilities of WSNs[5], the ZigBee[6] network was adapted for near real-time monitoring, ventilation control and emergency communication in underground mines.

4. CONCEPTUAL APPROACH FOLLOWED FOR DETECTING THE LAMP ROOM CONTAINER

Fundamentally, the objective of the study is to apply science and technology to determine the likely locations of the container, the communicating devices of the miners inside the container and of cause the missing miners. The following specific objectives were set:

– to find the container lamp room in which the three missing miners are buried underground at Lily Mine;

– to identify potential technologies that can locate the container lamp room;

– to apply a combination of science and technology to determine the location of the lamp room container;

– to test certain technologies in a mining environment and to compile a record of findings;

– to compile a record of suitable technologies for future mine search and rescue purposes;

– to collect information that will assist a research project to understand what happened at Lily Mine.

4.1. Data requirements

The data used in this study comprised remotely sensed imageries and related tabulated data. Three sets of digital data were used for the analysis. First, low resolution freely available data was acquired and used for visualization of the area and plotting of geothermal results measured by the UAV. The data comprised of a 10 m spatial resolution[7] SPOT 5 imagery (with a radiometric resolution of 8 bit[8]) which was acquired from the South African National Space Agency (SANSA), 30 m ASTER Global Digital Elevation Model[9] (GDEM) and 10 m GeoEye Google image. Second, high resolution tasking data for simulation and modelling in fluid mechanics software was used. For simulating the movement of the container in dynamic fluid movement software, it is necessary that this data is acquired for both pre and post collapse scenarios. Third, Mine Underground data was acquired from the mine so that the movement of the container can be simulated in the underground environment. This underground mine data was in Lo 31 Cape datum and was first transformed into WGS84[10] to conform with other forms of data being used in the study. The spatial data was geo-referenced to conform to WGS 84 projection and then converted to GIS format for analysis. Data characteristics are given in Table 1.

4.2. Data processing

Raw digital data is generally inconsistent, incomplete, noisy and containing errors or outliers. Data preprocessing involve data cleaning[11], data integration and data transformation (Ye, 2011). Before the digital data can be useful, it is also necessary to pre-process it to remove the inherit inconsistencies. A methodological flow was developed and followed to pre-process the data for the project (Fig. 2). The general image orientation at Lily mine for Google Earth imagery is approximately 30 m offset. This offset is due to an error caused by the spatial resolution and the elevation of acquisition of the imagery (Potere, 2008). The instantaneous field of view(IFOV*)*[12]makes it difficult to distinguish linear features and thus has known horizontal error (Fareed, 2014). In order for the positional accuracy to be accurate we recorded six ground control points (GCP) points in the area (Fig. 3).

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[5] Wireless sensor networks (WSN), are spatially distributed autonomous sensors to monitor physical or environmental conditions, such as temperature, sound, pressure, etc. and to cooperatively pass their data through the network to a main location.

[6] ZigBee is a specification for a suite of high-level communication protocols used to create personal area networks with small, low-power digital radios.

[7] Resolution means smallest observable (measurable) difference in a digital image.

[8] Radiometric resolution is the ability of an image to record many levels of brightness. The finer the radiometric resolution of the sensor, the more sensitive it is in detecting small differences or omitted energy. Image data is represented by positive digital numbers which vary from 0 to a selected power of 2. This range corresponds to the number of bits used for coding numbers in binary format. Each bit records an exponent of power 2. Thus, if 8 bits are used to record the data, there would be $2^8 = 256$ digital values available, ranging from 0 to 255.

[9] The ASTER Global Digital Elevation Model (ASTER GDEM) is a joint product developed and made available to the public by the Ministry of Economy, Trade, and Industry (METI) of Japan and the United States National Aeronautics and Space Administration (NASA). It is generated from data collected from the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), a spaceborne earth observing optical instrument.

[10] The World Geodetic System 1984 (WGS84) is the datum used by the Global Positioning System (GPS). WGS84 is an Earth-cantered, fixed terrestrial reference system and geodetic datum.

[11] Fill in missing values, smooth noisy data, identify or remove outliers, and resolve inconsistencies.

[12] The term Instantaneous Field of view corresponds to the two dimensional ($H \times V$) angular area that is viewed by a *single pixel* of a detector through the optics of an infrared camera. It defines the spatial resolution, or the size of smallest object that can be viewed/resolved at a specific distance from the camera. IFOV is specified in milliradians (mRad) for a given camera and lens combination. This error was clearly visible when we plotted the electromagnetic survey points acquired by the UAV for the possible locations of the container underneath the Lily mine.

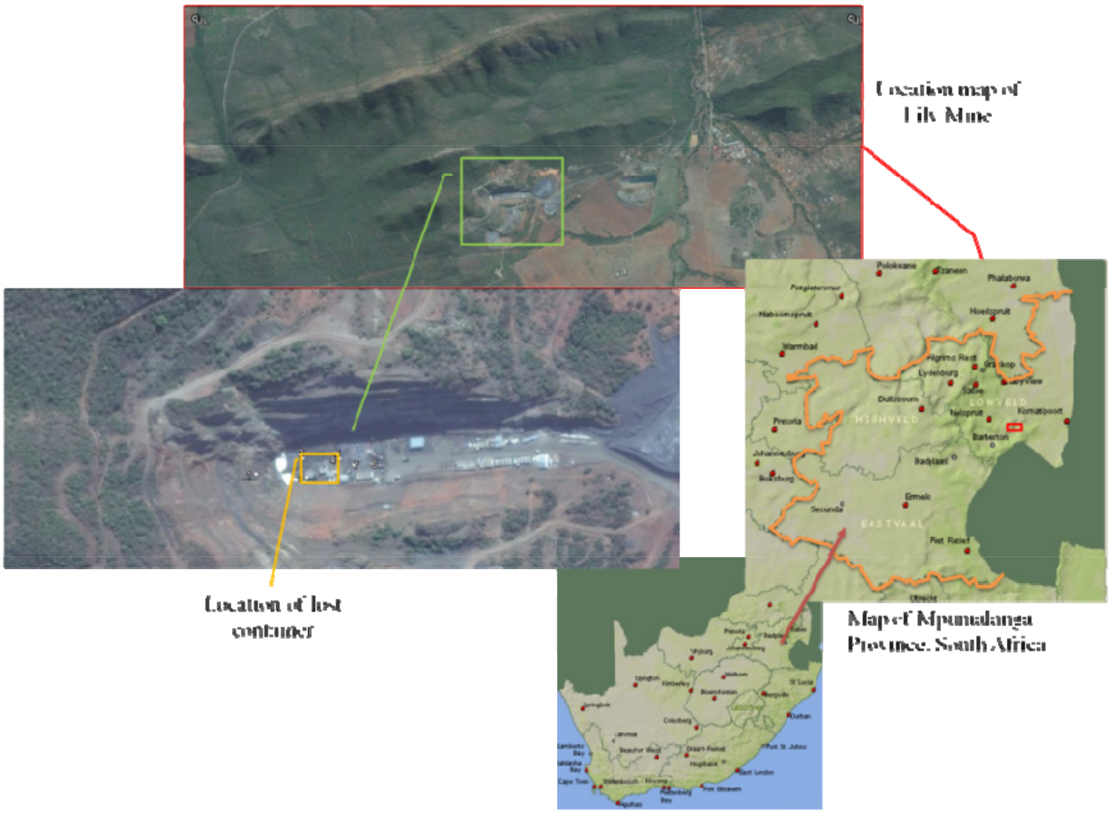

Figure 1. Locality map of the study area

Table 1. Spatial data selected for the model

No.	Data set	Data type	Resolution	Description	Use
			Data set 1 (Free-Low Resolution data)		
1	SPOT 5 Imagery	Raster	10 m	With 90% in cloud cover	Land cover
2	Global Digital Elevation Model	Raster	30 m	Free – ASTER GDEM	Slide hazard assessment on the southern slopes and Slope failure simulation in RAMMS[13]
3	Google Earth image	Raster	10 m	The image was 30 m offset – rectified using 6 GCPs[14]	Land cover
			Data set 2		
4	Pleiades-1 satellite image data	Raster	1 m	Pre 5th February, 2016 data	Pre-collapse slope failure simulation in RAMMS and container movement simulation in FLOW-3D[15]
5	WorldView-2 satellite image data	Raster	1 m	Post 5thFebruary, 2016 data	Post-collapse slope failure simulation in RAMMS & container movement simulation in FLOW-3D
6	2 × DSM[16]	Raster	1 m	Tasking acquisition of new stereo satellite imagery of our project area	Pre and Post-collapse slope failure simulation in RAMMS and container movement simulation in FLOW-3D
			Data set 3 (Mine Underground data)		
7	Underground Mine Data	.dxf[17] in GEMS	—	Underground pit shells data in Lo31° Cape Datum	Pre and Post-collapse container movement simulation in FLOW-3D

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[13] Rapid Mass Simulation Software (RAMMS) is a numerical simulation tool yielding runout distance, flow heights, flow velocities and impact pressure of dense flow snow avalanches, hillslope landslides, and debris flows.

[14] In order for satellite imagery to be of correct spatial perspective, the images need to map the real world locations, for which ground control points (GCPs) are recorded. These are the precise coordinates of locations that can be identified within an image, which are recorded by the surveyors and then communicated to the vendor of the satellite imagery. After acquisition of the image it can then be georeferenced and remapped using GIS software. Without recording GCPs, the accuracy of satellite imagery can be from 10 – 50 meters off. However, once GCPs have been applied to the image, the accuracy improves to 0.5 to 2 meters or better.

[15] FLOW-3D is a CFD software that simulate physical flow processes and free-surface flows. FLOW-3D provides flow simulation solutions for investigating the dynamic behaviour of liquids and gases.

[16] A DSM is an image (raster) in which the pixel values represent the elevations above sea level of the ground and all features on it. So, if there are buildings or trees in the area, for example, the DSM can include those building and tree heights in the elevation values it provides.

[17] AutoCAD DXF (Drawing Interchange Format or Drawing Exchange Format) is a CAD data file format developed by Autodesk for enabling data interoperability between AutoCAD and other programs.

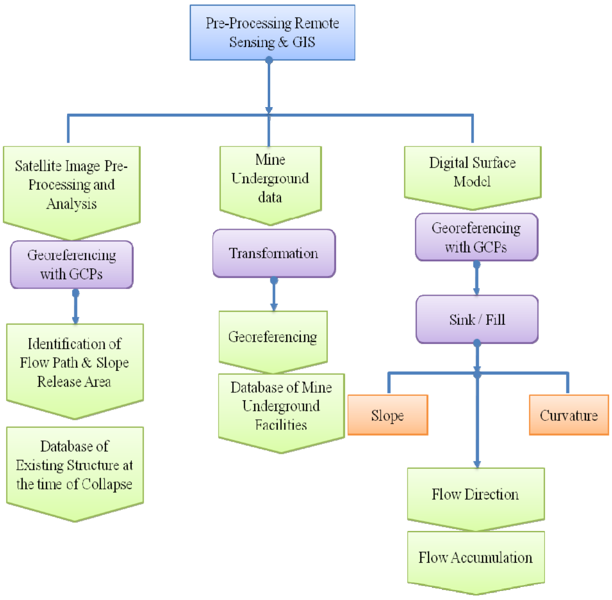

Figure 2. Methodological work flow of pre-processing of data

The image was then geo-referenced in Global Mapper GIS software for correct referencing and modelling. All maps were enhanced and then geometrically corrected prior to the use of satellite imageries. Some visual screen digitization was also done for features like roads and small buildings. As the area under investigation is only confined to the boundary of Lily Mine and its surroundings, it was necessary to extract the area of interest from the complete digital data. This extraction will reduce the calculations required to be done by the FLOW-3D, RAMMS and the GIS model, thereby saving time. Prior to extraction, a new shape file with the extent shown in Figure 4 was created in an ArcGIS environment. The shape file is in the polygon vector format and is in WGS 84 coordinate system.

For horizontal accuracy a digital surface model (DSM) will be created by tasking new stereo satellite imagery of the project area. We provided the vendor with six GCPs for this purpose. As far as vertical accuracy is concerned, we decided on a Level 1 vertical accuracy which has a post spacing of approximately 90 meters. Level 1 vertical accuracy will result in sub-meter accuracy which is important for tracking the vertical movement of the container.

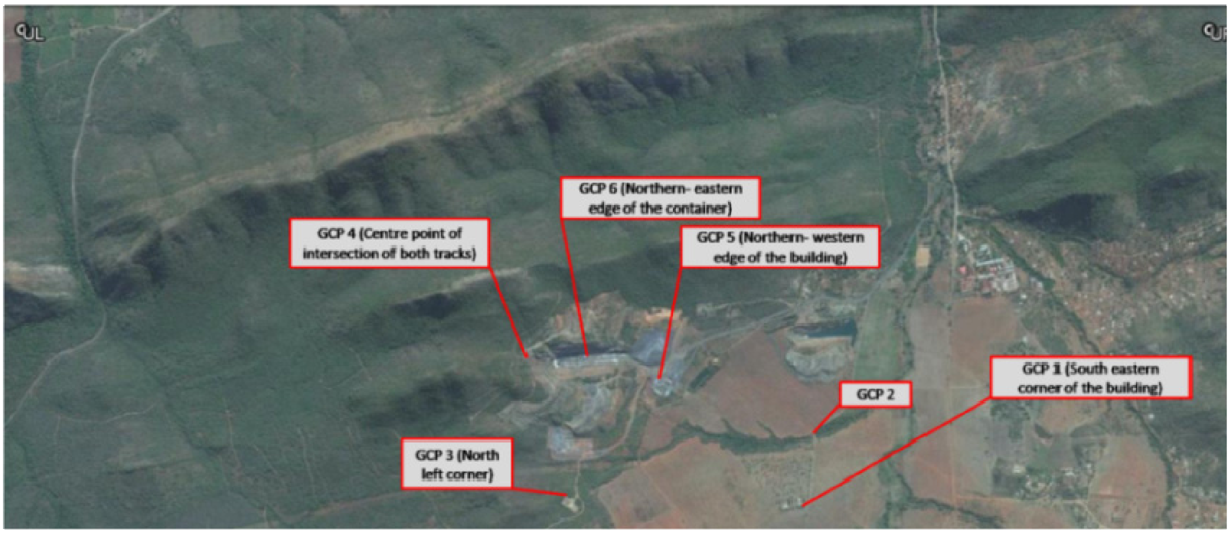

Figure 3. Six GCP points recorded for correct Georeferencing of the digital data

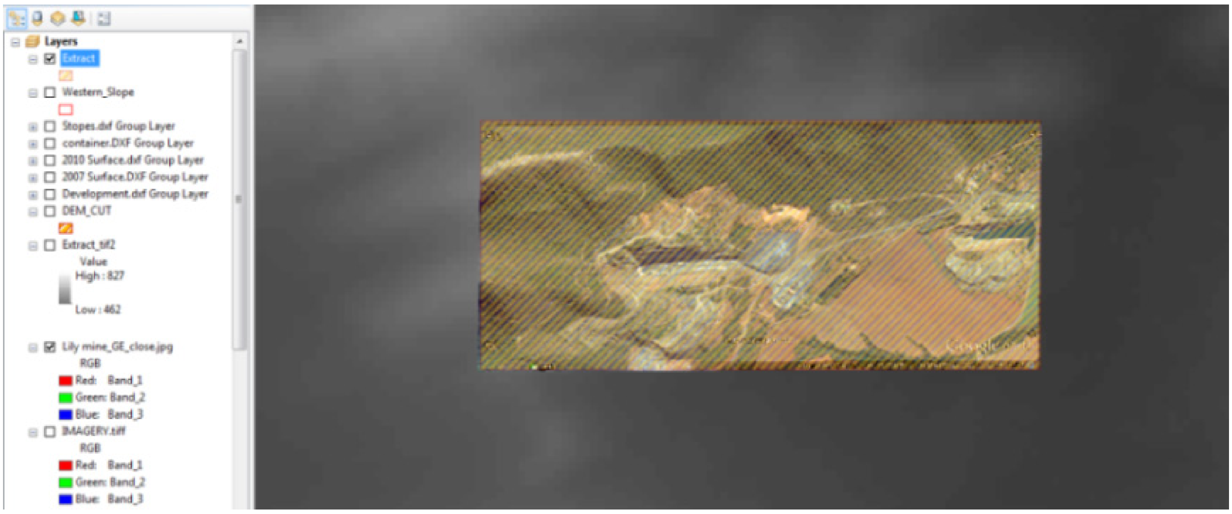

Figure 4. Extents of shape file for extraction of required data

4.2. Datum transformation

The project environment was developed in the WGS 84 coordinate system (Hartebeesthoek datum), while the Mine underground data was in the Lo 31 Cape datum. The underground data was first transformed to the WGS84 coordinate system by applying the transformation parameters using Micro station and Surpac (surveying) software. The transformation parameters were calculated and then applied to the Underground Mine plans using Jador add-on in Microstation. Image enhancement was done by traversing low pass 3 × 3 cell neighbourhood window filters[18] over the raster image. A low-pass filter smoothes the data by reducing local variation and removing noise. It calculates the average value for each 3 × 3 neighbourhood. The effect is that the high and low values within each neighbourhood would average out, reducing the extreme values in the data. The image enhancement technique produced an enhanced scene for clear visual presentation and provided clear information contents for the interpreter.

4.3. Data presentation

For the purpose of modelling in both FLOW-3D and RAMMS, digital elevation data is required. Two types of digital elevation data were used for the modelling. First, the low resolution freely available ASTER GDEM 30 m and second, the high resolution Digital Surface Model (DSM), which incorporates breaklines and manmade features. A DSM includes features above the ground, such as buildings and vegetation and is mostly used for engineering modelling and vertical analysis. The correct requirement of DSM was narrowed down through a process of elimination, whereby two vendors were contacted simultaneously for the acquisition of the DSM. As DSM has to be extracted from a specially tasked aerial photograph, it was necessary to be very specific about its acquisition properties, the level of accuracy and preprocessing parameters. A 1m spatial resolution DSM with 1m vertical accuracy was decided for the modelling.

5. TESTING THROUGH SIMULATION AND MODELLING: OPTIONS CONSIDERED

The unstable slope conditions at the Southern slope after the collapse permitted only one way to rescue the container and that is to remotely find its location with the help of software or technological instrument. The Lily Mine collapse can be divided into three distinct phases:

– first, the initial collapse of the crown pillar, which resulted in a sinkhole, causing the container to drop vertically down and to be buried underneath the debris;

– second, the west slope failure, causing a mass of new debris that was channelled into the portion that already collapsed;

– third, west slope failure triggered the southern slope to become unstable, causing further collapse (Fig. 5).

While Phase 1's collapse is comparable to sinkhole formation, Phases 2 and 3 are similar to the mechanics of an avalanche or slide triggering (Christen, Kowalski, & Bartelt, 2010). A comprehensive literature review was then done to explore software solutions that can track the movement of the container in the process of Lily Mine collapse. There are software (statistical and deterministic) that can predict and simulate the flow of the mass debris for the purpose of locating people and objects buried underneath snow after avalanche occurrence[19]. These can possibly be used to simulate the runout of the debris, there extent, height, mass of the debris deposited and the velocity with which the mass has moved. Three dynamics flow simulation models were identified and a process of elimination was applied by developing a criteria based on the three phases of collapse at Lily Mine (Fig. 5).

Before discussing the three models short-listed for this study it is necessary to establish the methodology which will be followed to locate the container in the underground debris. The conceptual framework is to simulate the movement of container in the first two phases of the collapse, and then plot an underground rescue map to reach the container. The inputs required and the conceptual schema for the modelling are given in Figure 6 and 7.

5.1. Rapid mass movements simulation (RAMMS) software

RAMMS is a numerical simulation tool yielding runout distance, flow heights, flow velocities and impact pressure of dense flow snow avalanches, hill slope landslides, and debris flows (Christen, Kowalski, & Bartelt, 2010). Conceptually, RAMMS could simulate the movement of the container, when it is carried by the moving mass (Phase 1 – Figure 5) (Hergarten & Robl, 2015). This requires a type of "particle tracking" – which the RAMMS team have already considered adding to RAMMS[20], but the software is presently not capable of doing because RAMMS is a Depth-Averaged model. RAMMS assume a constant velocity, meaning the flow velocity is constant through the depth of flow (Christen, Kowalski, & Bartelt, 2010). This is in reality not the case. Material at the bottom of the flow is not carried as far as material at the top of the flow, because of the changing velocity gradients.

Therefore, if the user wants to simulate the container in the sinkhole cavity drop scenario, it would be best to use a full three-dimensional program, because we have to apply a realistic flow rheology for simulation of large particles which are dropping straight down (Phase 1 – Figure 5) (Strnadel, Šiška, & Machač, 2013). If the container is much larger than the debris size, then it will be "pushed" to the top of the flow, called reverse segregation, and end up flowing a long way (Fig. 8). Of course, the container could get jammed behind rocks at the bottom, be crushed, and end up towards the tail of the flow. There are, many different possibilities and assumptions to be made in modelling Phase 1 scenario.

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[18] The Filter tool in ArcGIS was used to eliminate spurious data or enhance features otherwise not visibly apparent in the data. Filters create output values by a moving, overlapping 3 × 3 cell neighbourhood window that scans through the input raster. As the filter passed over each input cell, the value of that cell and its 8 immediate neighbours were used to calculate the output value.

[19] S. Ali and F. Cawood also did mine collapse back analysis using Advance Numerical Modelling Technique in 3DEC. Although the purpose was to understand the collapse and not to locate the container, 3 DEC modelling also allowed for estimating the migration route of the container.

[20] Email correspondence between H. Ashraf and the RAMMS technical team dated 11 March, 2016.

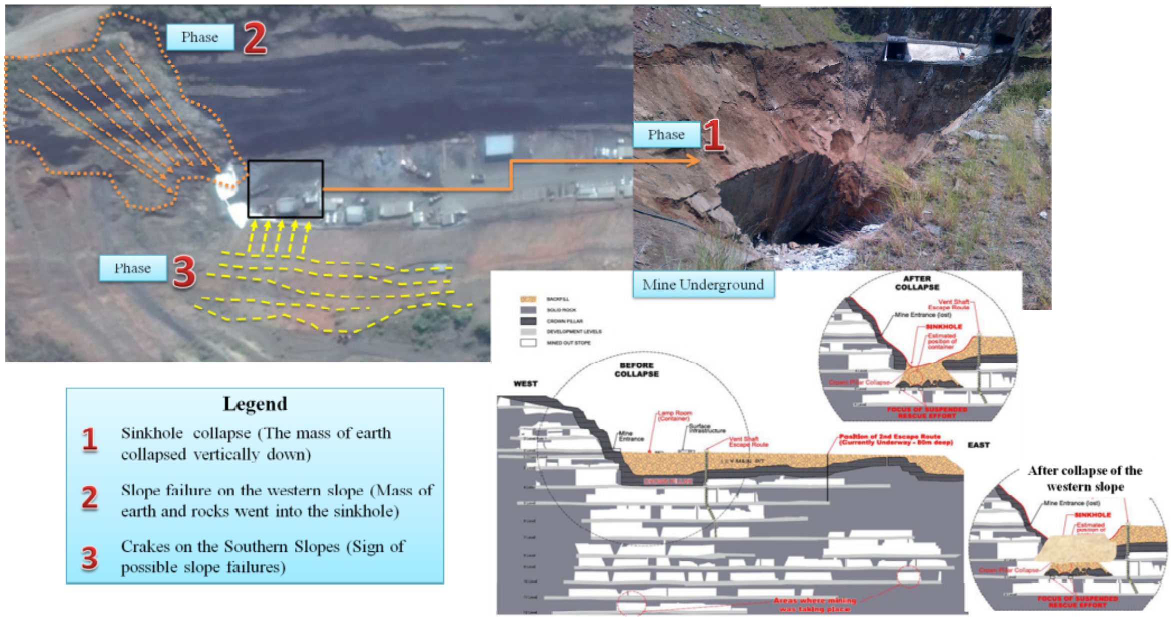

Figure 5. Three phases of the collapse (surface and underground) and the present unstable slope conditions at the Lily Mine

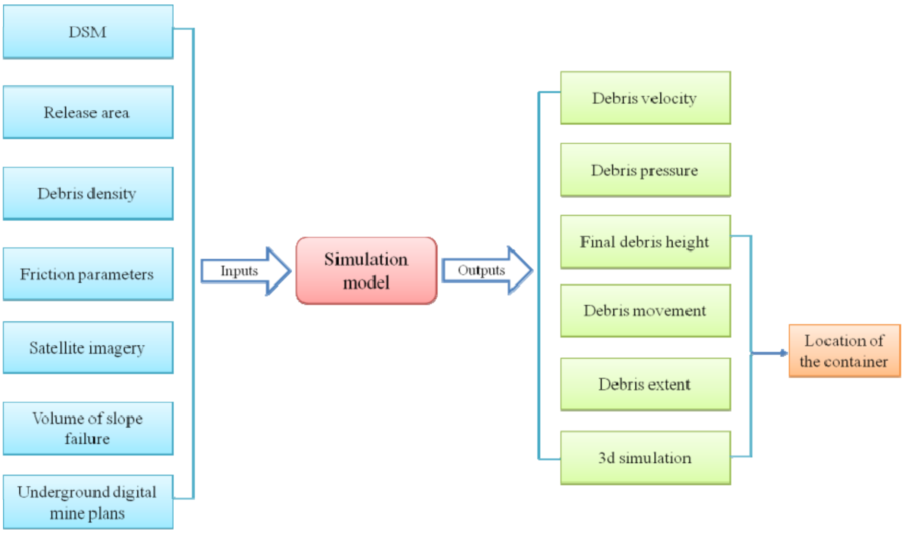

Figure 6. Methodological workflow of Flow Simulation model

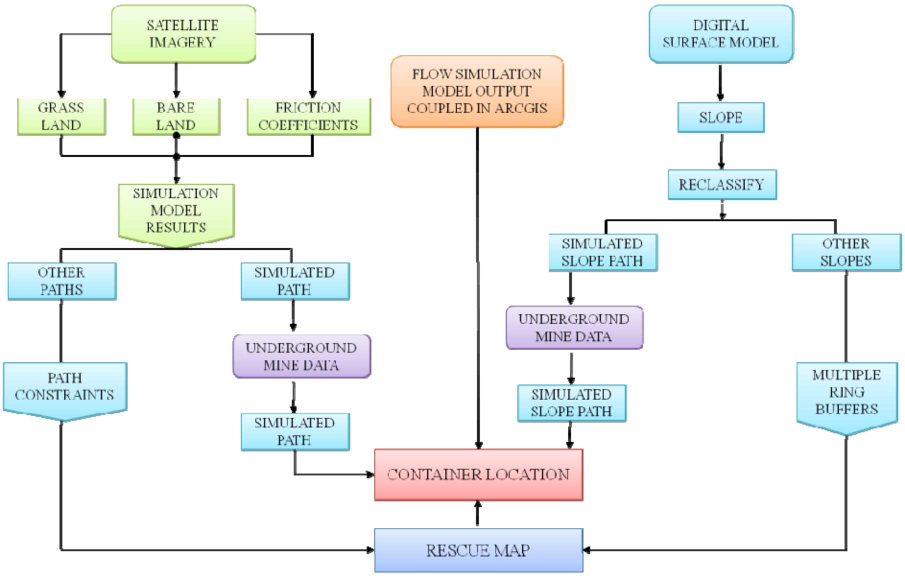

Figure 7. Methodological work flow of Container location and rescue map

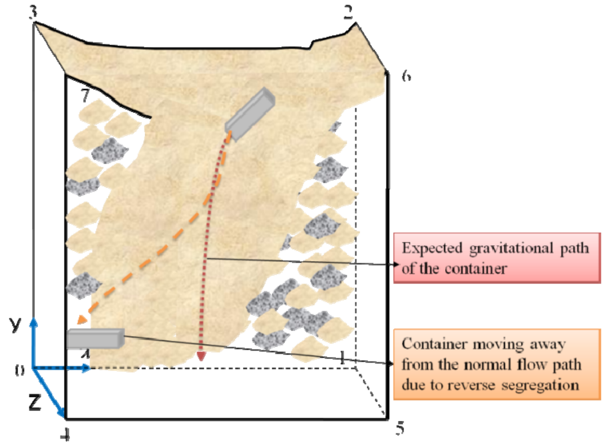

Figure 8. Flow rheology of container dropping straight down and the effect of reverse segregation

Phase 2, i.e. the west slope failure, can be modelled and simulated in RAMMS. It is possible to define a flow surface and let the debris run down the slope. Knowing the volume of debris that has gone into the collapsed mine and the geological parameters of the site, we can predict the location of the container under the mass of debris after the simulation is complete for both the phases. If RAMMS is used for the simulation of the container there are two possible ways to do it:

– we consider the container as part of the earth mass by digitizing it in digital elevation model and then include it as input in the model. This will help us to predict the location of the container, when the simulation of the debris flow is completed in the RAMMS. This option however, would not take the correct flow rheology and reverse segregation into account and may lead to faulty assumptions and results;

– we can consider the container as a granular particle of the earth mass with its own metallic properties and then include it in the input to the model. However in this option, we will have to pre-condition the model to consider the centre of the mass of container to be a tiny earth particle. This condition may give us false simulation as the container may have changed its mass and shape during the debris flow.

5.2. FLOW-3D

FLOW-3D is a powerful and highly-accurate CFD[21] software that gives engineers valuable insight into physical flow processes. With special capabilities for accurately predicting free-surface flows, FLOW-3D is the preferred CFD software for use during the design phase and for improving production processes (Hirt, 2009). FLOW-3D provides flow simulation solutions for investigating the dynamic behaviour of liquids and gases in a wide range of industrial applications and physical processes. FLOW-3D specializes in the solution of time-dependent (transient), free-surface problems in one, two and three dimensions, but can tackle confined flows and steady-state problems as well (Hirt, 2009).

The simulation of the container movement will be based on the Finite-Volume Method to solve the Reynolds Averaged Navier-Stokes (RANS) equations[22] of the fluid motion in Cartesian coordinates. For each cell, average values for the flow parameters (pressure and velocity) are computed at discrete times using a staggered grid technique (Flow3D, 2010). The scale (container versus domain of interest) of the problem is critical to understand. The container itself can be modelled as a moving object. The earth mass may have to be treated a fluid (non-Newtonian) slurry.

Finite element meshes can be imported from third-party mesh generation tools via the Exodus-II file format (Chapokpour, 2012). This provides the means to use high-quality meshes in FLOW-3D's simulations. However, care must be taken to ensure that the domains covered by the imported meshes coincide with the definition of the geometry in FLOW-3D (Wang, 2008). The geometrical model for sinkhole cavity is in the form of wireframes generated in GEMS[23] and are in the form of .dxf files (CAD files). These wireframes[24] (and pit shells) were based on Lo31° Cape Datum (Fig. 9). The Container as a wireframe fixed in its original position is also included. The surface terrain can be included either using AUTOCAD 3D or as digital data. The mesh grid was composed by four different mesh blocks, including one nested-block for the surface of the Mine (Fig. 9). The boundary conditions can be specified for the initial Sinkhole collapse which was vertically down.

In a FLOW-3D simulation, a general moving object (GMO) is a rigid body with any kind of motion that is either user-prescribed or dynamically coupled with fluid flow (Wang, 2008). It can have six-degrees-of-freedom or motion constraints such as a fixed axis/point. Prescribed forces and torques can be applied on a GMO under coupled motion. The GMO model allows multiple rigid bodies under independent motion types as well as rigid body interactions including collisions and continuous contact (Hirt, 2009). The Sediment Scour Model in FLOW-3D can simulate all the sediment transport processes of non-cohesive soil including bed load transport, suspended load transport, entrainment and deposition (Wei et al., 2014). It allows multiple sediment species with different properties such as grain size, mass density and critical shear stress. The container can be modelled in the sediment scour model as bed load transport for the initial Sinkhole collapse (Phase 1 – Fig. 5). As it moves, it is considered as suspended load transport for simulation of its final deposition. The modelling must be done on a coarser mesh (1 m cell size) to validate and set the project environments according to the FLOW-3D default simulations configurations (Wang, 2008).

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[21] Computational fluid dynamics, usually abbreviated as CFD, is a branch of fluid mechanics that uses numerical analysis and algorithms to solve and analyze problems that involve fluid flows.

[22] The Reynolds-averaged Navier-Stokes equations (or RANS equations) are time-averaged (the limit must be independent of the initial time condition) equations of motion for fluid flow. The RANS equations are primarily used to describe turbulent flows.

[23] GEM is a metafile format that contain vector image information created when using programs such as GEMDraw. GEM stands for Graphical Environment Manager, and is generally linked to the desktop publishing programs created by Ventura.

[24] The wireframes were first converted to WGS84 coordinate system using Surpac Survey software.

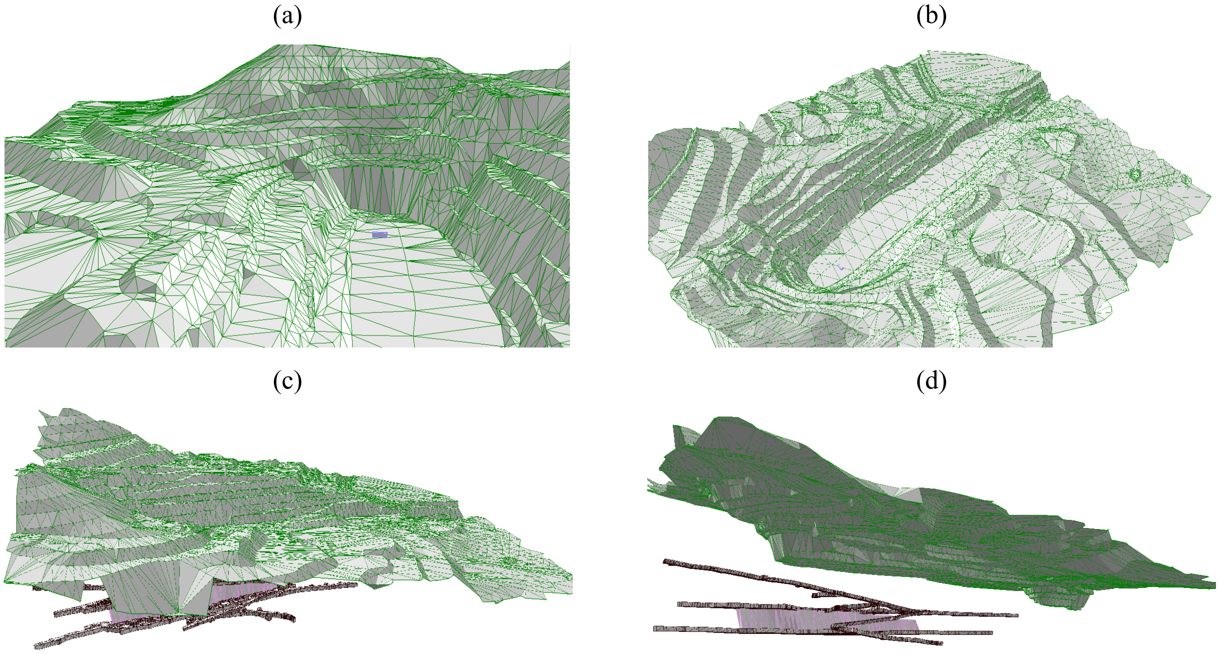

Figure 9. Mesh grid generated for Lily Mine: (a) nested-block for the surface of the mine; (b) mesh block generated for the mine general area; (c) mesh-block created for the mine underground environment; (d) mesh-block created for the mine underground environment, from a different angle

FLOW-3D has following capabilities:

– the characteristic to fully couple the objects with fluid flow, alternatively, the user can prescribe motion;

– objects can be of several materials characterized by their density and there is no restriction on complexities of geometry;

– motion of objects and specified time-dependent forces and torques can be applied to the objects (Cast, 2016);

– FLOW-3D can also model and simulate the slope failure on the western side of the Mine (Phase 2 – Figure 5) in Sediment Scour Model and Granular Flow, which is an inbuilt capability of the model.

We can finally locate the location of the container with FLOW-3D in the underground Mine. The model results can then be integrated in GIS to view a holistic view of the simulation scenario.

5.3. OpenFOAM

OpenFOAM (Open Field Operation and Manipulation) CFD Toolbox is a free, open source CFD software package which has a large user base across most areas of engineering and science, from both commercial and academic organisations (Jasak, 2009). OpenFOAM has an extensive range of features to solve anything from complex fluid flows involving chemical reactions, turbulence and heat transfer, to solid dynamics and electromagnetic (Ospald, 2014). It includes tools for meshing[25], notably SnappyHexMesh[26], a parallelised mesher for complex CAD geometries, and for pre- and post-processing (Jasak, 2009; Monakov, 2012). One of the strengths of OpenFOAM is that new solvers and utilities can be created by its users with some pre-requisite knowledge of the underlying method, physics and programming techniques involved (Fitzpatrick, Glass, & Pascoe, 2015).

Using OpenFOAM,a mesh can be created to symbolize the sinkhole created by the collapse at Lily Mine (Fig. 10). OpenFOAM Project parameters can be set in a 3D Cartesian coordinate system and all geometries can be generated in three dimensions. The Sinkhole cavity domain consists of a square of side length $d = 0.1$ m in the $x - y$ plane. A uniform mesh of 20 by 20 cells can be used initially, whose block structure is shown in Figure 10. The mesh generator supplied with OpenFOAM, blockMesh, generates meshes from a description specified in an input dictionary, blockMeshDict located in the system (or constant/polyMesh) directory for a given case. The blockMeshDict entries for this case are shown in Figure 10.

Once the mesh is generated (at start time $t = 0$), the initial field data (before the collapse) is stored in a 0 sub-directory. The boundary conditions are set, which consists of two wall patches namely:

– fixed Walls for the fixed sides and base of the Sinkhole cavity;

– moving Wall for the moving top of the sinkhole cavity. Both walls should be given a zero Gradient boundary condition for the pre-collapse scenario.

For simulating the movement of the container, the movingWall boundary conditions for the sinkhole cavity (top earth surface) can be set moving with certain slope for the time when the collapse triggered. The execution of the simulation can then be setup according to conditions which were observed after the collapse. The fixed-Walls boundary conditions for this case, has to be static

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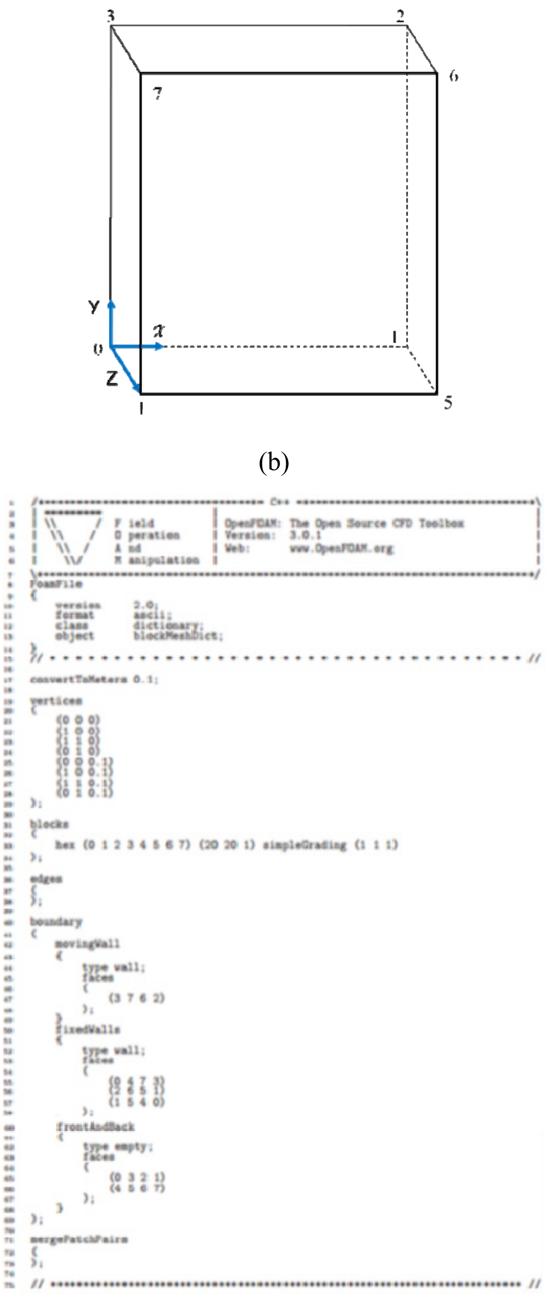
[25] Mesh generation is the practice of generating a polygonal mesh that approximates a geometric domain. The term "grid generation" is often used interchangeably. Image-based meshing is the automated process of creating computer models for computational fluid dynamics (CFD) and finite element analysis (FEA) from 3D image.

[26] SnappyHexMesh is a mesh generator that takes an already existing mesh (usually created with blockMesh) and chisels it into the mesh you want.

and uniform because the model cannot execute the simulation with all boundary conditions moving. The boundary field for velocity requires the same boundary condition as for the simulation. OpenFOAM software can yield encouraging results for simulation of the lost container if the boundary conditions remain the same throughout the simulation. Further simulation in OpenFOAM, after subsequent level collapse could however, be difficult as the boundary conditions cannot be set moving for both movingWalls and fixedWalls. The software's utilization for slope failure is also not ideal as it cannot be bounded into a complete mesh with boundary conditions.


(a)

(b)

```
/*--------------------------------- C++ -----------------------------------*\
| =========                 |                                                 |
| \\      /  F ield         | OpenFOAM: The Open Source CFD Toolbox           |
|  \\    /   O peration     | Version:  3.0.1                                 |
|   \\  /    A nd           | Web:      www.OpenFOAM.org                      |
|    \\/     M anipulation  |                                                 |
\*---------------------------------------------------------------------------*/
FoamFile
{
    version     2.0;
    format      ascii;
    class       dictionary;
    object      blockMeshDict;
}
// * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * //

convertToMeters 0.1;

vertices
(
    (0 0 0)
    (1 0 0)
    (1 1 0)
    (0 1 0)
    (0 0 0.1)
    (1 0 0.1)
    (1 1 0.1)
    (0 1 0.1)
);

blocks
(
    hex (0 1 2 3 4 5 6 7) (20 20 1) simpleGrading (1 1 1)
);

edges
(
);

boundary
(
    movingWall
    {
        type wall;
        faces
        (
            (3 7 6 2)
        );
    }
    fixedWalls
    {
        type wall;
        faces
        (
            (0 4 7 3)
            (2 6 5 1)
            (1 5 4 0)
        );
    }
    frontAndBack
    {
        type empty;
        faces
        (
            (0 3 2 1)
            (4 5 6 7)
        );
    }
);

mergePatchPairs
(
);

// ************************************************************************* //
```

Figure 10. Block structure mesh for the sinkhole cavity at the Lily Mine: (a) the Sinkhole cavity domain consisting of a square created in Open-foam; (b) the blockMeshDict entries for the mesh created in Open-foam

5.4. Spatial Analyst – ArcGIS

The Spatial Analyst extension of ArcGIS provides a broad range of powerful spatial modelling and analysis capabilities. According to Bai, Chen, & Yu (2012) spatial analyst provides capabilities to:

– create, query, map, and analyze cell-based raster data;

– perform integrated raster/vector analysis;

– derive new information from existing data;

– query information across multiple data layers;

– fully integrate cell-based raster data with traditional vector data sources.

ArcGIS is an excellent GIS software which can be integrated with other statistical and deterministic models for easy visualization. In addition, the simulation results of RAMMS, FLOW-3D and OpenFOAM can be visualized in ArcMap and its results can be integrated with the GIS database. Due to the collapse at Lily Mine, the surrounding slopes have become more unstable. This is because of the change in the stability conditions of the ground and the subsequent force stability ratio which has disturbed in the area. There are visible cracks (0.05 – 100 mm in width) on the southern slopes of the mine which are increasing with time (Fig. 11).

Figure 11. Visible crakes in the Southern Slopes above the Mine

For the safety of the mine workers and the general security of the area it is necessary to create a slope analysis map of the area. Hazard assessments are a simple way to understand the complicated dynamics that control observed natural phenomena. What is more, they can guide us to be better prepared for inevitable damage resulting from natural disasters, such as slope failure. ArcGIS can be used for slope failure analysis and is based on slope analysis in the Spatial analyst. Future assessments could take into account other factors for a more complete analysis, such as known fault zones, soil cohesion, logging/deforestation rates and erosion rates.

6. STRATEGY ON THE ROLE OF MODELLING SOFTWARE TO DETECT THE CONTAINER IN WHICH THE MINERS WERE TRAPPED – A POOR MAN'S APPROACH

The strategy to follow is to identify suitable software to determine the likely locations of the container. We have followed a poor man's approach to model the simulation in open source software using freely available low resolution data. However, the simulation to find the exact location of the container can be done with the help of fit for purpose software identified as a process of this research. Due to the time required for acquisition and purchasing of new satellite imagery, DSM and model, the simulation was first done on the freely available data and model. OpenFOAM is an open source software and as discussed earlier it can simulate the lost container in Phase 1. This will give us the approximate location of the container after the sinkhole collapse. We can then do the slope failure analysis in ArcGIS for both Phase 2 and 3. These results will then be plotted with the help of ArcGIS to approximate the location of the container.

6.1. Imagery and DEM

The complexity of the problem and the presence of human lives necessitates the use of highly accurate data. In order for the correct simulation of the movement of the container, it is necessary to visualize and simulate-both before and after the collapse. As the purpose of the modelling is to locate the container, it is recommended that high resolution data should be used in all the simulations and modelling discussed above. A 1m resolution DSM and a 1 m resolution satellite imagery should be acquired using GCPs for correct spatial perspective. The mine underground data should be used after transforming it into WGS84 coordinate system for similar project environment. The recommended data for the project is given in Table 2.

Table 2. Recommended digital data for simulation and model

No.	Data set	Data type	Resolution	Description	Use
1	2 × DSM[27]	DEM	1 m	Stereo Imagery extracted 1 m posting	Slope failure simulation in RAMMS Container movement simulation in FLOW-3D
2	2 × Satellite image data[28]	Raster	1 m	4-band pansharpened (inc. Near IR) or 0.5 m panchromatic and 2.0 m 4-band multispectral	Slope failure simulation in RAMMS Container movement simulation in FLOW-3D
3	Underground Mine Data	.dxf[29] generated in GEMS	—	Underground pit shells data in Lo31° Cape Datum	Pre- and Post-collapse container movement simulation in FLOW-3D

6.2. Software

The fit for model for simulating the location of the container is based on its ability to simulate and model three phases of the collapse (Phase 1, 2 and 3 – Figure 5). Conceptually, RAMMS can simulate the movement of the container in the cavity like collapse, when it is carried by the moving mass, but is presently not implemented in RAMMS being a Depth-Averaged model. RAMMS, therefore, is not a suitable option for simulating the "Phase 1" collapse. The "Phase 2" scenario of slope failure on the western slope can however, be simulated in the RAMMS by defining the flow surface. The Sediment Scour Model in FLOW-3D can simulate the Sinkhole cavity collapse (Phase 1). The container can be modelled as a bed load transport, and when it moves, it can be considered as suspended load transport. FLOW-3D can also simulate the slope failure on the western side of the Mine (Phase 2) in Sediment Scour Model and Granular Flow, which is an inbuilt capability of the model. OpenFOAM software can simulate the lost container only if the boundary conditions remain constant throughout the simulation (Phase 1). The software however, may not yield realistic results for the slope failure in "Phase 1". ArcGIS has limited simulation capabilities, so it cannot be used for simulation in "Phase 1 & 2". However, it has excellent coupling capabilities and the results of the simulations can be visualized in correct geographic context in ArcGIS. The results of the three software capabilities as regards to the simulation in the three phases of the collapse are summarized in Table 3.

Table 3. Flow simulation models and the criteria for their selection

No.	Software	Phases of the collapse			Recommended model
		Sinkhole simulation	Slope collapse simulation	Hazard analysis	
1	RAMMS	—	✓	✓	FLOW-3D & Spatial Analyst ArcGIS
2	FLOW-3D	✓	✓	—	
3	OpenFOAM	✓	—	—	
4	Spatial Analyst ArcGIS	—	—	✓	

The nature and complexity of the situation at Lily mine does not allow us to use one model for all three phases of the collapse. It is recommended that FLOW-3D (Phase 1 & 2) and ArcGIS (Phase 3) should be used for the modelling at Lily mine.

7. SAMPLE MODELLING OF THE CONTAINER USING OpenFOAM AND SLOPE ANALYSIS IN ArcGIS

A mesh was created in OpenFOAM having origin at (0, 0, 0) and dimensions in X, Y, Z direction as (0.5, 0.5, 0.01). The initial mesh bounds were defined which is 3 dimensional cube. All the dimensions in OpenFOAM are set in SI system. All the boundary conditions were set to wall for X, Y and Z plans, so that the movement of the container remain confined to the boundaries of the mesh created. An enclosed computational domain was developed to put the container in the domain. To specify the initial location of the container we created another cube in the geometry panel and de-

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[27] 1 × Pre disaster and 1 × Post disaster DSM.

[28] 1 × Pre disaster and 1 × Post disaster Satellite image.

[29] AutoCAD DXF (Drawing Interchange Format, or Drawing Exchange Format) is a CAD data file format developed by Autodesk for enabling data interoperability between AutoCAD and other programs.

fined the container's origin and dimensions (Table 4). As it is a known fact that the collapse was like a sinkhole into a known space (i.e. mined area), it was assumed that the container will fall into a bowl of soil at level 4 of the Mine. A third box was created which will define this underground soil like a bowl.

Table 4. Box geometries created in OpenFOAM with origins and dimensions

Box	Description	Origin (*XYZ*)	Dimension (*XYZ*)
1	Lamp room container at surface of the mine	(0.17, 0.5, –0.02)	(0.05, 0.025, 05)
2	Box representing the soil at level 4 of the underground mine	(0, 0.1, –0.1)	(0.5, 0.05, 0.2)
3	Spatial resolution refinement layer in the region between the level 4 of the underground mine and ground surface	(0, 0.15, –0.1)	(0.5, 0.15, 0.2)
4	Spatial resolution refinement layer close to the container which will be falling driven by the gravitational acceleration	(0.15, 0.3, –01)	(0.1, 0.2, 0.2)

When the container fell into the sinkhole, some movement can be expected in the underground soil. To improve the spatial resolution in the regions between the soil and void surfaces, the mesh was refined near the interface between these two faces. We used two more boxes in order to define the regions of the mesh which will be refined. One to refine the soil region and a layer of voids just above the level four (Fig. 5), and the other, close to the container which will be falling driven by the gravitational acceleration. The refinement operation was done for *X* and *Y* axis only because we have used only one cell across the *Z* axis[30].

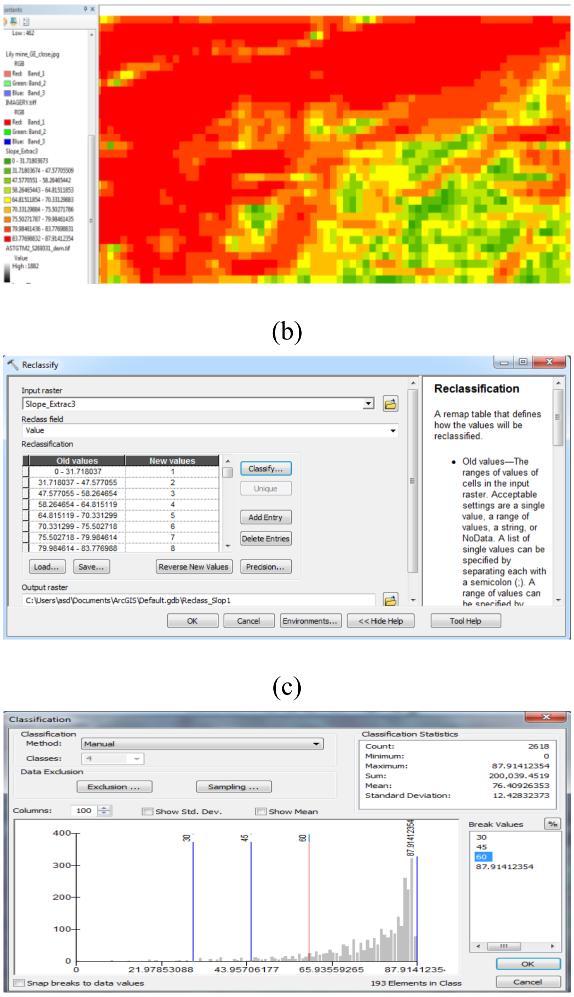
The mesh was then renumbered in the software to renumber the cells list in order to reduce the band width reading and renumbering all fields for all the time directories. The mesh was then verified for correctness in Check mesh tool. A Transient-Species transport-ReactingParcelFilmFoam solver was used in OpenFOAM for solving the problem. The solver is an inbuilt OpenFOAM solver for solid particle movement in transient PISO[31] solver for compressible, laminar or turbulent flow with reacting Lagrangian parcels, and surface film modelling. The algorithm is summed up as follows:

– set the boundary conditions;
– solve the discretized momentum equation to compute an intermediate velocity field;
– compute the mass fluxes at the cells faces;
– solve the pressure equation;
– correct the mass fluxes at the cell faces;
– correct the velocities on the basis of the new pressure field;
– update the boundary conditions;
– repeat from third step for the prescribed number of times;
– increase the time step and repeat from first step.

The transport properties were then defined by selecting properties from the software database. In the software database soil was added as new material with its properties, whereas the container was assigned the properties of Steel-solid from the available materials in the database. The operating conditions were then set by assigning gravitational acceleration in the negative *Y* axis. Output control parameters were set in the control panel of the software. The write control was set to run time whereas the time interval was modified to 0.02 seconds, so that the software save files for the run time independent of the actual time step used during the simulation.

The most important factor in a slope failure or landslide is the slope itself (Sharifzadeh, Sharifi, & Delbari, 2009). Since these events are gravity-driven, it stands to reason, that the closer the topography gets to true gravitational acceleration, the more probable a landslide will occur (Bouissou, Darnault, Chemenda, & Rolland, 2012). The slope analysis for the Lily mine area was then done in ArcGIS Spatial Analyst tool. Slope for the extracted DEM of the area were calculated in Slope tool of spatial analyst (Fig. 12). The slopes were reclassified in Reclassify tool to get the most critical DEM cells according to the value of their slope.

(a)



Input raster: Slope_Extrac3
Reclass field: Value
Reclassification

Old values	New values
0 - 31.718037	1
31.718037 - 47.577055	2
47.577055 - 58.264654	3
58.264654 - 64.815119	4
64.815119 - 70.331299	5
70.331299 - 75.502718	6
75.502718 - 79.984614	7
79.984614 - 83.776988	8

Output raster: C:\Users\asd\Documents\ArcGIS\Default.gdb\Reclass_Slop1

Reclassification

A remap table that defines how the values will be reclassified.

- Old values—The ranges of values of cells in the input raster. Acceptable settings are a single value, a range of values, a string, or NoData. A list of single values can be specified by separating each with a semicolon (;). A range of values can be specified by

Classification
Method: Manual
Classes: 4
Data Exclusion
Columns: 100

Classification Statistics

Count:	2618
Minimum:	0
Maximum:	87.91412354
Sum:	200,039.4519
Mean:	76.40926353
Standard Deviation:	12.42832373

Break Values
30
45
60
87.91412354

193 Elements in Class

Figure 12. Slope analysis of Lily Mine area in Spatial Analyst – ArcGIS: (a) slope calculation of the area; (b) classification of the slopes; (c) analysis of the slope

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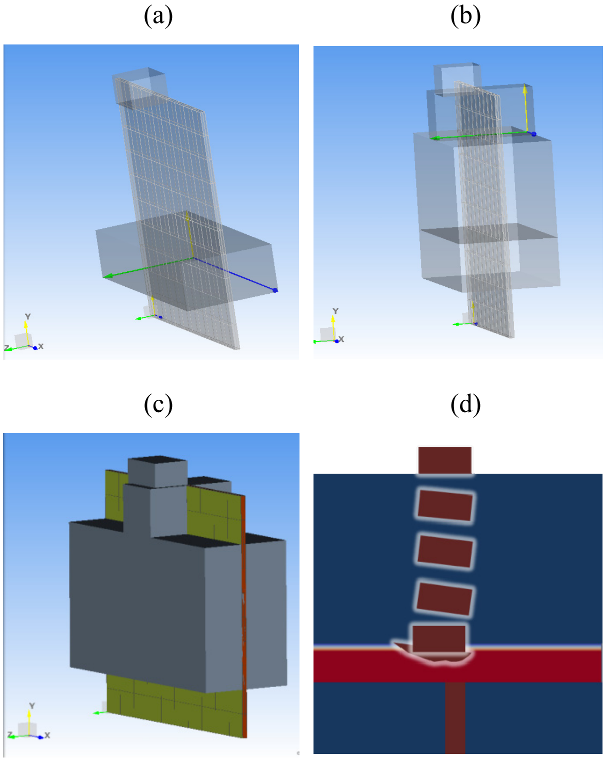
[30] The refinement along the *Z* axis is not allowed on the free version of the software. The free version does not allow mesh larger than 100000 nodes.

[31] The PISO (Pressure Implicit with Splitting of Operators) is an efficient method to solve the Navier-Stokes equations in unsteady problems.

8. RESULTS AND DISCUSSION

A simulation was run and the results were analysed in post processing unit. Paraview software was used to post process the results. The container took a vertical path and the final location is shown in Figure 13.


(a) (b)

(c) (d)

Figure 13. Mesh generation, box generation and simulation of container collapse: (a) mesh generation; (b) block generation; (c) geometry of the collapse scenario; (d) simulation of the fall of the container

ParaView is an open-source, multi-platform application designed to visualize data sets of varying sizes from small to very large. ParaView uses the Visualization Toolkit as the data processing and rendering engine and has a user interface written using the *Qt* cross-platform application framework. The further collapse of the level 4 and the pillar underneath it cannot be performed in the OpenFOAM. It is however, suggested that the container will be laying to the left of the pillar due to its geometry and the pattern of the further collapse.

One of the important aspect of the rescue operation for the location of the container is the safety of the rescue team. The slope conditions at the southern slope of the Mine are unstable and were analysed in the ArcGIS software (Phase 3). The slope analysis results are shown in Figure 14. There are a total of thirty six DEM cell whose slope values are between 30 – 60°. Ten DEM cell are critical from slope failure point of view as their slope values are between 40 – 50° and these should be continuously monitored.

9. CONCLUSION

Underground mining is an activity which is prone to accidents, sometimes even disasters. These accidents may cause fatalities, injuries and also have significant economic losses as consequences. Such an accident occurred at the Lily Mine on 5th February, 2016, when the crown pillar of the underground mine collapsed. The lamp room container with three miners subsided and was lost in the sinkhole along with two 550 KVA transformers, one generator and two steel water tanks. The collapse was divided into three distinct phases, Sinkhole collapse, slope failure on the western slope and slide hazard on the southern slopes. Software technologies were identified which can simulate the movement of the container in first two phases of the collapse.

Figure 14. Slope hazard assessment map of the Lily Mine area

Rapid Mass Movement Software can simulate the movement of the container in the "Phase B" of the slope failure on the western slope, whereas it is not suitable for simulating the "Phase A" of the Sinkhole collapse. FLOW-3D flow dynamic software can simulate both "Phase A & B" of the collapse due to its rich 3D modelling capabilities. OpenFOAM is an open software and was used to simulate the "Phase A" of the collapse by creating a block mesh for the sinkhole at the Mine and then setting up the necessary boundary conditions. The simulation was done in the ParaView software and approximate location of the container was ascertain. ArcGIS was used to perform the slope analysis on the southern slope of the mine and slope hazard map was created for the area.

10. RECOMMENDATIONS

A combination of ArcGIS and FLOW-3D simulation software can be used to simulate the estimated migration path of objects following a mine collapse.

An underground rescue map with evacuation routes should be developed based on the results of the FLOW-3D in ArcGIS to attempt a rescue.

The skill-set of Mining Engineering graduates must be such that they are able to identify and apply sophisticated software package after receiving some basic training on these software.

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ПОЛІПШЕННЯ БЕЗПЕКИ ГІРНИЧИХ РОБІТ: РОЛЬ КОМП'ЮТЕРНОГО МОДЕЛЮВАННЯ У РОЗШУКУ ЛЮДЕЙ, ЗНИКЛИХ У РЕЗУЛЬТАТІ ОБВАЛЕННЯ ШАХТИ

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Мета. Визначення можливого місця локалізації лампового приміщення контейнера, в якому опинилися три шахтаря після аварії на шахті Лілі (Барбертон, Мпумаланга) методом комп'ютерного моделювання. Після обвалення стельового цілика на шахті Лілі 5 лютого 2016 року почалася національна кампанія з порятунку трьох шахтарів, які залишилися у ламповому приміщенні поверхневого транспортного контейнера, що провалився в утворену після вибуху воронку.

Методика. Співробітниками Гірничого Інституту (Уітуотерс) запропонована двостадійна стратегія пошуку контейнера, в якому існує ймовірність знаходження шахтарів. В рамках першого підходу (який розглядається у даній статті) для виявлення контейнера здійснювалось випробування комп'ютерної технології 3D-моделювання в часі. Другий підхід передбачав технологію проведення наукового вимірювання та експерименту. В цілому, методологія включала, насамперед, підключення викладацького та наукового складу університету до вирішення проблеми шляхом комплексної генерації ідей, які були об'єднані в загальний список, вивчені із залученням відповідних літературних джерел, і найбільш реалістичні ідеї були виділені із загального переліку. Дана стаття розглядає результати комп'ютерної експертизи цих ідей та перевірки надійності відповідного програмного забезпечення.

Результати. Для зручності моделювання процес обвалення був розділений на три окремі фази: руйнування воронки, руйнування західного схилу та небезпека ковзання на південних схилах. Ідентифіковано програмні технології, які можуть імітувати рух контейнера у перших двох фазах обвалення. В результаті моделювання у програмному забезпеченні ParaView виявлено місце розташування даного контейнера. Виконано аналіз південного схилу за допомогою ArcGIS і складені карти небезпеки схилу для району, а також підземні карти порятунку з маршрутами евакуації. Встановлено, що комп'ютерне моделювання може визначити місцезнаходження контейнера, але для цього потрібні точні вихідні дані й комплекс дорогих високоефективних програмних пакетів.

Наукова новизна. Вперше застосовано комплекс комп'ютерних технологій та програмного забезпечення для пошуку зниклих шахтарів після аварійних ситуацій у підземному просторі шахт.

Практична значимість. При застосуванні двостадійної стратегії пошуку шахтарів, що опинилися під завалом порід, команда рятувальників отримає сигнал про наближення до їх місцезнаходження.

Ключові слова: *безпека гірничих робіт, зниклі шахтарі, комп'ютерне моделювання, фази обвалення, програмне забезпечення, підземна розробка*

УЛУЧШЕНИЕ БЕЗОПАСНОСТИ ГОРНЫХ РАБОТ: РОЛЬ КОМПЬЮТЕРНОГО МОДЕЛИРОВАНИЯ В РОЗЫСКЕ ЛЮДЕЙ, ПРОПАВШИХ В РЕЗУЛЬТАТЕ ОБРУШЕНИЯ ШАХТЫ

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Цель. Определение возможного места локализации лампового помещения контейнера, в котором оказались три шахтера после аварии на шахте Лили (Барбертон, Мпумаланга) методом компьютерного моделирования. После обрушения потолочного целика на шахте Лили 5 февраля 2016 года началась национальная кампания по спасению трех шахтеров, оставшихся в ламповом помещении поверхностного транспортного контейнера, который провалился в воронку, образовавшуюся после взрыва.

Методика. Сотрудниками Горного Института (Уитуотерс) предложена двухстадийная стратегия поиска контейнера, в котором существует вероятность нахождения шахтеров. В рамках первого подхода (который рассматривается в данной статье) для обнаружения контейнера производилось испытание компьютерной технологии 3D-моделирования во времени. Второй подход предполагал технологию проведения научного измерения и эксперимента. В целом, методология включала, прежде всего, подключение преподавательского и научного состава университета к решению проблемы путем комплексной генерации идей, которые были объединены в общий список, изучены с привлечением соответствующих литературных источников, и наиболее реалистичные идеи были выделены из общего списка. Настоящая статья рассматривает результаты компьютерной экспертизы данных идей и проверки надежности соответствующего программного обеспечения.

Результаты. Для удобства моделирования процесс обрушения был разделен на три отдельные фазы: разрушение воронки, разрушение западного склона и опасность скольжения на южных склонах. Идентифицированы программные технологии, которые могут имитировать движение контейнера в первых двух фазах обрушения. В результате моделирования в программном обеспечении ParaView выявлено местоположение данного контейнера. Выполнен анализа южного склона с помощью ArcGIS и составлены карты опасности склона для района, а также подземные карты спасения с маршрутами эвакуации. Установлено, что компьютерное моделирование может определить местонахождение контейнера, но для этого нужны точные исходные данные и комплекс дорогостоящих высокоэффективных программных пакетов.

Научная новизна. Впервые применен комплекс компьютерных технологий и программного обеспечения для поиска пропавших шахтеров после аварийных ситуаций в подземном пространстве шахт.

Практическая значимость. При применении двухстадийной стратегии поиска шахтеров, оказавшихся под завалом пород, команда горноспасателей получит сигнал о приближении к их местонахождению.

Ключевые слова: *безопасность горных работ, пропавшие шахтеры, компьютерное моделирование, фазы обрушения, программное обеспечение, подземная разработка*

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