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Published in:
JOURNAL OF MINING SCIENCE

DOI:
[10.1134/S1062739114040152](https://doi.org/10.1134/S1062739114040152)

Published: 01/01/2014

Document Version
Publisher's PDF, also known as Version of record

Please cite the original version:
Mishra, R. K., & Rinne, M. (2014). Guidelines to Design the Scope of a Geotechnical Risk Assessment for Underground Mines. *JOURNAL OF MINING SCIENCE*, 50(4), 745-756.
<https://doi.org/10.1134/S1062739114040152>

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MINERAL MINING
TECHNOLOGY

Guidelines to Design the Scope of a Geotechnical Risk Assessment for Underground Mines¹

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Received February 16, 2014

Abstract—Risk assessment has been seen as an important tool in reducing accidents. Use of risk assessment tools also has its significant presence in the underground mining industry in preventing work related hazards. Geotechnical uncertainty however is among the leading cause behind major accidents such as roof collapse, airblast etc., which leads to multiple fatalities and financial loss. Geotechnical risk assessment done at stages as early as mine design can help justify a different mine design aspect such as support methods for a risky area different from the rest of the mine. The aim of this paper is to organize the geotechnical risk assessment process to suit the underground mining needs. A numerical ranking system has been developed to plan the risk assessment process and choose amongst the risk assessment tools. The risk assessment process has been redefined into four sections namely – hazard identification tool, risk assessment approaches, risk assessment parameters and risk representation tool. Risk identification tools have been shortlisted to suit underground mining needs through literature review. Risk assessment approaches have been defined into deterministic, probabilistic and possibilistic approaches with relevance to geotechnical assessment. Elements to be considered in an underground mine for a geotechnical risk assessment have been structured into classes. Establishment of scope of a geotechnical risk assessment based on these classes has been explained. Selection guideline for the appropriate risk identification tool has been defined based on the scope of risk assessment. The significance of the risk assessment approach has been explained and a numerical ranking system has been formulated which can be used by an underground mine to choose among the probabilistic, possibilistic and deterministic approaches.

Keywords: Underground mine, geotechnical accident, risk prevention, risk assessment scope, risk assessment tools.

DOI: 10.1134/S1062739114040152

INTRODUCTION

Underground mining industry involves working in a confined and uncertain environment. Such projects often operate at a very tight net present value where the risk of economic loss is compounded by the fluctuation in metal prices. Over time, rigorous planning procedures have emerged in the mining industry where a project is extensively analysed for its economic sensitivities. This is to ensure that the project is sustainable as mining projects can last up to a couple of decades or more. Accidents in an underground mine however can cause extensive damage to lives and property thus severely affecting the profitability of the mine. The uncertain geotechnical environment in which a mine operates is among the prime reasons for geotechnical accidents. Such accidents in the form of roof collapse, fallouts, uncontrolled caving etc. can lead to loss of lives and machinery along with substantial ore loss and loss in productivity.

Risk assessment practices across several industries have proven instrumental in foreseeing and controlling accidents. Industries such as oil and petroleum, nuclear power and aviation have adopted extensive assessment practices in its design and operation to assure a failsafe system of working [1]. Damages in underground mining accidents can be equally catastrophic as in petroleum and aviation industry. Thus inclusion of risk assessment practices in the underground mining industry from stages

¹The article is published in the original.

as early as feasibility study and mine design can help foresee potential threats in the operation. Such an approach can be termed as risk based mine design approach in which a mine design is weighed for its competency to tackle or avoid potential geotechnical hazards in the mine.

The evaluation of a geotechnical hazard in an underground mining operation comes under geotechnical risk assessment (GRA). This can help plan contingency in mine economics towards risk assessment and control expenses. This paper discusses the ways in which a geotechnical risk assessment should be planned and organised. It redefines the elements of risk assessment to suit the mining industry and suggests guidelines to establish the scope of a geotechnical risk assessment.

1. GEOTECHNICAL RISK ASSESSMENT

Geotechnical risk assessment (GRA) is in line with the ideology of a normal risk assessment [2] with emphasis given to geotechnical failures. Geotechnical risk thus can be defined as:

Geotechnical Risk

= Likelihood of geotechnical hazard occurrence $\times$ Severity of geotechnical hazard occurrence. ⁽¹⁾

1.1. Scope of a Geotechnical Risk Assessment (GRA)

Preparing an appropriate scope of the geotechnical risk assessment is as important as conducting the risk assessment itself. An underground mine consists of various elements ranging from small sized stope surfaces to large sections. In order to prevent a GRA from getting into unnecessary details, it is important that the objective of the GRA be clearly and formally defined before its commencement. This involves deciding upon the physical areas which the GRA will cover and it takes input from the resources that are available to carry out the risk assessment. The considerations in a GRA are mentioned below which help decide the scope and select appropriate GRA tools.

1.1. Considerations in a GRA

For the purpose of structuring the scope of a GRA, its elements are organised and subdivided. The subdivision is as given below:

GRA Type: This deals with the nature of the geotechnical risk assessment and is divided into:

Proactive GRA: This deals with risk assessment of a site which is done in advance of a planned operation. This forms part of estimation of a design capability to counter geotechnical risks and thus the level of confidence required is high. The areas to consider include risk estimation due to depth, pillar dimensions, proposed blasting, proposed excavation shape/size, support system, haul roads etc.

Reactive GRA: Reactive GRA is carried out on an existing operation for the geotechnical risks. This contains the category when risk mitigation is carried out after an incident has occurred in a mine site and when monitoring of installed control measures to prevent failure is being carried out. Thus reactive GRA forms an important part of the feedback system for the continual improvement of the risk management system in the mine. Reactive GRA has 2 types:

Routine: This is to monitor the performance of existing control measures against geotechnical risks. It involves evaluation of the support system in place, pillar/excavation design in use, warning systems etc.

Symptom based: Symptom based GRA is carried out when an incident has occurred or signs of an imminent or progressive failure are observed. This GRA aims at identifying the cause behind the accident or the failure symptoms for immediate mitigation measures such as change in support type, increased shotcreting, change in blasting pattern etc.

Change implementation GRA: This is carried out when the mine migrates from one system of operation or methodology to another. This is partly proactive for the new methodology/operation proposed and partly reactive from the old system as geotechnical lessons can be learnt from the previous mode of working and implemented in the new system.

GRA area scale: This governs the extent of area which is covered under the geotechnical risk assessment. This can be subdivided into:

Small scale GRA: This GRA deals with work places in operation. This includes smaller section such as stope surfaces, individual pillars, faces etc. Small scale GRA can be an informal GRA where the work personnel carry out the risk assessment prior to carrying out an operation. Small scale GRA can be associated with troubleshooting of an area suffering from potential problems. The local scale of a mining activity can be divided into local geology based hazards, hazards arising from local excavation geometry, hazards arising from blasting and scaling, hazards due to improper reinforcement including error in design, installation and performance. Detailed GRA must be carried out in order to establish the impact of local scale hazards on the mining infrastructure. Such GRA requires high degree of confidence and is carried out with a GRA team and sophisticated measurement/monitoring tools.

Large scale GRA: It deals with large areas such as large stopes or series of stopes, network of drifts and the entire mine system itself. This stage involves a lot of input towards planning of the mine layout. Large scale GRA has an important role of confirming the mining method to the rock structure. The mining system consists of various elements such as ventilation, material movement, operation etc. Large scale GRA attempts at establishing the association of these elements with respect to a hazard. The risk scenarios in large scale GRA is an expanded version of the small scale GRA which covers multiple stopes and sections of the mine. Things to consider in large scale GRA include hazards due to rock mechanics of the entire mine/large section of mine, stope/pillar/face design, hazards due to mining method and mining sequences and any other large scale operation.

Hazard scope: Hazard scope defines the types and number of hazards that is being looked at. GRA under such category can be:

Hazard specific GRA: This GRA is carried out to assess individual major hazards in a mine. This can be done for air blast in a stope, roof collapse in a stope etc. The consequences from such hazards are generally multiple fatalities along with financial loss. Certain hazards may not be directly caused by geotechnical reasons but are associated with it. For e.g. high groundwater seepage can obstruct ventilation causing methane built up and can lead to explosion in coal mines [5] as seen in the Upper Big Bench Disaster.

Site specific GRA: This is specific to an area where all the potential hazards which can disrupt the normal routine operations are considered. Hazard having the potential to cause severe damage may be noticed at this stage and be subjected to a rigorous hazard specific GRA.

Reporting requirements: The audience for which the risk assessment is done also affects the way in which the GRA is carried out. This can be divided into the following two categories:

Internal reporting: This GRA is carried out to be used within the company. Along with confirming that the work place is safe, such GRA can aid in designing and comparing various methods and alternatives. The audience for such GRA can be from a mine worker to the mine management. The level of detail is high if done for design purpose while if the reporting is done for information purpose alone, the final result is more important (to be communicated to mine personnel) than the input parameters.

External reporting: This kind of GRA can be for meeting legal requirements. This GRA aims at justifying the operations in a way that it confirms with all the standards. The input parameters used to defend a mine's situation is as important as the final result. The audience for such a GRA may not be necessarily from a mining background. Hence emphasis should be made on which input parameters were used and the result from the analysis.

Resources available: This also plays an important role in GRA as it limits the extent of detail to which a GRA can enter. This can be classified as follows.

Table 1

Mine component/ Element/ section	Failure mode	Failure effect	Likelihood	Consequence	Risk ranking
Section 1	Mode 1	Effect 1	-	-	-
		Effect 2	-	-	-
	Mode 2	Effect 1	-	-	-
		Effect 2	-	-	-
		Effect 3	-	-	-
Section 2	-	-	-	-	-

High resource availability: This means sufficient personnel are available to carry out GRA amidst the mine schedule. This also includes equipment available such as convergence monitoring, in-situ stress measurement, seismic monitoring etc. This provides an excellent database to assess likelihood of a hazard.

Average resource availability: This is when sufficient geotechnical data is not available but historical records exist of the geotechnical problems in the mine. Historical data is required in carrying out probabilistic analysis.

Low resource availability: This implies low availability of data and personnel. This can also be due to poor core logging of exploratory drilling. Such a situation arises when on-site instruments are not present in abundance to measure changes in rock properties in the form of extensometers, over – coring equipment etc.

2. GRA TOOLS AND THEIR SELECTION GUIDELINES

Appropriate tool selection to carry out the risk assessment is important in conducting an efficient and effective assessment. GRA can be divided into logical steps and each step has its tools from which the selection must be made. GRA can be broadly divided into the following sections:

1. Hazard identification tool
2. Risk assessment parameters
3. Risk assessment approach
4. Risk representation tool.

2.1. Hazard Identification Tool

These are formal tools which facilitate the identification and documentation of hazards in a site. There are various such tools (often termed as risk assessment tools/methods) developed over years across industries (FMEA, WRAC, BTA etc.). The fundamental idea behind the tools is to break down a site/system into smaller sections and identify hazards in each section. Most of the tools have their own format of recording the findings. One such example is Failure Mode Effect and Criticality analysis FMECA [6] with the form structure as shown in Table 1. The failure modes are the different ways a failure can happen such as poor rock strength, presence of a fault while the effect enlists all the possible result of an underlying cause such as roof collapse or slabbing etc.

The likelihood and consequence section allows quantification of risk. While describing the risk assessment methods such as FMECA, little information is mentioned on how exactly a likelihood and consequence should be calculated for a certain type of risk which eventually leads to risk ranking. Hence it is advised that they should be solely used for risk identification and each risk should be subjected to detailed assessment separately as mentioned in section 3.3. Through literature review, the following four risk identifications tools have been identified to be used in geotechnical risk assessment:

Work place risk assessment and control (WRAC): WRAC [3] offers speedy risk identification and can be done individually or by a GRA team. Informal recording of risk by the working personnel is easy with the simple format. Mine can be divided into sections and each section can be documented for identified hazards through WRAC.

Failure mode and effect analysis (FMEA): FMEA [6] approach includes breaking down the elements of a component into individual sections. This in case of a mining system can be haul roads, stopes etc. Each element is then identified for possible modes of failure and their effect. This format works well in identifying multiple failures and their co-relation with the mining system.

Bow-tie analysis (BTA): BTA [4] has been widely used in the past for major failure analysis. A large scale underground accident such as unpredicted caving or flooding are major failure events and BTA helps identify the multiple threats which can result in a particular hazard. This also involves breaking down the operational area into sections and identifying each of them for hazards.

Fault tree—Event tree analysis (FTA–ETA): FTA–ETA [7] system enables easy quantification to arrive at probability of failure. FTA enables a top down approach where a particular hazard is evaluated for the various series of event combination which can lead to the hazard being realized. ETA enables in identifying various consequences scenario that can arise if the hazard is realized.

Selection of the appropriate hazard identification tool: This selection is made among work place risk assessment and control (WRAC), failure mode and effect analysis (FMEA), bow tie analysis (BTA) and fault tree and event tree analysis (FTA–ETA). The parameters which govern the selection among the options are GRA area scale and GRA hazard scope as defined in section 2.2. Guidelines for selection based on the merits of the mentioned risk identification tool are shown in Table 2.

2.2. Risk Assessment Parameters

A risk assessment parameter in GRA is the way in which the likelihood and consequences of a hazard is expressed. The two ways in which they can be evaluated are as follows:

Qualitative parameter: This approach involves expressing likelihood of a hazard as very high/very low. The appropriate selection criteria for a hazard likelihood being termed as very high/very low can be done based on expert opinion/experience or from the geotechnical data available or both. Qualitative terms are excellent for communication of hazard likelihood among work force. This is also an efficient way to communicate a situation to a non-expert audience. Qualitative parameters however can sometimes be a necessity due to lack of available geotechnical data. In such scenarios the likelihood is determined based on site scoping, expert opinion, interviews etc. Hazard likelihood can be qualitatively represented as high likelihood/low likelihood; the severity can be qualitatively assessed as catastrophic/insignificant.

Quantitative parameter: Quantitative assessment aims at identifying the likelihood of occurrence of a particular hazard in its numerical form. This is often expressed in terms of number of events per unit period. One such example would be expressing a roof fall event as once in every 2 years for a particular rock type. This kind of representation paints a clear picture of the actual risk that is being dealt with. This can be used in detailed analysis of risks and should be used when the stakes are high such as design change, stope design planning, support calculation etc. The calculation draws inputs from the experience of an expert but has a large influence by the statistical history of an event and the associated geotechnical reasons behind the event. This method is more mathematical and hence adds to the engineering rigour. Hazard likelihood can be quantitatively assessed as events per unit period, percentage of occurrence chances (probability of failure – 10% etc.) while the severity can be assessed as cost per event, fatality per event, lost time per event, percentage rise in costs per event etc.

Table 2

GRA area scale and hazard scope	Proposed risk identification tool	GRA area scale and hazard scope	Proposed risk identification tool
Large scale and hazard specific	Bow tie analysis (BTA)	Small scale and hazard	Fault tree–event tree analysis

Large scale and site specific	Failure mode and effect analysis (FMEA)	specific Small scale and site specific	(FTA–ETA) Work place risk assessment and control (WRAC)/ FMEA
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Table 3

Geotechnical Data Level	Stage of Risk Assessment	GRA Parameter
Low	Pre-feasibility	Qualitative
Intermediate	Bankable Feasibility	Quantitative (Qualitative for large mine sections)
High	Mine Planning and Operation	Quantitative

Selection of appropriate risk assessment parameters: Once the hazards for a given site/condition are identified; the next step is to assess it for its severity and likelihood. One of the elements in the assessment is to decide upon whether to use quantitative or qualitative parameters in the assessment. This selection can be made based on the geotechnical data available as shown in Table 3.

2.3. Risk Assessment Approach

This forms the most significant part in a geotechnical risk assessment where the likelihood and consequences that are identified are subjected to evaluation to assign them qualitative/quantitative values. These values in turn lead to risk calculation. In risk based design approach, a detailed and extensive assessment leads to rejection or selection of a particular design/methodology and hence each risk identified should be subjected to assessment. This can be divided into assessment of likelihood and assessment of consequences. Likelihood assessment in a GRA falls under the following three categories:

Deterministic approach: Deterministic approach includes direct measurement of hazard symptoms and drawing conclusions on the likelihood of occurrence from it. Such method involves extensive geotechnical instrumentation in site. This can be specific for a hazard or can be part of the routine geotechnical data collection. One example for hazard based instrumentation can be of the case of roof convergence monitoring. Large scale roof convergence can lead to roof collapse. Hence regular measurements at site can be carried out for rate of convergence. This can be achieved with advanced instrumentation such as use of extensometers or through routine survey of roof levels. The data collected can be then converted into a numerical model to simulate convergence rate. This site specific model can then be used as a bench mark to assign low/high likelihood to the incident of roof collapse in a mine section.

Probabilistic approach: Probabilistic approach takes into account the underlying variability and uncertainty of the geotechnical data in an underground mine. The influence of variability and uncertainty on hazard likelihood is incorporated using statistical analysis of geotechnical parameters which influence a hazard. This has more emphasis on the causes behind the geotechnical hazard than the direct measurement of hazard itself. If the hazard under consideration is roof fall, the underlying reason can be weak strata, seismic event, mining induced stresses, occurrence of a major discontinuity etc. For probabilistic approach, all the measurable causes behind a hazard are identified and data is collected from the mine site. To account for the variability in the data, these parameters are subjected to suitable distribution functions to obtain statistical distribution of these parameters in the strata in the form of probability density function (pdf), cumulative distribution function (cdf) etc. From such

graphs the likelihood of failure is calculated. At times these distribution curves are subjected to random number simulation such as the ‘Monte- Carlo’ simulation to account for the uncertainty in geotechnical data.

Possibilistic approach: Possibilistic approach is an index based approach where the likelihood of hazard occurrence is established by translating geotechnical condition into indices similar to Q, RMR, and GSI etc. One such example is Roof Fall Risk Index (RFRI) [8]. In RFRI several strata conditions are taken into account such as roof bedding thickness, groundwater etc. These parameters are assigned values from 1 to 5 and the cumulative of all the parameters is converted into a RFRI value. Depending on the RFRI, the strata are classified as high/low roof fall risk strata. Other similar example is the use of stability graphs for slope stability [9]. Possibilistic approaches give a quick understanding of the stability of the strata but have less engineering rigour to justify a major design change. Also it requires development of hazard specific indices/methods. However, such methods when developed for major hazards encourage routine risk assessments due to their ease of use.

Consequence assessment in a GRA is similar to any risk assessment method. Damages caused by an accident consist of tangible and intangible damages. Tangible damages can be further divided into loss of property/financial loss and injury/fatality. Countries often have guidelines for setting compensation amount in case of injury fatality [10]. Work has also been carried out towards compensation calculation in mines in case of fatalities/injuries and accident cost estimation [11]. These guidelines can be used to convert damages caused by a geotechnical accident into financial terms for the purpose of risk assessment. Human life and wellbeing can never be evaluated on financial terms but the use of a common bench mark for both loss of life and property caused by an accident enables better risk planning and project management.

Selection of appropriate risk assessment approach: This selection is crucial as this determines whether a risk is acceptable or unacceptable depending on the value it receives. Hence for the purpose of this selection, all the elements of the scope of a GRA defined in section 2.2 are used. A numerical ranking system has been developed to be used for this purpose. Each category considered for the scope of a GRA is assigned a numerical weighting corresponding to deterministic, probabilistic and possibilistic approaches depending on their suitability. An empty ranking form is shown in Fig. 1. An empty box in the form always receives numerical inputs from the right. The boxes with numerical inputs offer various choices for a GRA element. For instance GRA type can be ‘Proactive’, ‘Reactive’ or ‘Change Implementation.’. Reactive GRA can be further divided into ‘Routine’ and ‘Symptom Based’ GRA. The various De, Pr and Po values represent their suitability for a given situation. For e.g. for routine GRA, the Po, Pr and De values are 2, 2, 2 respectively which means any of the 3 methods are equally suited for a routine GRA. However, for a symptom based GRA the Po, Pr and De values are 1, 2 and 3 respectively. This implies that De (Deterministic Method) is the most suited risk assessment method for symptom based risk assessment. Similarly different score is assigned for different aspects of GRA as seen in Fig. 1. Figure 2 shows a sample form which has been completed. The arrows indicate the direction in which the form is completed. The steps involved in using the numerical ranking method are as follows:

Step 1: Start filling the checklist for the boxes on the right for each of the 5 considerations in scope of a GRA. For e.g., in the completed form shown in Fig. 2, the GRA is identified to be ‘Routine’. It’s ‘Deterministic (De),’ ‘Probabilistic (Pr)’ and ‘Possibilistic (Po)’ values are transferred to the ‘Reactive’ box whose values are then transferred to the ‘GRA Type’ box.

Step 2: Step 1 should be repeated for the remaining 4 boxes on the left to receive numerical values for deterministic, probabilistic and possibilistic approach.

Step 3: The “De.” “Pr” and “Po” values for the boxes on the left, i.e. GRA type, GRA hazard scope, GRA area scale, reporting requirement and resource availability should be added and entered in the “Cumulative of above” box. The approach with the highest sum is the preferred risk assessment approach. For e.g. in Fig. 2, “Cumulative of Above” box shows the sum of all the approaches. Probabilistic approach (Pr) has the highest score (12) and thus is the preferred method for the choices made.

The numerical checklist can also be used to keep track of and communicate the scope of the GRA as the selected boxes in the list give a quick reference to what is being considered.

Fig. 1. Numerical ranking form of GRA.

Fig. 2. Example of a completed GRA ranking form.

2.4. Risk Representation Tool and Usage Guideline

Once a geotechnical hazard is identified, its likelihood and consequences evaluated, risk caused by such hazards can be represented as a function of likelihood and consequence as shown in equation 1. Depending on the risk assessment parameters used to express likelihood and consequence, geotechnical risk can be represented using the following two formats:

Table 4

Likelihood range (events/year)	Likelihood category	Severity range (Euros/event) in thousands	Severity category
8–10	Very high (5)	200 and above	Very high/Catastrophic (5)
6–8	High (4)	100–200	High/Major (4)
3–6	Moderate (3)	50–100	Moderate (3)
1–3	Low (2)	10–50	Low/Minor (2)
Less than 1	Very low (1)	1–10	Very low/Negligible (1)

Table 5

Likelihood of an Accident	Severity of an Accident					
	Likelihood X Consequence (Risk Number)	Very Low (1)	Low (2)	Moderate (3)	High (4)	Very High (5)
	Very low (1)	1	2	3	4	5
	Low (2)	2	4	6	8	10
	Moderate (3)	3	6	9	12	15
	High (4)	4	8	12	16	20
	Very High (5)	5	10	15	20	25

Table 6

Risk Number Range	Risk Level
1–2	Very Low
3–5	Low
6–10	Moderate
12–15	High
16–25	Very High

Matrix format: Matrix format is best used when either of the likelihood or consequence assessment is expressed in qualitative parameters. Matrix format involves formation of a 5×5 matrix with likelihood and consequence on the axes. This requires separate classification of likelihood and consequence into an index of 1 (very low) to 5 (very high). One such example is shown in Table 4.

Using Table 4, a risk matrix can be created indicating risk number which is the product of likelihood and consequence as shown in Table 5. Such matrix format is good for communication within the workforce regarding geotechnical risk at a particular work site. Such charts can be posted at sites with the risk marked for the particular site/operation. Local benchmarks can be set to classify risk numbers into high/low risk categories and this can be colour coded for ease of use. One such risk ranking is as shown in Table 6.

Graphical format: Graphical format is a way of directly representing the measured likelihood and consequence on a graph. This doesn't require separate classification of likelihood and consequence into classes as in case of the Matrix format. This however requires that both likelihood and consequence are expressed in quantitative parameters. The principle behind the graphical format is similar to an F–N diagram that is used in representing societal risks [12]. The slight modification to represent geotechnical risk involves changing the N parameter of an F–N diagram with a consequence value which is expressed in financial terms like Euros per event. Similar to F–N diagram, the

graphical representation involves a log–log plot of likelihood of an accident on the vertical axis and the consequence of an accident on the horizontal axis. The product of the likelihood and consequence which represents risk (Eq. 1) can thus be plotted on the graph. Local benchmarks can be set by a company to deem the risk into tolerable/intolerable zone by dividing it into the following categories:

Intolerable Line: Any risk plotted above this is deemed intolerable and the site must either be abandoned or steps must be taken to bring the risk below the intolerable line.

Objective Line: This is the line which sets the objective risk goal of the company. If resources permit, the company must aim to bring all the risks below this line. The zone between the objective and intolerable line is the tolerable zone. Risk in these areas can be afforded. However, if resources are available, efforts must be made to bring the risk further down to objective zone

If a mine “A” sets a benchmark for total intolerable risk cost as 500,000 Euros per year, and for objective risk cost as 50,000 Euros per year, a standard guideline risk graph can be prepared by the company.

Following a comprehensive risk assessment of the site, the mine can then plot each hazard on this graph to categorize an area as tolerable/ intolerable for geotechnical risks. The impact of risk mitigation measures in bringing down the risk can be directly monitored from the graph. This however is a fairly mathematical tool and not effective in communicating risk among the work force. This however serves as a planning tool and helps weigh a mine design/methodology against its risk aversion/prevention capabilities.

CONCLUSIONS

Geotechnical risk assessment (GRA) can help identify and mitigate hazards before they pose risk to the working environment. Before a GRA can be commenced, a formal scope preparation enables planning the risk assessment and defining the physical boundaries within which the assessment falls. This planning ensures that the risk assessment is done in the fastest possible time and to the required detail. The systematic approach and breakdown helps organise the resources in terms of finance and time, that are needed to conduct an efficient geotechnical risk assessment. The scope preparation is designed keeping the mining industry in mind which assists in mining specific risk assessment planning. Table 7 explains the process of GRA once the scope is prepared.

Once a Geotechnical risk assessment is completed, the result should be analysed to see if the risk must be mitigated or completely avoided (switching to a different method, abandoning the area etc.). The above methodology needs to be tested across mine sites to assess its ease of use and also to ascertain the numerical weighting of the 3 risk assessment approaches as used in the ranking. GRA process in a mine should be subjected to continual improvement through feedbacks from the mine and via lessons learnt during every assessment. An efficient GRA will help establish an accident free working environment and thus preserving life and property and promoting well being in a confined working environment.

Table 7. GRA process after scope preparation

Stage	Description	Tools used	Proposed options
Stage 1	Identify the hazards	Hazard identification tools	WRAC, FMEA, BTA, ETA–FTA
Stage 2	Assess the likelihood and consequence	Risk assessment parameters	Qualitative parameters
			Quantitative parameters
		Risk assessment approach for likelihood assessment	Deterministic approach
			Probabilistic approach
			Possibilistic approach
		Consequence assessment	Accident cost model
Stage 3		Risk representation tools	Matrix format
			Graphical format

ACKNOWLEDGMENTS

Work contained in the paper was carried out as part of the of the project titled “Innovative Technologies and Concepts for the Intelligent Deep Mine of the Future (I2 Mine),” under the 7th framework program of the European Union, which stresses on the need of a formal geotechnical risk assessment to be documented along with a proposed mining activity to justify its ability to tackle geotechnical accidents in underground mines.

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