Challenges in the use of verbal probability expressions in communicating risk

by J. Hadjigeorgiou[1], J. Wesseloo[2]

Affiliation:
1University of Toronto, Toronto, Canada
2University of Western Australia, Australia

Correspondence to:
J. Hadjigeorgiou

Email:
john.hadjigeorgiou@utoronto.ca

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ORCiD:
J. Hadjigeorgiou
http://orcid.org/0000-0002-6047-3964
J. Wesseloo
http://orcid.org/0000-0001-7124-2267

Abstract

Mining companies employ a multitude of risk management tools. The effectiveness of these tools for decision-making and communicating risk has not been addressed. This paper investigates the use of verbal probabilistic expressions in communicating geomechanical risk. Analysing survey data obtained from a group of mining geomechanics professionals, it identifies limitations of common probabilistic expressions. The paper concludes by making specific recommendations to avoid the use of certain expressions that may result in increased uncertainty, thus compromising the use of risk management tools.

Keywords

mining geomechanical risk, verbal expression of probability, risk matrix

Introduction

A mining company is exposed to a multitude of risks, of which the financial risks include credit, liquidity, market, foreign exchange, interest, and commodity prices. In addition, it must address and mitigate operational, geomechanical, environmental, community, political, and reputation risks in an interconnected global economy. In a cultural shift change, since the 1990s, most mining companies now require some type of risk assessment for practically all mining activities. The International Organization for Standardization's (ISO) guidelines on risk management (International Organization for Standardization, 2018) provides a template for a risk management process that can guide a mining company in developing fit for purpose guidelines, as illustrated by Figure 1.

The challenges associated with understanding, managing, and communicating geomechanical risk have been previously discussed by Hadjigeorgiou (2020). There are multiple tools that are used in all elements of risk management, including operational, ground control, and mine design. These include the use of risk registers and matrices. A risk register identifies the consequences of an event, ownership of risks, and how risks are to be allocated and controlled. In effect, they provide the basis for developing and implementing systems to manage and mitigate risks through contingency measures and controls. Risk matrices are also widely used at multiple levels within an organisation. This often includes a requirement that workers undertake a risk assessment prior to any activity. In addition, engineering is mandated to undertake a risk assessment of any critical design.

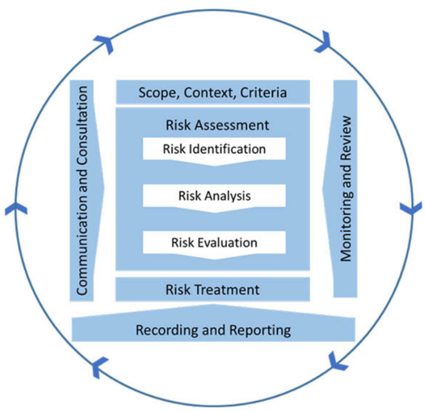

Figure 1—Risk-management process (International Organization for Standardization, 2018)

An integral part of any risk management process is an effective communication strategy. There are several challenges in using risk management tools, including the asymmetry of knowledge between the various stakeholders (Hadjigeorgiou, 2020). Another practical issue is the validity of the assumption that the risk management tools are well applied, interpreted, and communicated within an organisation.

The focus of this paper is the challenges in communicating levels of uncertainty between the various stakeholders of geomechanical risk. In particular, it investigates how mining risk professionals communicate quantitative and verbal probabilities. An experiment was conducted to address the consistency of and variations in how geotechnical professionals assigned a numerical value to verbal descriptors of uncertainty commonly used in mining engineering. The effectiveness of this process has significant influence on the quality of analyses and communication tools such as risk matrices. This has significant implications for all elements of mining beyond a geotechnical audience.

Risk matrices

A common risk management tool is the use of a risk matrix, which is often recommended by both national, international, and corporate organisations. A risk matrix is a two-dimensional representation of the relationship between the likelihood and consequence or impact of an event. An example of a risk matrix is provided in Figure 2, where mining personnel are asked to assess the likelihood that an action or event, e.g., the installation of ground support under certain conditions, may result in an injury with different consequences, ranging from minimal to disability. The results are assigned to ranges of similar risk (e.g., high, medium, or low risk) and are often allocated colours (e.g., red for the highest risks to green for the lowest given risk); hence, the use of the term 'heat map'. The implication is that high risk items will trigger a response that will require a specific mitigation action.

Appendix A provides ten more examples of risk matrices sourced from mining operations worldwide that are used to identify and communicate risk for geomechanical operational and design activities processes.

A risk matrix is perceived as an integral part of developing and implementing a risk-management culture and people engagement. Risk matrices have become omnipresent and are used by workers to assess all activities, operations, engineering, consultants, and all levels of management. Risk matrices are sometimes used to provide guidance to employees on what is acceptable, and to guide the actions taken to manage the risk. Low-level risks are usually acceptable without any management involvement, while medium risk would require that management needs to be actively involved to ensure the risk is kept under control (Hadjigeorgiou, 2020).

According to Thomas et al. (2014), one of the perceived benefits of using risk matrices is its intuitive appeal and simplicity. They are supposedly easy to construct, easy to explain, and easy to score. They might appear authoritative and intellectually rigorous. However, the development of risk matrices have taken place completely isolated from scientific research in decision-making and risk management (Thomas et al., 2014).

Likelihood	Consequences				
	Minimal	First aid	Medical treatment	Lost time	Disability
Almost certain	Low	Moderate	High	High	High
Likely	Low	Moderate	High	High	High
Possible	Low	Moderate	Moderate	High	High
Rare	Low	Low	Low	Moderate	High
Almost impossible	Low	Low	Low	Low	Low

Figure 2—Risk matrix for mining activities used by personnel

Risk matrices are often circulated widely across an organization, with guidance notes that explain the details of how the matrices were developed and how they were meant to be used for risk assessment, risk communication and risk management are often brief and cryptic (Porter et al., 2019).

They also highlight the lack of guidance on how they are to be applied at different project scales. "Was the matrix developed for the executive team to assess the summation of risks for entire projects and all associated infrastructure? Was it intended to be used by a mine manager to assess the summation of all risks associated with specific facilities? Was it intended to be used by the foreman for assessment of individual geohazard threats? Or was it intended to be used by work teams to help assess and manage their risks on a daily basis? Each scenario involves a different scale of assessment". These different project scales may influence the interpretation of both the probability and consequence axes of the matrix.

A review of the reproduced matrices compiled in Appendix A reveals some common trends. The consequence items typically vary if they are health and safety risks as opposed to monetary or business risk. Most matrices use five classes on both the probability and consequence axes with one exception being a 4x3 matrix. All except one of the matrices use the vertical axis for probability and the horizontal for consequence. The use of colour coding consists of 3 to 6 colours with the general preference being the four-colour scale: green-yellow-orange-red. Five-colour scales typically include the blue before or after green and the six-colour scale uses two shades of green and ads two extra colours. The general trend, however, seems to be the mapping of the risk level to the "hotness" of the colour. The colour use in risk matrices seem to have some influence on the interpretation of risk gravity and decision-making, (Proto et al., 2023). This raises concerns about the potential biasing effect of colour, but this is outside the scope of this paper.

All risk matrices reproduced in Appendix A provide a two-dimensional representation of the relationship between the likelihood and consequence or impact of an event. Although not always explicitly defined, the consequences can refer to a range of risks including:

- ➤ reputation
- ➤ business
- ➤ environment
- ➤ damage
- ➤ safety

It is not surprising that the consequences are defined differently by different organisations and often within stakeholders of the same operation. The severity of consequences is usually qualified based on company guidelines and is a function of tolerance to risk. This has been addressed in multiple publications, e.g., by Wesseloo and Read (2009), Joughin (2017), and Hadjigeorgiou (2020) and will not be discussed further in this paper where the focus is on the use of verbal expressions employed to capture different levels of probability expressions or the likelihood of an event. The challenges in the use of verbal expressions for these purposes have been discussed in the past by a number of researchers, including Reagan et al. (1989) and (Wintle et al., 2019), but not with respect to their use in risk matrices or in geomechanical applications.

Table 1

Numerical guidelines associated with verbal probability statements, Wintle et al. (2019)

Almost no chance	Very unlikely	Unlikely	Roughly even chance	Likely	Very likely	Almost certainty
01 – 05%	05 -20%	20 -45 %	45 -45%	55 -80%	80 – 95%	95 -99%

Quantitative meanings of verbal probability expressions

A verbal probability is a way to qualify and communicate uncertainty and is widely used both in everyday interactions as well as in technical communication. An inherent assumption, that may not always be correct, is that both the sender and receiver have the same understanding of these expressions. This is further confounded as most people prefer expressing their uncertain beliefs with verbal probabilities, but the receiver of this information translates it to numerical values. A differential understanding and usage of verbal probabilities can result in disastrous decision errors (Karelitz, Budescu, 2004).

Hamm (1991) points out that poor verbal-probability mapping used by NASA contributed to the overconfidence in shuttle safety prior to the Challenger explosion. Engineers made verbal assessment of the reliability of the shuttle components but were not involved in the numeric interpretation of the verbal expressions. Vick (2002) concludes that with poor verbal-numeric probability mapping, NASA built an over-confidence bias into their system.

There have been several studies aiming to determine if probability expressions are used consistently and thus, are an effective means of communication (Reagan et al., 1989; Mosteller, Youtz, 1990; Wintle et al., 2019) . These studies have been quite diverse in participants (students, doctors, science writers, etc.) and format (pencil and paper, online). The work presented in this paper is, to the author's knowledge, the first that is specific to mining personnel with an interest or expertise in geomechanical risk management.

The seminal work of Reagan et al. (1989) provided one of the earlier experiment results to quantify the meanings of verbal probability expressions. A set of 18 expressions were selected, and 115 undergraduate psychology students were asked to assign a number from 0 to 100 to best represent the probability of that outcome occurring. The probability of expressions used was grouped under four stems, namely:

1. Possible (almost impossible, possible, very possible).
2. Probable (very improbable, improbable, probable, very probable).
3. Likely (very unlikely, unlikely, likely, very likely).
4. Chance (very low chance, low chance, medium chance, even chance, high chance, very high chance).

An interesting observation in Figure 3 is that verbal probability expressions were good at representing the lower and higher range, and at the middle. This was attributed to these areas of the scale as being the most natural places to anchor descriptive terms. The numbers were also confined within the limited range 2%–90% with limited representation in the extremes.

Since then, a number of researchers have identified similar trends with most studies relying on students or medical professionals or patients. The work of Wintle et al. (2019) reproduced in Figure 4 is of particular interest as it was based on an online survey completed by 924 members of the general public. Figure 4 charts the frequency with which given best estimate values were assigned by participants to verbal probability expressions, namely: almost no chance, very unlikely, unlikely, roughly even chance, likely, very likely, and almost certainty. In this visualisation of the results the cut-off between two adjacent probability expressions (e.g., very unlikely and unlikely) is the point at which the frequency of people associating that number with the two adjacent expressions is the same. This is where two curves intersect in Figure 4. An interesting observation by Wintle et al. (2019) was that providing subgroups in-text numerical guidelines, as in Table 1, resulted in reduced variability in responses.

Data collection methodology

This study expanded the terminology used in previous studies to those words that are included in risk matrices employed in the mining industry (Appendix A). The questionnaire was developed with focus on likelihood probability expressions. The expressions were presented in random order on the questionnaires. The participants were provided with a list of verbal expressions and given the following instruction:

> *If someone told you an outcome was/had a [verbal expression], what number from 0 to 100 would best represent the probability of that outcome occurring?*

The particularity of the present work was that the participants were all mining professionals with experience in geomechanical risk management or at least a strong interest in the field. The survey was undertaken in person prior to a Geomechanical Risk Workshop in 2019. Arguably this would suggest that these participants may have been better prepared than people at mine sites routinely required to undertake risk assessment.

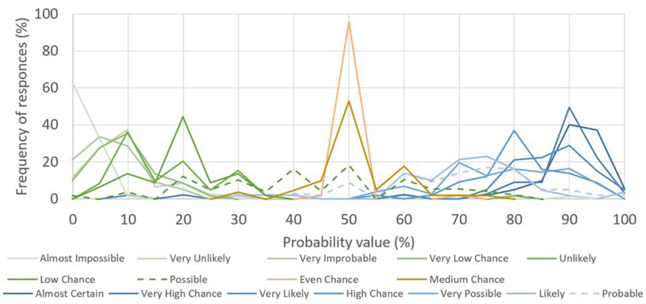

Figure 3—Data from Reagan et al. (1989) showing a lack of verbal probability representation in mid-lower and mid-upper ranges and in the extremes

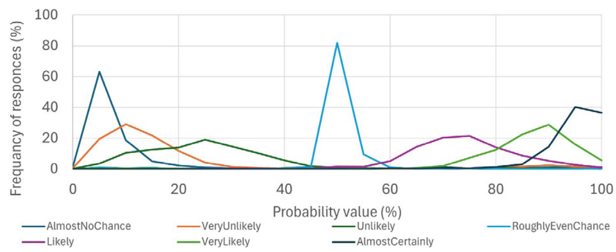

Figure 4—Frequency distribution of assigned probability for different verbal probability expressions, modified after Wintle et al. (2019)

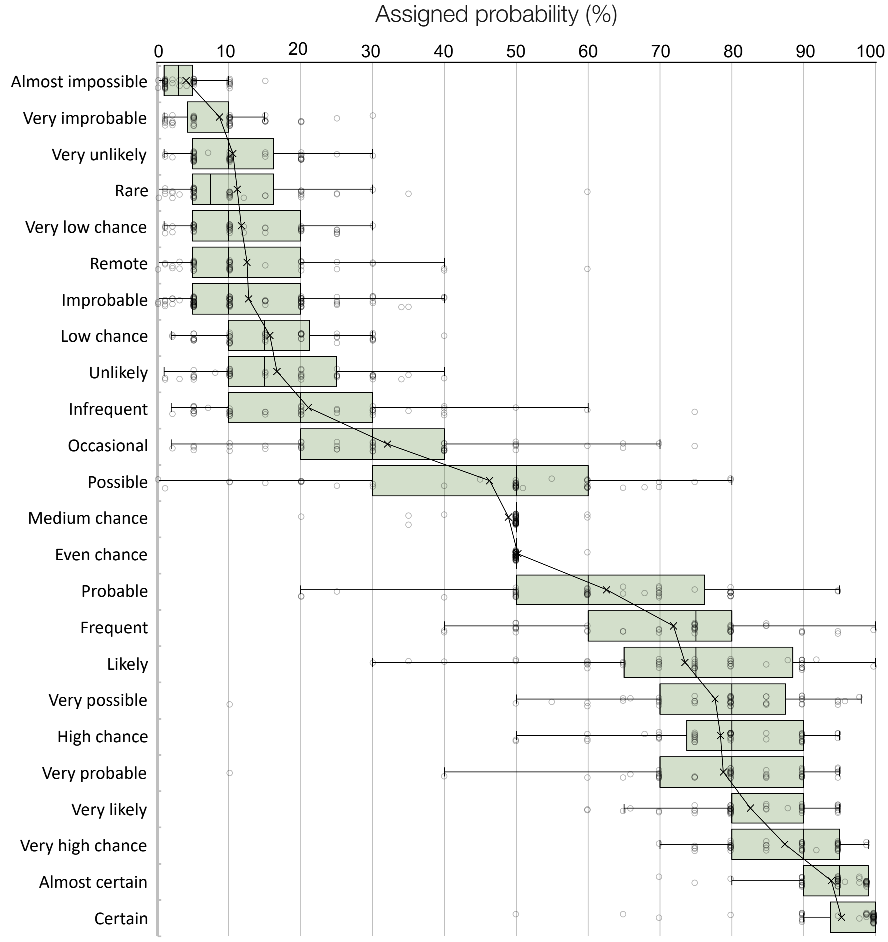

Figure 5—Box-and-whiskers plots listing the assigned value for a given probability expression

The participants were all industry professionals with both an interest and previous exposure to geomechanical risk management. To avoid influencing the results the test was issued prior to the workshop. A total of 46 questionnaires were used in the analysis.

Data analysis and interpretation

The assigned probability for the verbal probability expressions is represented in Table 2 and in a box-and-whiskers plot in Figure 5. To facilitate the interpretation of Figure 5 a definition sketch is also provided in Figure 6. The results in both Table 2 and Figure 5 were sorted by the mean value to provide a monotonic progression from lower to higher probability expressions.

This allowed for an interpretation of how well the specific responses clustered around a value. The inter-quartile range is a good indicator of this. The use of the median over the mean has been favoured in other studies (Reagan et al., 1989) based on the assumption that means are more sensitive to extreme responses and because responses to probability expressions often yield asymmetric frequency distributions. In our investigation we chose to present both. Our results indicated that there was not much difference between the median and the mean.

Table 2 lists the several statistical metrics from the data displayed in Figure 5. An interpretation of the responses is provided in the subsequent sections with emphasis on the limitations of specific probability expressions.

In Figure 5 and Table 2, the results are sorted by mean values to show the systematic progression from lower to larger verbal probabilities with a line connecting the mean values. The graph confirms the conclusion by Reagan et al. (1989) and Wintle et al. (2019) regarding the lack of vocabulary to describe the lower and upper mid-ranges and the extreme probabilities. It also highlights the fact that the lower and upper ranges are represented by several probabilistic synonyms with larger differences in the ranges than in the median values.

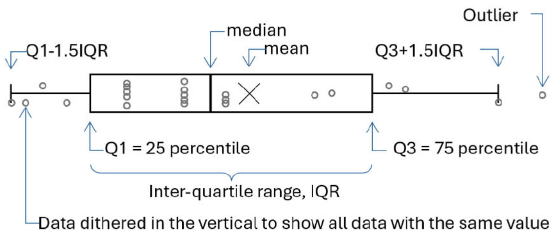

Figure 6—Definition sketch for box-and-whiskers plot

Dispersion in response

Across the full probability range, there is almost a symmetrical response in the box length with the low probability expressions mirroring the high-probability expressions (Figure 5). This is also reflected in the symmetrical distribution of the inter-quartile range (IQR) and standard deviation in Table 2, where dispersion is lower for both low and high probability expressions and higher towards the middle. There is no dispersion for 'medium chance' or 'even chance', indicating that there is a clear and very narrow understanding of these two expressions. These two expressions

Table 2

Probability expressions and statistical metrics

Class	Median	Mean	St. dev	Min	0.25	0.75	Max	IQR	Max-Min	Usage*
Almost impossible	3.0	4.1	3.7	0.0	1.0	5.0	15.0	4.0	15.0	1
Very improbable	10.0	8.7	6.7	1.0	5.0	10.0	30.0	5.0	29.0	0
Very unlikely	10.0	10.6	7.0	1.0	5.0	15.0	30.0	10.0	29.0	0
Rare	7.5	11.2	11.0	0.1	5.0	15.0	60.0	10.0	59.9	8
Very low chance	10.0	11.8	7.9	1.0	5.0	20.0	30.0	15.0	29.0	0
Remote	10.0	12.5	11.9	0.0	5.0	18.8	60.0	13.8	60.0	1
Improbable	10.0	12.8	9.8	0.0	5.0	20.0	40.0	15.0	40.0	1
Low chance	15.0	15.7	9.3	2.0	10.0	20.0	40.0	10.0	38.0	0
Unlikely	15.0	16.7	10.3	1.0	10.0	25.0	40.0	15.0	39.0	7
Infrequent	20.0	21.1	15.7	2.0	10.0	30.0	75.0	20.0	73.0	1
Occasional	30.0	32.1	18.2	2.0	20.0	40.0	75.0	20.0	73.0	0
Possible	50.0	46.3	20.0	0.0	32.5	60.0	80.0	27.5	80.0	8
Medium chance	50.0	48.9	5.9	20.0	50.0	50.0	60.0	0.0	40.0	0
Even chance	50.0	50.2	1.5	50.0	50.0	50.0	60.0	0.0	10.0	0
Probable	60.0	62.6	16.6	20.0	50.0	73.8	95.0	23.8	75.0	0
Frequent	75.0	71.9	14.9	40.0	60.0	80.0	100.0	20.0	60.0	0
Likely	75.0	73.5	15.4	30.0	65.0	87.3	100.0	22.3	70.0	7
Very possible	80.0	77.7	15.0	10.0	70.0	85.0	98.0	15.0	88.0	0
High chance	80.0	78.4	10.9	50.0	75.0	90.0	95.0	15.0	45.0	0
Very probable	80.0	78.8	14.9	10.0	71.3	90.0	95.0	18.8	85.0	0
Very likely	80.0	82.6	9.3	60.0	80.0	90.0	95.0	10.0	35.0	0
Very high chance	90.0	87.4	7.5	70.0	80.0	95.0	99.0	15.0	29.0	0
Almost certain	95.0	93.8	6.1	70.0	90.0	99.0	99.0	9.0	29.0	7
Certain	100.0	95.3	10.1	50.0	95.8	100.0	100.0	4.3	50.0	1

* Number of times used in the risk matrices provided in Appendix A.

are not used in the risk matrices included in Appendix A. The expression 'medium probability' is used in the matrix. It would be reasonable to expect that 'medium chance' and 'medium probability' would have similar interpretation. This cannot be confirmed with the current dataset as the latter was not included in the survey.

The IQR provides a metric to quantify the consistency of interpretation. Bars were added to the IQR column in Table 2 to visually display the IQR values with colours added to show different categories of similar IRQ value. Class boundaries were chosen to avoid coincidence with the round number bias in the data and define the categories as follows:

1. IQR < 12
2. 12 ≤ IQR < 18
3. 18 ≤ IQR

Terms in the first class provide the most consistent interpretation and should be preferably used for verbal expression of probability. In our opinion, terms falling in category 3 should be avoided. Terms in category 2 should be used to supplement that of category 1.

Another form of dispersion is observed by looking at the extreme lengths of the whiskers. This follows the same trends as the boxes with 'unlikely', 'infrequent', 'occasional', and 'possible' on the top part of Figure 5, and 'probable', 'frequent', and 'likely at the bottom representing wider distribution, suggesting more scatter in the data.

Similarity in groups

There is a surprisingly large overlap in responses on both sides of the spectrum. Consider, for example, the value of 10% probability, which falls within the IQR of nine verbal probability terms, from 'very improbable' to 'infrequent' in Figure 5.

Outliers

It is interesting to note that all expressions have some outliers, indicating the consistent wide range of interpretations for most of the expressions. Considering the cohort of the survey, some of the outlier values are quite surprising.

Skewness

As shown in Figure 5, the majority of the distributions are skewed. In fact, only the following expressions, being 'almost impossible', 'very unlikely', 'infrequent, and 'occasional' are symmetric. A positive (right) skew is observed for 'very improbable', 'very unlikely', 'rare', 'very low chance', 'remote', 'improbable', 'low chance', and 'unlikely'. A negative (left) skew was observed for 'very improbable', 'frequent', 'very possible', and 'very high chance'. The skewness of the distributions is attributed to the floor and ceiling values of 0% and 100%, leading the wide distributions being skewed to the 'open' end.

Rounding numbers

The human preference for rounding numbers is also evident in the data. This is illustrated in the responses to possible and probable in Figure 7. With the freedom to choose any numbers, almost all chosen numbers were limited to numeric decades or half decades with a clear preference for decades. This leads to

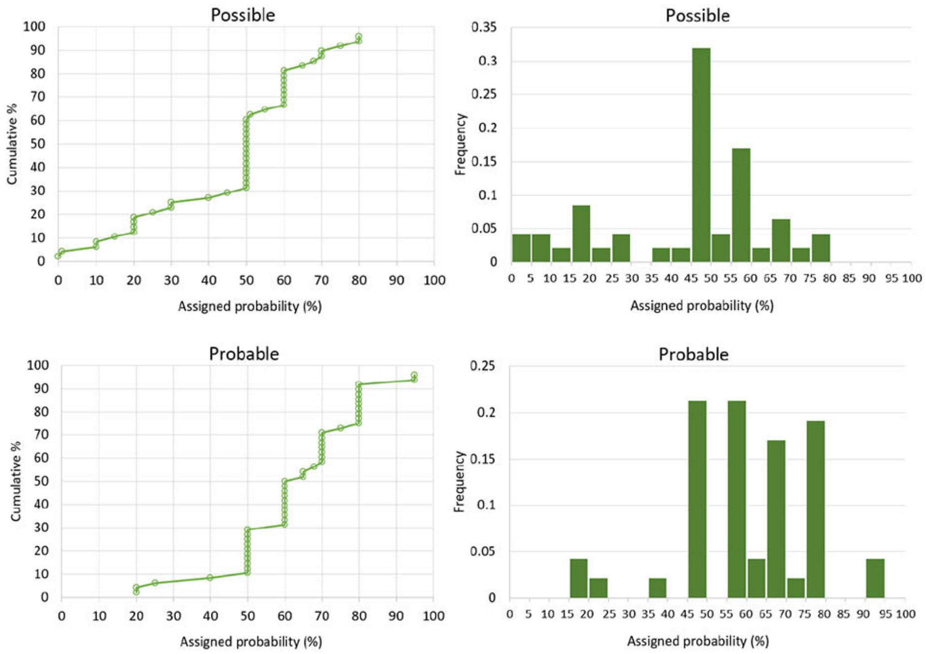

Figure 7—Cumulative frequency distribution and frequency distribution of the data for 'possible' and 'probable

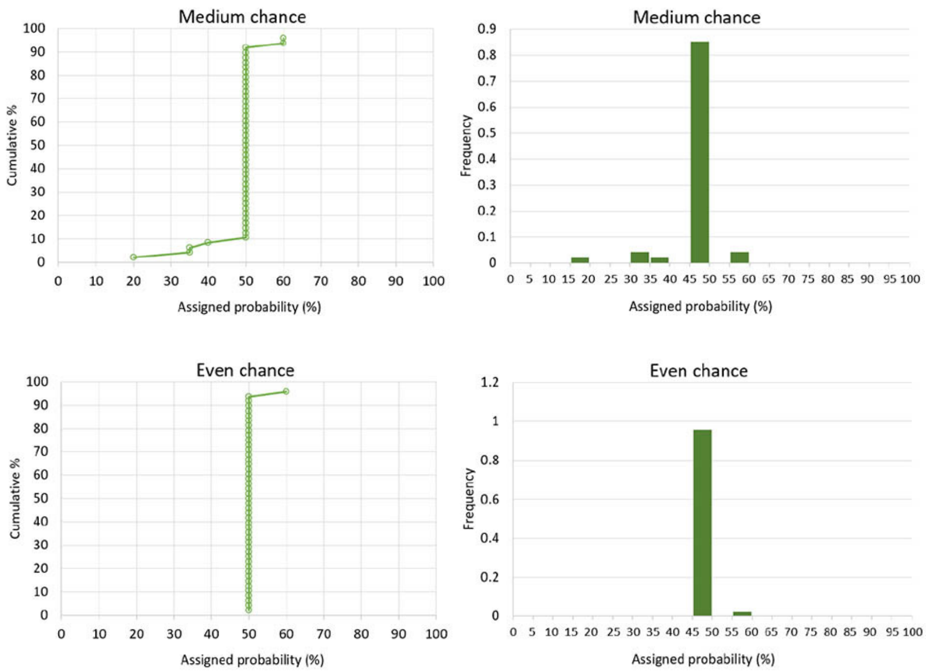

Figure 8—Cumulative frequency distribution and frequency distribution of the data for 'medium chance' and 'even chance'

'sawtooth' histogram distributions with half decade frequencies being considerably less than the neighbouring decades (Figure 7). This may be attributed to the participants' intuitive understanding of the inherent lack of resolution with verbal-numeric probability translation.

Ambiguity of interpretation

The technical meaning of the word 'possible' includes any probability between 0% and 100%. It is interesting to note that the wide distribution of assigned probabilities with a spike at 50% (Figure 7), the data appear to follow a uniform distribution between 0% and 80% overlain with a spike at 50%. This would be consistent with a cohort, which understands the technical meaning of the term but is forced to choose a single number. The indication that 'possible' had a distinctly different meaning for different people was also the conclusion of Mosteller and Youtz (1990). The ambiguity of the interpretation of the word 'possible' should disqualify it from use in risk matrices. The word 'probable' also shows a wide range of interpretation with the bulk having similar representation of 50%, 60%, 70%, and 80%, as illustrated in Figure 7. The terminology 'even chance' and 'medium chance' appear to be interpreted as probabilistically equal with an almost exclusive meaning of 50% (Figure 8). As such, the use of 'medium change' as a descriptor in the risk matrix should be avoided.

Inter-quartile range (IQR)

The quartile values and the inter-quartile range (IQR) are also provided in Table 2. The preference for round numbers mentioned earlier influences the calculation of quartile values from the data with most of these values limited to the decades and sometimes to the half-decade.

Also included in the last column of Table 2 is the number of times the term is used in the risk matrices included in Appendix A. There is no correlation between the IQR and the frequency of use, two of the most used terms falling into the highest IQR category. The terms 'possible' and 'likely are very popular in risk matrices, but the data shows that people are inconsistent in their interpretation on what they mean.

The list of matrices in Appendix A is not exhaustive and may not be representative of all matrices in use. It does, however, raise the question whether due consideration is given to the choice of verbal probability terms in the development of risk matrices.

Synonymity

The concept of synonymity was previously discussed by Reagan et al. (1989), noting that certain expressions such as 'probable' were quantitatively synonymous with expressions incorporating 'likely'. This was further explored in the database by plotting the assigned probability against the frequency and the cumulative percentage.

As illustrated in Figure 9, two groups of expressions (improbable, remote, very low chance, rare, and very unlikely) and (very likely, very probable, high chance, and very possible) can be considered to a degree as synonymous.

Saturation

The difference between median values of different terms is smaller the closer it is to the floor and ceiling values of 0% and 100%. The difference between different classes in many of the risk matrices is therefore greater in the centre chosen classes and less in the outer classes. This is illustrated in Figure 10, showing the assigned probability distributions for the 5 classes: Very high-, high-, medium-, low-, and very low chance. Linguistically, these classes represent a natural and reasonable progression. The distributions for these classes, however, show little difference between the two lower and two upper classes with a wide gap left for the centre class.

Implications for risk matrices

This investigation was motivated to determine the effectiveness of verbal probability communication of a specialised group of geotechnical mining engineers. Of particular interest was the use of risk matrices that are often reported as communication tools. A

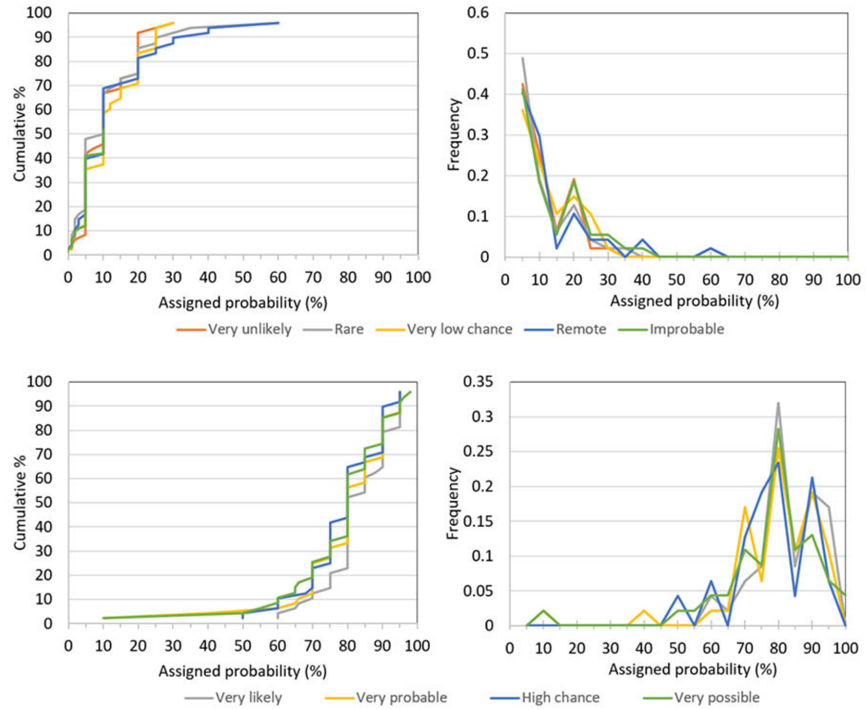

Figure 9—Cumulative frequency distribution and frequency distribution for potentially synonymous probability expressions

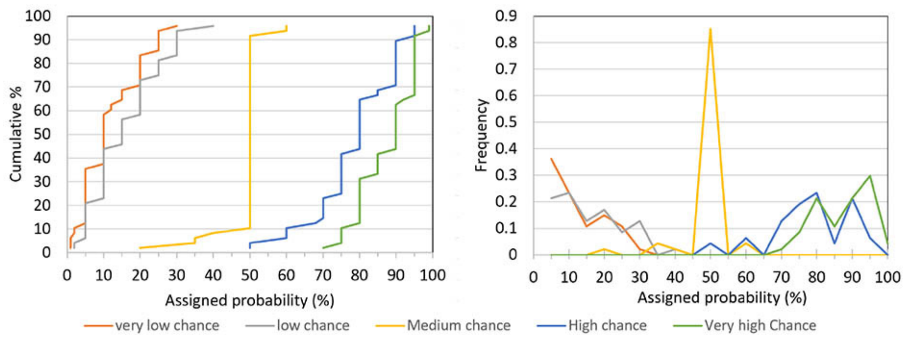

Figure 10—Distribution of assigned probabilities for terms 'very low-', 'low-', 'medium-', 'high-', and 'very high chance'

review of the risk matrices in Appendix A identified a number of likelihood terms that were also part of this study, as per Table 2. Although the risk of matrices in Appendix A may not constitute a representative sample, it is informative to note the most popular terms:

- ➤ Rare, 8/12
- ➤ Possible, 8/12
- ➤ Unlikely, 8/12
- ➤ Likely, 7/12
- ➤ Almost certain, 7/12

The application of verbal probability terms in the risk matrices appear to have several unintended consequences resulting from the characteristics of the distributions of assigned probabilities discussed previously.

As shown in Figure 11, some of the matrices use probabilistic synonyms for two of the adjacent classes. The lack of representation in the middle low and middle high ranges and the effect of saturation lead to a lack of representation over large ranges and significant overlap and small separation between the remaining classes (Figure 12).

Figure 11 and Figure 12 brings into questions the contention that risk matrices aid clear communication and facilitate consistent assessment of risk. Coupled with the observation made by Wintle et al. (2019) that numerical guidelines coupled with the verbal expressions result in reduced variability in responses and the fact that receivers of verbal probabilities translate it into numeric equivalents, raise the question whether these purposes will not be better served using numeric ranges rather than verbal probability classes.

Conclusions

A risk assessment is an integral part of all critical mining operations and practice and there are multiple tools available for these purposes. In the opinion of the authors, the quality of these risk assessment tools, and by consequence, confidence in the results, has not received the requisite attention. This paper focused on geomechanical mining risk, and in particular the challenges in the use of verbal probability expressions to effectively and consistently communicate geomechanical risk.

The participants in this study were mining professionals with experience in geomechanical risk management or at least a strong interest in the field. Arguably, this may have solicited more consistent results than the general mining force who is tasked to communicate and understand verbal probability risk as both input providers and receivers of information.

To fascilitate the discussion, all verbal probability expressions were presented from the less likely (starting from 'almost impossible' to 'certain'). A series of statistical analyses identified several significant trends as well as inherent advantages and limitations of specific words commonly used in communicating risk:

- ➤ Verbal probability expressions were good at representing the lower and higher range, and middle ranges but underrepresented between about 25% – 40% and 60% – 75%. The lower, higher, and middle ranges of the scale are the most natural places to anchor descriptive terms. Chosen numeric translations are largely between integer values from 0 to 100 (inclusive) with very few choosing fraction values between 0% and 1%.
- ➤ Responses for specific terms, using the IQR as guidance, revealed a lower dispersion on both sides of extreme probability expressions with an increase towards the middle. A greater scatter was observed for the following expressions: 'unlikely', 'infrequent', 'occasional', 'possible', and 'probable', 'frequent', and 'likely'.
- ➤ An overlap in ranges for different terms was observed on both sides of the spectrum. The implication is that certain expressions are difficult to distinguish from each other and are assigned a similar probability rating.
- ➤ The majority of observed distributions are skewed with only the following: 'almost impossible', 'very unlikely', 'infrequent', and 'occasional' being symmetric and considered as normal distributions.

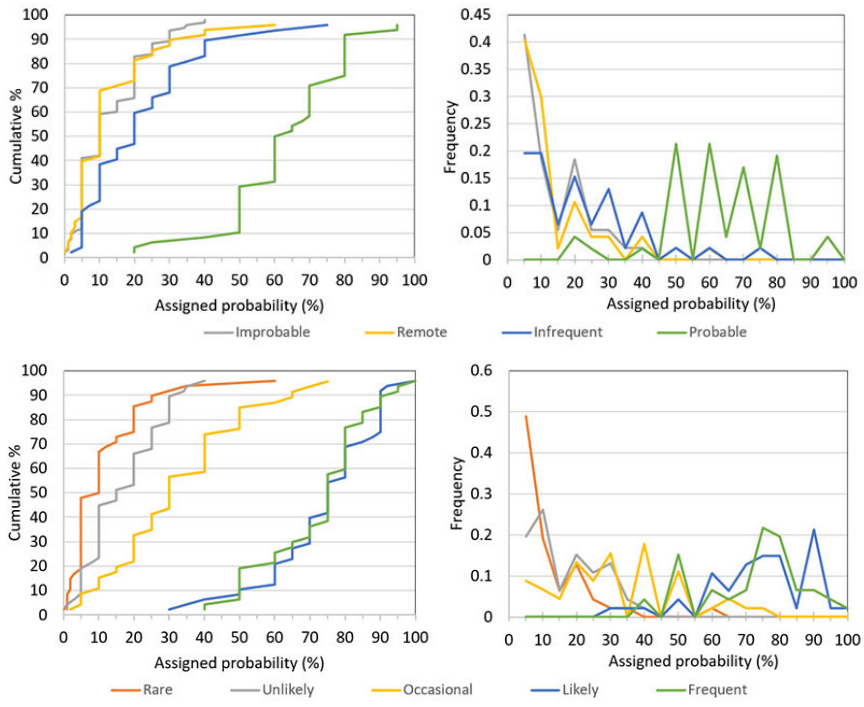

Figure 11—Distribution of assigned probabilities for sets of verbal probability terms used in Matrices A2 and A4

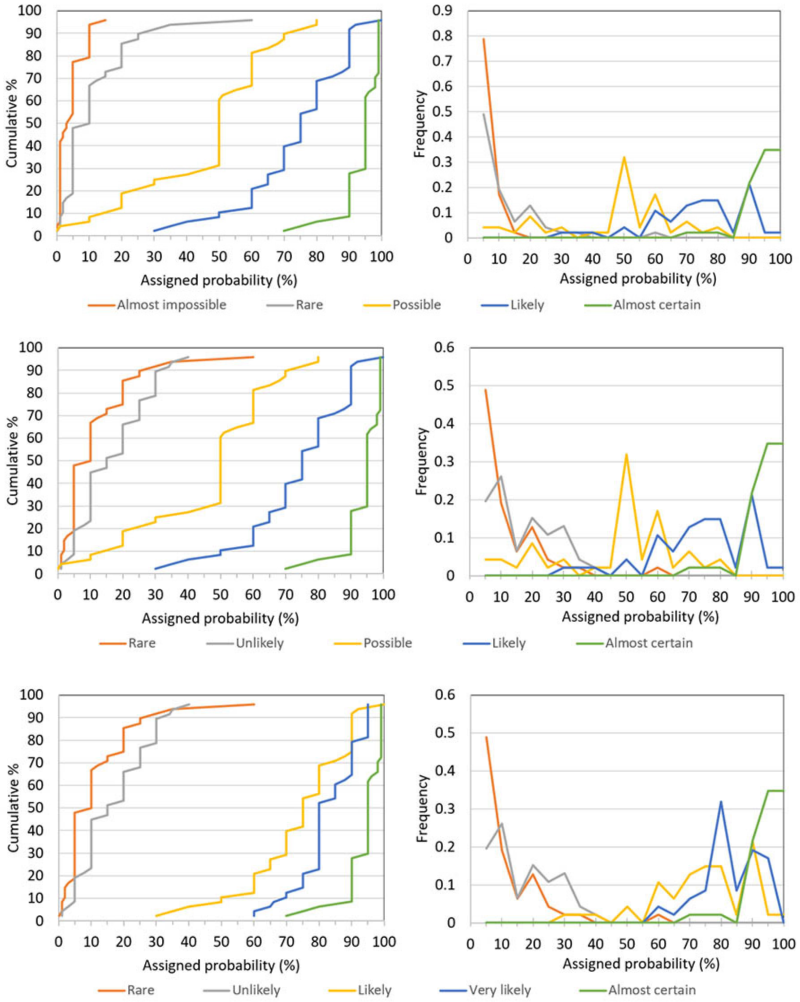

Figure 12—Distribution of assigned probabilities for sets of verbal probability terms used in Matrices A1, A3, and A7

- There is a preference, when given a choice, to assign a round number when converting a verbal probability to a numerical value. This has an influence in the calculation of quartile values during the verbal-numerical translation.
- Words, such as 'possible' and 'probable' have a significant ambiguity of interpretation and a distinctly different meaning for different people. On the other hand, words like 'even chance' and 'medium chance' appear to be interpreted with the very clear and narrow meaning of 50%. Consequently, both sets of words should be avoided in communicating risk.
- Certain expressions (improbable, remote, very low chance, rare, very unlikely) and (very likely, very probable, high chance and very possible) are quantitatively synonymous. The implication is that only one word from each set should be used to differentiate degrees of probability.

The paper employed the results of the analysis to address their impact on the quality of risk matrices. It is important to identify concerns about some of the most common terms used in the presented matrices in Appendix A. As discussed, the most used terms are: rare, possible, unlikely, likely and almost certain. The present as well as other studies suggest that the ambiguity of interpretation of the word 'possible' should disqualify it from use in risk matrices. Similarly, the use of 'likely' is also problematic due to the scatter (IQR > 18) that implies a lack of consistency in interpretation between users.

Viewing these findings in light of the fact that Wintle et al., (2019) found a reduced variability in responses when verbal probability statements were accompanied by numerical range guidelines, begs the question whether better risk communication is not possible with risk matrices avoiding verbal probabilities and instead employing numeric ranges. This question cannot be answered by this study and is suggested for further work.

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Appendix A – Examples of risk matrices used in the mining industry

Likelihood	Consequences				
	Minimal	First aid	Medical treatment	Lost time	Disability
Almost certain	Low	Moderate	High	High	High
Likely	Low	Moderate	High	High	High
Possible	Low	Moderate	Moderate	High	High
Rare	Low	Low	Low	Moderate	High
Almost impossible	Low	Low	Low	Low	Low

Figure A1—Risk matrix for mining activities used by personnel

Likelihood	Consequence severity		
	Marginal	Critical	Catastrophic
Probable	Acceptable	Acceptable	Unacceptable
Infrequent	Acceptable	Acceptable	Acceptable
Remote	Marginal	Acceptable	Acceptable
Improbable	Marginal	Marginal	Marginal

Figure A2—Risk matrix for geomechanical design

Likelihood	Consequences				
	Insignificant	Minor	Moderate	Major	Catastrophic
Almost certain	High	High	Very High	Very High	Very High
Likely	Moderate	High	High	Very High	Very High
Possible	Low	Moderate	Moderate	High	Very High
Unlikely	Low	Low	Low	High	Very High
Rare	Low	Low	Low	High	High

Figure A3—Risk matrix for multiple mining applications

Severity	Likelihood				
	Rare	Unlikely	Occasional	Likely	Frequent
Catastrophic	Moderate	High	Very High	Very High	Very High
Critical	Moderate	High	High	Very High	Very High
Serious	Low	Moderate	Moderate	High	High
Moderate	Low	Low	Low	Moderate	Moderate
Minor	Low	Low	Low	Low	Moderate

Figure A4—Risk matrix for multiple mining applications

Likelihood	Consequence severity				
	Low	Minor	Moderate	Major	Critical
Almost certain	High	Very High	Extreme	Extreme	Extreme
Likely	Moderate	High	Very High	Extreme	Extreme
Possible	Low	Moderate	High	Extreme	Extreme
Unlikely	Low	Low	Moderate	Very High	Extreme
Rare	Very Low	Low	Moderate	High	Very High

Figure A5—Risk matrix for ranking crown pillar stability for closure planning, (Carter 2014)

Probability of occurrence	Damage loss				
	Insignificant <$0.01M	Minor $0.01M–$0.10M	Moderate $0.10M–$1.0M	Major $1M–$10M	Catastrophic >$10M
Certain	Low	Medium	High	Extreme	Extreme
Likely	Low	Medium	High	High	Extreme
Possible	Low	Low	Medium	High	High
Unlikely	Low	Low	Medium	Medium	High
Rare	Low	Low	Low	Medium	Medium

Figure A6—Risk matrix for deep and high stress mining applications, (Joughin 2017)

Likelihood	Consequence				
	Low	Minor	Moderate	Major	Extreme
Almost certain	Moderate	Moderate	High	Critical	Critical
Very likely	Low	Moderate	High	High	Critical
Likely	Low	Moderate	Moderate	High	High
Unlikely	Low	Low	Moderate	Moderate	Moderate
Rare	Low	Low	Low	Low	Moderate

Figure A7—Risk matrix used in corporate risk assessments

Likelihood	Consequence				
	Minor	Medium	Serious	Major	Catastrophic
Almost Certain	Moderate	High	Critical	Critical	Critical
Likely	Moderate	High	High	Critical	Critical
Possible	Low	Moderate	High	Critical	Critical
Unlikely	Low	Low	Moderate	High	Critical
Rare	Low	Low	Moderate	High	High

Figure A8—Risk matrix for rock engineering applications

Probability	Consequence				
	Insignificant	Minor	Moderate	Major	Catastrophic
Almost Certain	Low	Medium	High	Very High	Very High
Likely	Low	Medium	High	High	Very High
Possible	Low	Low	Medium	High	High
Unlikely	Very Low	Low	Low	Medium	Medium
Rare	Very Low	Very Low	Low	Low	Low

Figure A9—Risk matrix used for assessing risks at a deep and high-stress mine

Probability	Consequence				
	Very Low	Low	Medium	High	Very High
Very High	Low	Medium	High	Very High	Very High
High	Low	Medium	High	High	Very High
Medium	Low	Low	Medium	High	High
Low	Very Low	Low	Low	Medium	Medium
Very Low	Very Low	Very Low	Low	Low	Low

Figure A10—Risk matrix used for assessing risks at a deep and high-stress mine

Likelihood	Consequence				
	Catastrophic	Major	Moderate	Minor	Low
Almost Certain	Extreme	Extreme	High	High	Medium
Likely	Extreme	Extreme	High	Medium	Medium
Possible	Extreme	High	High	Medium	Low
Unlikely	High	High	Medium	Low	Low
Rare	High	Medium	Medium	Low	Low

Figure A11—Risk matrix for multiple mining applications