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Impact of draw strategy on wet muck spill hazard severity at the Deep Ore Zone mine

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Abstract

A wet muck spill is a sudden inflow of wet material into an underground mine excavation, typically from an extraction level drawpoint. Wet muck spills pose a major risk to personnel safety, assets (equipment and infrastructure) and production. A key factor that determines the extent and impact of a wet muck spill is its severity, which can be described by its volume, flow velocity and runout distance. Evidence from historical wet muck spill events has shown that the volume and runout distance of a spill can exceed 3,000 m^3 and 200 m, respectively. Wet muck spill severity assessments are an essential component of a mine's risk management plan, serving to guide the delineation of potential wet muck impact zones and the development of effective mitigation strategies. The potential for the occurrence of a severe spill event increases as the amount of fines and water exposed at a drawpoint increase. One strategy to mitigate the risk of a severe spill event is to limit draw at high-risk drawpoints or close them entirely. However, this approach might not be as effective for a mature cave with high quantities of rapidly percolating fine material and stored water, where many drawpoints are likely prone to severe spills. In such conditions, understanding how draw strategy influences spill severity can guide risk-informed draw optimisation, with the goal of minimising severe spill events. A practical approach towards a better understanding of how draw strategy contributes to severe spills must include a systematic review of historical spill data. In this study, statistical methods were used to analyse spill data from the Deep Ore Zone (DOZ) cave mine in Papua, Indonesia, with the aim of identifying trends between the probability of a high-volume spill (defined as spill volume > 500 m^3) and draw strategy. Draw strategy was quantified by two draw-related variables: draw rate and differential draw index. Spill probability was calculated based on the frequency of high-volume spill observations at different ranges of these variables. Results from this study showed that high-volume spills were more likely to happen under high draw rates and non-uniform draw conditions. The probability of a high-volume spill was highest when both draw rate and differential draw index were in their upper ranges, and much less when either of these variables were in their lower ranges.

Keywords: *wet muck spill severity, risk assessment, spill volume, draw strategy, differential draw index*

1 Introduction

One of the major risks to operations in a block cave mine is associated with an underground hazard known as a wet muck spill or mud rush. A wet muck spill is a sudden inflow of material into an underground mine excavation, typically from an extraction level drawpoint. Four elements are required to cause wet muck spills: fine-grained material, water, disturbance and a discharge point (Butcher et al. 2005). Fine-grained material is characterised as ore that is sufficiently fine to retain water and flow under external loads. Typically, this is considered to be materials less than 2 mm in size (Call & Nicholas Inc. 1998). These fines are generated in the cave through secondary fragmentation processes, but can also enter the cave from external sources, such as when the cave breaks through another underground mine above it or from the overlying soil cover, tailings, or an open pit when the cave breaks through to surface. (Hubert et al. 2000). Water may infiltrate into the cave from precipitation, surface runoff or water bearing zones intersecting the caving zone (Samosir et al. 2008).

Wet muck spills pose a major risk to personnel safety, assets (infrastructure and equipment) and production. A key factor that determines the extent and impact of a wet muck spill is its severity, which can be described by its volume, flow velocity and runout distance. Evidence from historical wet muck spill incidents has shown that the volume and runout distance of a spill can exceed 3,000 m^3 and 200 m, respectively (Edgar et al. 2020).

The potential for the occurrence of severe spills increases when a cave transitions to a relatively mature state. In the earlier stages of mine development, when coarse fragmentation is dominant, water percolates and drains from drawpoints more easily. However, as a cave matures, more fines are generated within the cave (Laubscher 2000). Fines have been shown to rapidly percolate down through the draw columns, accumulating in drawbells and filling the voids between larger blocks (Pierce 2010). When a significant amount of fine material is accumulated, cushioning may occur, where larger blocks are found to be floating in a matrix of fines (Dorador 2016). In such conditions, more water is stored within the cave, providing the environment for extensive mud formation. Draw activities (e.g. mucking and blasting) or arch collapse provide the triggers for the mud pockets to release as wet muck spills (Hubert et al. 2000; Butcher et al. 2005).

Wet muck spill severity risk assessments are an essential component of a mine's risk management plan, serving to guide the delineation of potential wet muck impact zones and the development of effective mitigation strategies (Castro et al. 2018; Navia et al. 2014). The most common measures taken by underground mines to reduce the risk associated with severe spills including surface and groundwater management, continuous drawpoint monitoring, rigorous draw control in zones with high spill susceptibility, placement of physical barriers to restrict wet muck spill flow, and remote operation of mining equipment (Holder et al. 2013; Castro et al. 2017; Widijanto et al. 2012).

Wet muck spill risk management plans have improved over time to address the risk that severe spills pose to safety, owing to the utilisation of evolving automated systems, which minimise human exposure to spill incidents. However, managing the impact of severe spills on equipment damage and reduced production has remained an area requiring improvement (Edgar et al. 2020). This impact is particularly significant in a mature cave with high quantities of rapidly percolating fine material and stored water, where a majority of drawpoints might be prone to severe spills. In such conditions, limiting draw at high-risk drawpoints or closing them entirely might not be feasible due to the reduced production rates associated with limited drawpoint availability, and the risk of spreading mud from the closed drawpoints to their adjacent drawpoints (Hekmat et al. 2018). This highlights the importance of identifying the significant factors contributing to the occurrence of severe spills, for better management of the risks associated with them.

Among the studies conducted in the area of wet muck spill risk assessment, few have focused on assessing wet muck spill severity. Edgar et al. (2020) proposed a 'large spill risk classification' system, where drawpoints were classified based on their fragment size and water content, number of closed neighbouring drawpoints, height of draw (HoD), historical spill frequency, and historical maximum spill volume and runout distance. However, in the case of a mature cave, the majority of drawpoints likely meet the high-risk criteria of the suggested classification system, with medium to fine dominant fragment sizes, moist to wet saturation conditions, neighbouring closed drawpoints, and a history of previous spills. In such conditions, it is important to understand how a more dynamically varying factor such as draw strategy impacts spill severity.

In this study, the impact of draw strategies on the occurrence of severe spill events is evaluated through the statistical analysis of draw patterns and spill history, in terms of spilled volumes, at PT freeport Indonesia's (PTFI) Deep Ore Zone (DOZ) Mine. Draw strategy is quantified by using two draw-related variables, draw rate and differential draw index, as proposed by Ghadirianniari et al. (2023). In this study, a spill event is considered to be a severe event when it has a volume over 500 m^3. The potential impact of draw strategy on the occurrence of a severe spill event is assessed by calculating the empirical probability of high-volume spills for different ranges of these draw-related variables. This study aims to improve the current understanding of the impact of draw strategy on the occurrence of severe spill events and guide risk-informed draw optimisation in mature caves, with the goal of minimising such events.

2 Wet muck spill history at the Deep Ore Zone mine

The DOZ panel cave mine (active 2000–2022) was the third lift in the East Ertsberg Skarn System (EESS) deposit, after the Gunung Bijih Timur cave (active 1980–1993) and the Intermediate Ore Zone (IOZ) cave (active 1994–2003) (Widijanto et al. 2012). The production level of DOZ lied at a depth of around 1,200 m below surface and had an offset herringbone layout that included 1,348 drawpoints and draw column heights up to 800 m.

DOZ was in a high precipitation environment with an average annual rainfall of 5,500 mm/yr. The majority of the water flow into the cave was from direct precipitation and surface runoff into the subsidence zone above the cave. Other sources of water inflow were the surrounding water bearing zones and aquifers, including limestone units in the northern area of DOZ, fractured diorite in the Erstberg Stockwork Zone (ESZ), and fault zones in the east and west of the cave (Samosir et al. 2008). The DOZ mine lied in two main geological zones: the ESZ in the southern part of the cave, dominated by hard diorite, and the EESS deposit in the northern part of the cave, hosting a variety of medium and low strength rocks, including forsterite skarn, magnetite skarn, forsterite-magnetite skarn and breccia (Widijanto et al. 2006). In 2003, the northern part of the DOZ cave broke through into the overlying IOZ mine, which contained fragmented ore and waste rock remaining from the previous mining activities (Szwedzicki et al. 2004).

Wet muck spills at the DOZ mine started in 2005. There was a steady frequency of approximately 50 spills per year until 2016, after which the frequency of spills started to increase significantly. The average severity of spills, in terms of spill volume and runout distance, also increased, reaching as high as 3,000 m^3 and 150 m, respectively, which resulted in spills extending from the production level into the haulage level and ore flow areas (Edgar et al. 2020). Figure 1 shows the geological units and fault zones, drawpoint layout and availability, and high-volume spill locations at the DOZ mine during the 2017–2019 period. The wet muck spill history at the DOZ mine is attributable to the complex hydrogeological conditions in the area.

In the DOZ mine's early production years, water was able to drain rapidly from the cave. However, as the cave matured and the proportion of fine-grained ore increased, more water was able to accumulate inside the cave due to the lower permeability and increased water retention capacity of the fragmented ore. By 2015, 60% of the DOZ's drawpoints were in a moist or wet condition. This number increased to 95% by the end of 2018 (Edgar et al. 2020).

The northern part of DOZ was characterised by an abundance of fine-grained ore due to the fine fragmentation characteristics of the EESS zone's medium to low strength units, as well as the downward movement of material from IOZ (Widijanto et al. 2006). Rilling of material and fines migration extended fines beyond the EESS to the ESZ, where diorite with coarse fragmentation was the dominant ore type (Figure 1) (Ramadhan et al. 2015). Rilling of material was attributed to the airgap generated by a lag in the DOZ cave progression during the 2008–2011 period, which was caused by the higher competency of the diorite (Wilson et al. 2016).

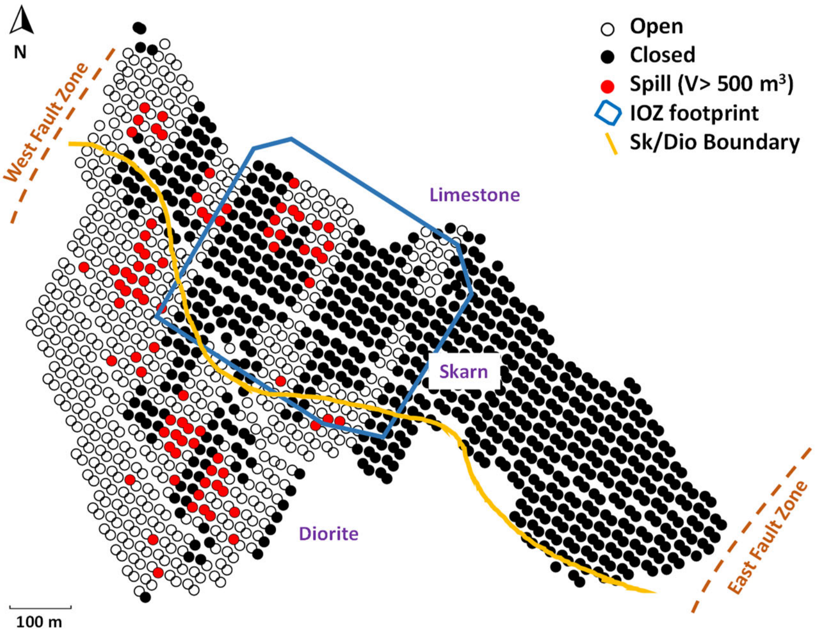

Figure 1 Deep Ore Zone geological units, fault zones, drawpoint layout and spill locations (2017–2019)

PTFI put a standard operation procedure in place to mitigate wet muck spill risk and ensure mine safety (Widijanto et al. 2012). A drawpoint classification system was developed based on drawpoint material size and water content, with the aim of classifying spill risk and establishing the safety protocols and draw regulations appropriate for the identified risk level. The drawpoint classification system is shown in Table 1. Drawpoints in the red class, mapped as having mixed to fine material and moist to wet conditions, were considered high risk and were mined using remote equipment. Drawpoints in the green class were considered safe for manual operations, while those in the yellow class were operated manually with specific constraints. Drawpoints were monitored on a weekly basis for potential changes in classification and the corresponding risk level. Drawpoints that were planned to be permanently closed were sealed with a concrete wall, whereas those that were temporarily closed had fibrecrete sprayed over the muckpile.

Table 1 Deep Ore Zone drawpoint classification matrix (Widijanto et al. 2012). M5 refers to a fragment size of 5 cm; w refers to water content

	M5>70% (Coarse)	30%<M5<70% (Mixed)	M5<30% (Fine)
w<8.5% (dry)	A1	B1	C1
8.5%<w< 11% (moist)	A2	B2	C2
w>11% (wet)	A3	B3	C3

NB: green = manual loader, yellow = manual loader with constraints, pink = remote loader

All of the load–haul–dumpers at DOZ were operated remotely in recent years, as the majority of active drawpoints were in the high-risk class. Although this strategy minimised human exposure to spills, the risk of the equipment being trapped by wet muck material after large spill events remained. In terms of production, the reduced mining capacity of remote equipment and the operational limitations imposed in high-risk zones resulted in a reduction in the average production rate over time, from 40 kt/d in 2015 to 25 kt/day in 2019 (Edgar et al. 2020).

Over the past several years, PTFI has compiled an extensive database of historical spill incidents at the DOZ mine, including the time, location, and approximate volume and runout distance of spills. The spill database was part of the mine's broader database, which included daily records of drawpoint draw tonnages, weekly records of drawpoint classification (Table 1), drawpoint geological mapping data, and daily rainfall data.

3 Methodology

The impact of draw strategies on the occurrence of high-volume spills was investigated through the statistical analysis of historical spill incidents and historical draw patterns at the DOZ mine. Draw characteristics were quantified by two draw-related variables, draw rate ($\dot{d}$) and differential draw index (DI), as proposed by Ghadirianniari et al. (in press). The DOZ mine daily draw and spill database was used to obtain the empirical probability of severe spills (spill volume > 500 m^3) at different ranges of $\dot{d}$ and DI values.

3.1 The Deep Ore Zone mine datasets

The dataset used for the analysis included daily drawpoint records (both spatial and temporal) for: draw tonnages, drawpoint hazard classification (fragment size and water content classes), and spill incidents that happened between January 2017 and August 2019 at the DOZ mine. The selected time frame corresponds with draw and spill history at the DOZ mine during its later stages, in terms of cave maturity, when the majority of the active drawpoints had mixed to fine fragment sizes and moist or wet conditions (i.e. already prone to spill). This represented a condition where understanding the role of draw strategy on the probability of severe spills was particularly important, because production was planned to be maintained at a series of drawpoints at which the fragment size and water observations suggested relatively high spill potential.

Table 2 reports the general information related to the dataset compiled for the analysis. Daily observations at high-risk drawpoints (B2, B3, C2 and C3 classes) were classified as spill versus no-spill based on whether or not a high-volume spill was observed at the drawpoints shortly after they were mucked.

Table 2 General information related to the dataset used for the analysis

Deep Ore Zone dataset	Value/count
High-risk drawpoints	225
Spill drawpoints (V>500 m^3)	78
Analysis period (days)	951
Mean HoD (m)	233
Drawpoint fragment size	Mixed or fine
Drawpoint water content	Moist or wet

The majority of spills happened within 24 hours after the drawpoint was last mucked, and therefore were assumed to be triggered by mucking. Occasional spills that happened at drawpoints without any recorded short-term (24-hours) mucking history, potentially due to other reasons, such as draw activities at adjacent active drawpoints, were not considered in this analysis. The developed dataset included information on draw history related to 86 high-volume spill observations (V > 500 m^3) and 45,208 low-volume spill or no-spill observations at high-risk drawpoints during days when they were mucked. The distribution of high-volume spills versus low-volume spill or no-spill observations across the different mapped drawpoint classes is shown in Table 3. Figure 2a shows the location of high-volume spills, and Figures 2b and 2c show the fragment sizes and saturation conditions, respectively, of the active drawpoints at the end of the selected period (August 2019).

Table 3 Number of spill (V > 500 m^3) and no-spill observations for different drawpoint classes

Drawpoint class	Observations		Total
	Spill (V>500 m^3)	No-spill or V<500 m^3	
B2	1	3,350	3,374
B3	27	25,129	25,156
C2	12	3,876	3,888
C3	45	13,672	13,717
Total	86	45,208	46,135

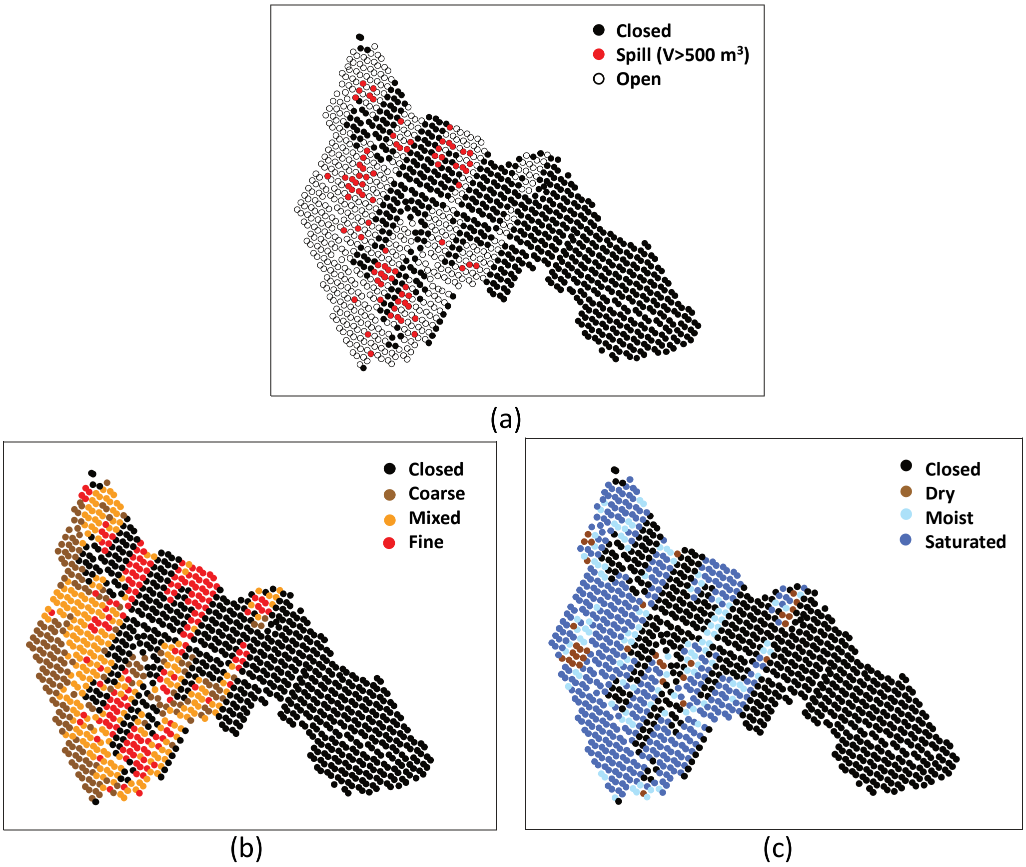

Figure 2 (a) Location of spill drawpoints (V>500 m^3) in the analysis; (b) Fragment size of Deep Ore Zone drawpoints in August 2019; (c) Saturation condition of DOZ drawpoints in August 2019

3.2 Draw-related variables

Draw characteristics were quantified by two draw-related variables, draw rate and differential draw index, as proposed by Ghadirianniari et al. (in press).

3.2.1 Draw rate

Draw rate ($\dot{d}$) is the cumulative tonnage of ore drawn from a drawpoint over a specified period (Equation 1):

$$\dot{d} = \frac{\sum_{i=1}^{n} d_i}{n} \tag{1}$$

where:

d_i = ore tonnage drawn from a drawpoint during the ith day of the specified period.

n = total number of days in the specified period.

A high draw rate is hypothesised to increase the potential for high-volume spills when water and fine material are present in a draw column. A High draw rate creates a larger loosened zone in the draw column (Pierce 2010), facilitating fines and water percolation and increasing the potential for accumulation of high quantities of wet muck material. The rapid unloading caused by high draw rates more likely results in wet muck material to settle in a loose state and become prone to undrained shear failure and static liquefaction (Jakubec et al. 2012; Castro et al. 2017). The fluid-like behavior of liquified wet muck material likely causes more severe spills, compared to when compact wet muck material loses it strength.

3.2.2 *Differential draw index*

Differential draw index (DI) is a parameter proposed by Ghadirianniari et al. (in press) to quantify draw non-uniformity. DI is developed based on the concept of differential movement of broken ore and wet muck material between a drawpoint and its neighbouring drawpoints (Equation 2):

$$DI = \frac{\sum_{j=1}^{m}(d_c - d_j)}{md_c} \tag{2}$$

where:

m = number of drawpoints surrounding the drawpoint for which DI is being calculated (centre drawpoint).

d_c = ore tonnage drawn from the centre drawpoint.

d_j = ore tonnage drawn from the adjacent drawpoint j.

Figure 3a shows the zone of drawpoint interaction in an offset herringbone layout, where the drawzone of an arbitrary drawpoint (centre drawpoint) interacts with the drawzone of the drawpoint in the same drawbell, as well as the neighbouring drawpoints across the major and minor apexes. For this case, DI is equal to the sum of the normalised differential tonnages drawn from the centre drawpoint and the surrounding drawpoints (Figure 3b).

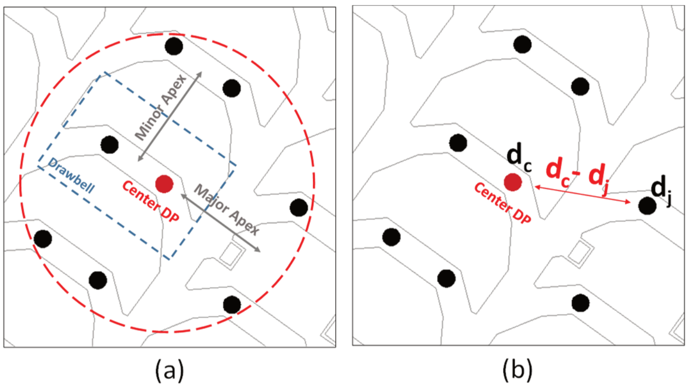

Figure 3 (a) Draw column interaction zone in an offset herringbone layout; (b) Differential draw tonnages between adjacent drawpoints

It is hypothesised that the probability of a high-volume spill increases with DI. When wet muck material is present above or near a series of neighbouring drawpoints, differential draw rates more likely result in the preferential flow and accumulation of the material into the drawpoint with higher draw rate, causing more severe spills. In contrast, similar draw rates more likely balance water percolation between the drawpoints.

3.3 Statistical analysis

The impact of draw strategy on the potential for the occurrence of a high-volume spill was evaluated by calculating the empirical probability of high-volume spills at different ranges of $\dot{d}$and DI, using Equation 3 and 4, respectively:

$$P'\left(spill \backslash\ d_i < \dot{d} < d_j\right) = \frac{N\left(spill \backslash\ d_i < \dot{d} < d_j\right)}{N\left(d_i < \dot{d} < d_j\right)} \tag{3}$$

$$P'\left(spill \backslash\ di_m < DI < di_n\right) = \frac{N\left(spill \backslash\ di_m < DI < di_n\right)}{N\left(di_m < DI < di_n\right)} \tag{4}$$

where:

P'	=	the empirical probability of a high-volume spill.
(d_i, d_j)	=	given range for $\dot{d}$.
(di_m, di_n)	=	given ranges for DI.
$N(\,)$	=	total number of observations for the given range.
$N(spill)$	=	number of spill observations with V > 500 m^3 for the given range.

Empirical probability is the likelihood of an event occurring based on historical data. Its accuracy in representing the actual probability increases with an increase in sample size (*N*). By comparing the empirical probability of spill at different ranges of $\dot{d}$ and DI, the relative impact of these draw-related risk factors on the probability of high-volume spills can be evaluated.

Equal frequency binning and equal width binning methods were used to discretise the $\dot{d}$ and DI data into various ranges. Equal width binning divides a continuous variable into several categories having ranges of the same width, while equal frequency binning divides the data into categories with the same number of samples. For DI discretisation, equal width binning was used because the maximum and minimum possible values of DI are known and different ranges within these DI limits show different conditions in terms of draw non-uniformity (0-0.2: uniform, 0.2-0.4 semi-uniform, 0.6-0.8 semi-isolated, 0.8-1 isolated). For $\dot{d}$ discretisation, however, the maximum possible value and the plausible ranges of $\dot{d}$ are not pre-defined. Accordingly, for an effective comparison of the probability of spill at different $\dot{d}$ ranges, the data was divided into ranges with a similar number of observations.

Although $\dot{d}$ and DI are hypothesised to impact wet muck spills, they are not mutually exclusive. A high $\dot{d}$ may correspond to a high DI as well, when the tonnage drawn from a drawpoint is significantly higher than the tonnages drawn from its adjacent drawpoints. Accordingly, it is also important that the potential for a high-volume spill be evaluated by concurrent consideration of $\dot{d}$ and DI values to investigate how independently $\dot{d}$ and DI impact the probability of a high-volume spill occurrence at a drawpoint. The empirical probability of a high-volume spill related to various ranges of $\dot{d}$ and DI values was calculated using Equation 5:

$$P'\left(Spill \mid d_i < \dot{d} < d_j \ \& \ di_m < DI < di_n \ \&\right) = \frac{N\left(Spill \mid d_i < \dot{d} < d_j \ \& \ di_m < DI < di_n\right)}{N\left(d_i < \dot{d} < d_j \ \& \ di_m < DI < di_n\right)} \tag{5}$$

To effectively compare the obtained probabilities, the Cochran–Armitage (CA) trend test (Armitage 1955) was used to evaluate whether the observed trends in the obtained probabilities at different ranges of $\dot{d}$ and DI were due to real differences in the $\dot{d}$ and DI categories or due to chance. The CA trend test modifies the Pearson's chi-squared test to assess the presence of an association between a binomial variable and an ordinal variable with *n* categories. In the CA trend test, the null hypothesis is that there is no trend between the observed proportions across different categories, and the alternative hypothesis is that there is an increasing or decreasing trend in the proportions with increasing levels of the ordinal variable.

4 Results and discussion

Figure 4 shows the empirical probability of a high-volume spill at various ranges of $\dot{d}$ calculated for 3-day (short-term), and 3-month (long-term) periods preceding daily observations at drawpoints. The $\dot{d}$ data was discretised to bins with comparable number of observations (mean = 7,500, standard deviation = 1,000). As shown in Figure 4, *P'* increased with an increase in draw rate. For example, comparing the *P'* values of the 3-day scenario shows that a high-volume spill was 12 times more likely to occur at draw rates of >250 t/d versus draw rates of 50-100 t/d (P' = 0.0065 versus 0.0005). This observation is in line with the hypothesis that higher draw rates result in the generation of larger loosened volumes above drawpoints, potentially entraining larger volumes of saturated fines and leading to high-volume spills. Similar patterns were observed for the 3-month scenario. These results suggest that both short-term and long-term draw rates impact the probability of high-volume spills.

The significant impact of a short-term high draw rate on the probability of a severe spill is evident in the obtained probabilities, where a higher probability of a high-volume spill is observed after a 3-day period of mucking with a draw rate higher than 250 t/d compared to a 3-month scenario ($P'_{3\text{-}day}$ = 0.064, versus $P'_{28\text{-}day}$ = 0.05). At lower $\dot{d}$ bins, however, the empirical probabilities were lower for the 3-day scenario, implying that longer-term periods of high draw rates more significantly impacted spill severity compared to shorter-periods.

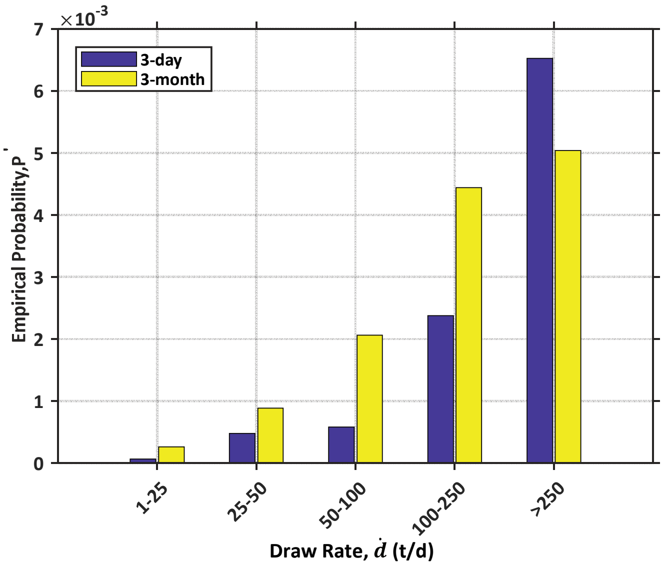

Figure 4 Empirical probability of a high-volume spill (V>500 m^3) at different $\dot{d}$ ranges, calculated for 3-day and 3-month periods

Figure 5 shows the empirical probability of a high-volume spill at different DI ranges, calculated for 3-day and 3-month periods preceding the daily observations. The empirical probability of a high-volume spill increased with an increase of DI for both periods.

For example, during the 3-day period preceding an observation, a high-volume spill was 10 times more likely at a DI range of 0.8-1 (i.e. isolated draw) than at a DI range of 0.2-0.4 (i.e. semi-uniform draw). This observation is in line with the hypothesis that differential draw more likely results in preferential movement of wet muck material towards the drawpoint with the higher draw rate. The *P'* values obtained for 3-month DI values were higher than those obtained for 3-day DI, except for the isolated draw scenario ($0.8 < DI < 1$). This observation implies that draw non-uniformity over longer periods more significantly impacts the probability of high-volume spills, while isolated draw conditions, whether over 3-day or 3-month periods (DI > 0.8), are equally critical.

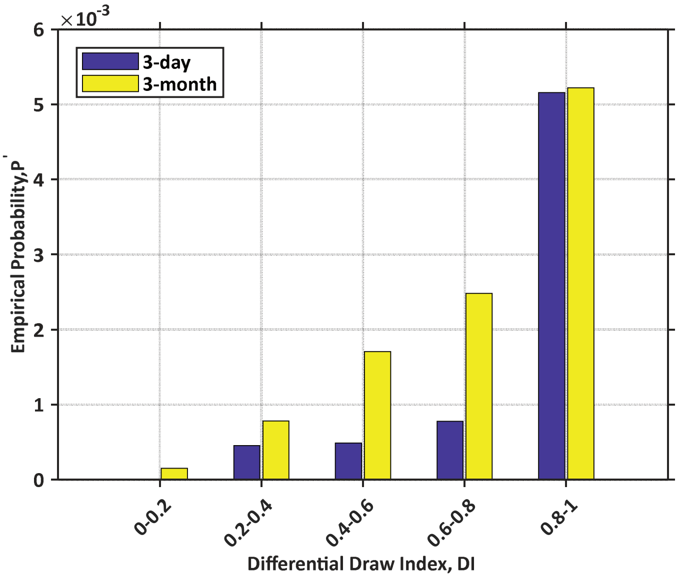

Figure 5 Empirical probability of a high-volume spill (V > 500 m³) at different DI ranges, calculated for 3-day and 3-month periods

Figure 6 shows the P' values obtained when the coupled impact of 3-day $\dot{d}$ and 3-day DI on the probability of a high-volume spill was assessed. Calculating $\dot{d}$ and DI for 3-day periods preceding observations allowed for the assessment of the immediate impact of dynamically varying draw patterns on the probability of high-volume spills.

As shown in Figure 6, the empirical probability of a high-volume spill increased with an increase in 3-day $\dot{d}$ and 3-day DI. P' was highest when both 3-day $\dot{d}$ and 3-day DI were in their upper ranges, showing the coupled impact of draw rate and draw non-uniformity on the probability of a high-volume spill. For example, at $\dot{d}$ > 150 t/d, spills were 16 times more likely if $\dot{d}$ corresponded to a DI range of 0.8–1 (i.e. isolated draw) than a DI range of 0–0.4 (i.e. uniform to semi-uniform draw). Similarly, in isolated draw conditions (DI = 0.8–1), spills were eight times more likely at draw rates of over 150 t/d than at draw rates of 50–100 t/d.

The trends observed in Figure 6 show how differently a specific draw rate over a short-term period can impact the probability of a high-volume spill, based on whether it corresponds to an isolated or uniform draw pattern. One reason explaining the significant impact of short-term draw non-uniformity on the observed probabilities is that, in this study, the spill and no-spill observations are related to clusters of drawpoints with medium to fine ore fragments, above which wet muck material potentially exists. In such conditions, short-term draw non-uniformity most likely contributes to the preferential movement of wet muck material to drawpoints with higher draw rates.

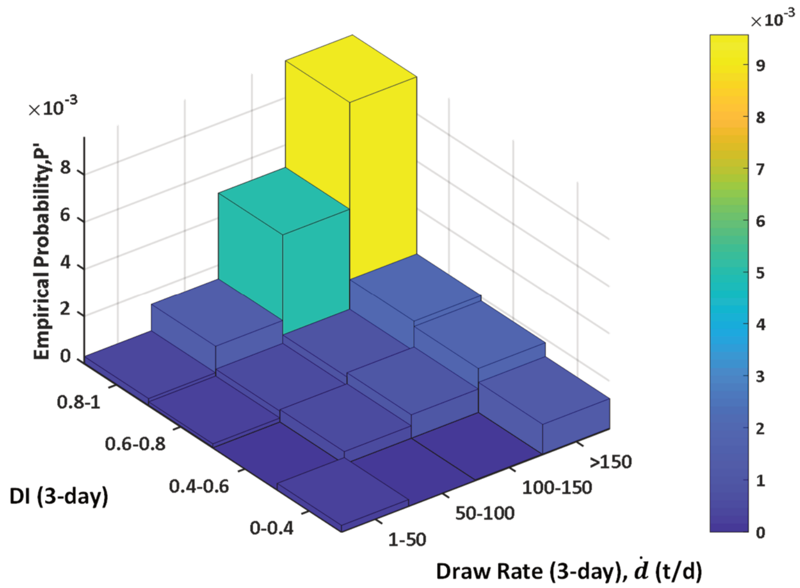

Figure 6 **Empirical probability of a high-volume spill (V > 500 m³) at different ranges of 3-day $\dot{d}$ and 3-day *DI* values**

Figure 7 shows the empirical probability of a high-volume spill obtained for different ranges of 3-day $\dot{d}$ and 3-month DI values. P' was significantly greater when a drawpoint which was under a high draw rate (e.g. >150 t/d) had a long-term history of non-uniform draw (3-month DI > 0.4). This observation suggests that when differential draw occurs over a long period of time, a memory is developed in the system that impacts the risk associated with short-term draw strategies.

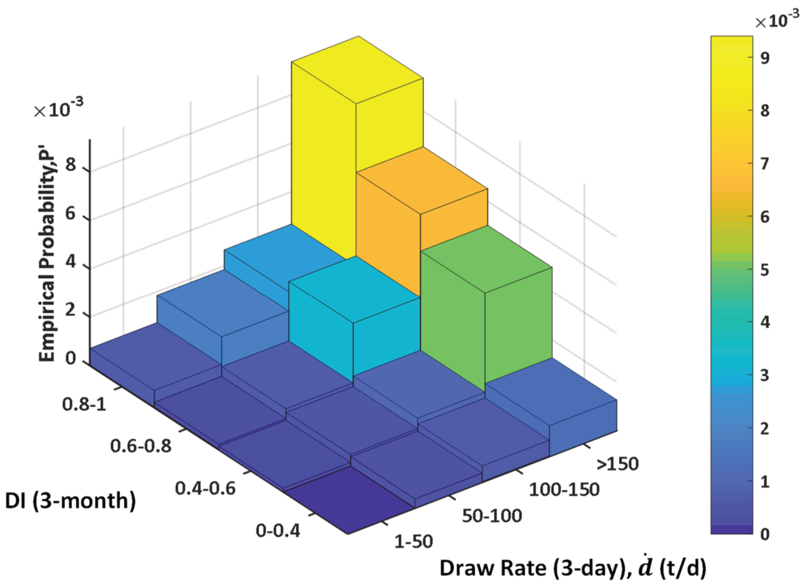

Figure 7 **Empirical probability of a high-volume spill (V > 500 m³) at different ranges of 3-day $\dot{d}$ and 3-month *DI* values**

Table 4 shows the results of sample CA trend tests performed to assess the validity of the observed trends in Figures 4 to 7. The results support the hypotheses explained throughout this section; all of the hypothesis test results were statistically significant, yielding a p-value of less than 0.01, corresponding to a 99% confidence level.

Table 4 Summary of p-values obtained from CA trend hypothesis tests

Figure #	Hypothesis	p-value
4	P' increases with 3-day $\dot{d}$	<0.005
4	P' increases with 3-month $\dot{d}$	<0.005
5	P' increases with 3-day DI	<0.005
5	P' increases with 3-month DI	<0.005
6	P' increases with DI at $\dot{d}$ > 150	<0.005
6	P' increases with $\dot{d}$ at DI > 0.8	<0.005
6	P' increases along $\dot{d}$- DI matrix diagonal	<0.005
7	P' increases with $\dot{d}$ at DI > 0.8	<0.005
7	P' increases with DI at $\dot{d}$ > 150	<0.005
7	P' increases along $\dot{d}$- DI matrix diagonal	<0.005

The results shown in Figures 4 to 7 suggest that the overall impact of draw strategy on the probability of a high-volume spill should be assessed considering the combined effect of draw-related variables, both in the short term and in the long term. The obtained empirical probabilities are based on the observations related to the entire database of high-risk drawpoints at DOZ. Although all of the selected drawpoints were considered high risk, the probability of a severe spill at individual drawpoints could be higher or lower, depending on drawpoint-specific risk factors, including: drawpoint fragmentation (mixed or fine) and water content (moist or wet), drawpoint proximity to high water flow zones, drawpoint location relative to the IOZ footprint and cave boundary, drawpoint ore type, and the amount of accumulated fines. The overall spill risk should be assessed by considering the combined effect of all of the potential risk factors. Nevertheless, the observed trends between $\dot{d}$, DI and *P'* show the significance of the relationship between draw strategy and spill severity at high-risk drawpoints, despite the influence of other risk factors.

The results shown in this study are based on data specific to the DOZ mine and its hydrogeological and fragmentation characteristics. The database used for the analysis covered draw and spill history at a relatively late stage of the DOZ mine life, when the mine experienced several spill incidents due to the presence of high quantities of fine material and stored water. However, the framework used in this study for the creation of draw-related spill probability matrices (as illustrated by Figures 6 and 7) can be used as a guideline for understanding and assessing the draw-related risk of spills at other cave mines, especially when the mine is mature and the goal is to dynamically optimise draw strategies to achieve the target production rate while minimising severe spills at high-risk drawpoints. In practical terms, this includes: 1) developing similar probability matrices using $\dot{d}$and DI, and the historical draw and spill data at the mine; 2) capping maximum draw rates at a specific value, derived from the probability matrices, when non-uniform or isolated draw is inevitable; and 3) capping the differential DI at a maximum value when the target draw rates are planned to be high. Furthermore, the draw-related variables can be fed into more holistic wet muck severity risk assessment tools such as machine learning models, with the goal of predicting when and where high-volume spills are likely to happen.

5 Conclusions

The impact of draw strategies on wet muck spill severity was assessed through the statistical analysis of historical draw patterns and historical high-volume spill incidents at the DOZ mine. Daily observations at 225 spill-susceptible drawpoints over 951 days were classified as high-volume spill versus low-volume or no-spill based on whether or not a high-volume spill was observed at a drawpoint shortly after it was mucked. Draw rate, $\dot{d}$, and differential draw index, DI, were used to quantify draw strategy. $\dot{d}$ and DI were calculated for 3-day (short term) and 3-month (long term) periods preceding daily observations. The impact of these variables on spill severity at DOZ was assessed by comparing the empirical probabilities of high-volume spills at different ranges of these variables.

The results from this study showed that both $\dot{d}$ and DI were significant risk variables for wet muck spill severity. The potential for a high-volume spill was highest when these variables were in their upper ranges, both in the short term and in the long term. Analysing the coupled impact of 3-day $\dot{d}$ and 3-day DI on spill severity showed that the empirical probability of a high-volume spill was highest when both variables were in their upper ranges at the same time, and much less when either of $\dot{d}$ or DI were in their lower ranges. These observations suggest that for a given 3-day $\dot{d}$, mucking uniformly can significantly reduce the probability of a high-volume spill. Similarly, when drawing in isolation, capping the draw rate at a maximum value can significantly reduce the probability of a high-volume spill. This study also showed that a drawpoint was more prone to a high-volume spill under a high draw rate, if it had a long-term history of non-uniform draw.

The results of this study are based on data specific to the DOZ mine. However, the framework used in this study to develop probability matrices for spill severity can be used as a guideline for risk-informed draw optimisation, with the goal of minimising the potential for high-volume spills at high-risk drawpoints while maintaining target production rates.

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