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Laboratory testing framework for assessing mud rush risk

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Abstract

Mud rush events remain a critical geotechnical and operational hazard in block and panel caving mines, reflecting the importance of understanding the mud-forming material potential as the cave matures. A consistent laboratory approach is required to describe the processes by which intact rock and fragmented material may evolve into fine-grained, flowable material under caving conditions. This paper summarises the mud rush risk assessment, which focuses on laboratory testing approaches used to characterise material behaviour associated with mud-forming potential and flowability.

The framework integrates existing operational experiences with modified laboratory testing to evaluate fines generation, physical and chemical weathering, and water sensitivity that reflects cave conditions. Fragmentation and fines generation are assessed through particle size distribution analysis, while durability loss associated with physical and chemical weathering is addressed through repeated wetting and drying cycles and chemical exposure testing. The influence of water is evaluated using Atterberg limits to characterise plasticity, consistency, and water retention behaviour. Material flowability is assessed through the slump flow test to assess its flow potential under saturated conditions. The laboratory testing framework, therefore, can be applicable across caving operations, which supports consistent assessment of mud-forming potential relevant to mud rush risk.

Keywords: *inrush, dry rush, mud rush, laboratory testing, risk assessment*

1 Introduction

Cave mining has increasingly become the preferred underground mining method over recent decades for the extraction of deep, massive, and lower-grade orebodies because of the economic advantage in bulk underground production. Its efficiency mainly relies on the gravity-driven fragmentation process of the orebody and internal comminution process within the cave zone, which enables bulk extraction at relatively low operating cost. Despite these advantages, it is susceptible to inrush-related hazards including dry rushes, mud rushes, and in rare cases, water inrushes. All these events may originate from different mechanisms but can produce the same result, such as injury, loss of life, excess dilution, operational delays and economic losses.

An inrush event can be defined as a sudden and uncontrollable inflow of unsorted fine-grained particles discharged from drawpoint or other underground openings (Butcher et al. 2000; Jakubec et al. 2016). Currently, there is limited published guidance that summarise the parameters contributing to inrush. The key challenge is identifying which lithologies are susceptible to degradation and fines generation, the potential to form mud as moisture content increases, and conditions that initiate flows. Previous studies have contributed toward understanding of the material characteristics, including the use of slump flow testing to assess the influence of moisture on material mobility (Vallejos et al. 2017), the investigation of mud rush behaviour under controlled moisture conditions (Castro et al. 2023), and the interpretation of fines generation and flowability indicators from mine geotechnical datasets (Musolino et al. 2024). Nevertheless, a consistent laboratory characterisation framework that links rock mass condition, site observations, and material flowability is still needed, particularly during the early stages of caving operations, to support the

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identification of inrush potential and management of mud rush risks. This paper presents a laboratory testing framework intended to improve the characterisation of mud rush prone material in caving operations. The proposed framework is based on industry experience and available literature on laboratory testing methods to assess fines generation, mud-forming potential, and flow behaviour. Although the focus of this paper is on mud rush, the broader application of this framework is applicable to other inrush-related hazards.

2 Mechanisms of mud-forming potential and inrush in caving operations

Mud formation and inrush in caving operations is a progressive process controlled by the interaction between mechanical and hydrogeological processes within the cave column that increase with cave maturity and is also controlled by rock mass characteristics. According to Butcher et al. (2000), the occurrence of a mud rush is a complex process requiring the simultaneous presence of 4 elements within the drawpoint vicinity:

- potential mud-forming materials (i.e. fines)
- accumulation of water
- disturbance of the mud in the form of drawing or other mining activities
- discharge point.

All of these elements are inherent to caving operations and are largely unavoidable. Experience from various caving operations have concluded that fines generation is a function of geology and the comminution process in the cave zone, while water originates from either surface precipitation or nearby aquifers. Mud rush events typically occur when fine-grained material becomes saturated and mobilised under reduced effective stress conditions. Therefore, it is necessary to identify key parameters contributing to the mud rush prior to the laboratory testing framework development. A risk assessment framework developed by Jakubec et al. (2016) is used as a baseline to identify the mud rush risk process as illustrated in Figure 1.

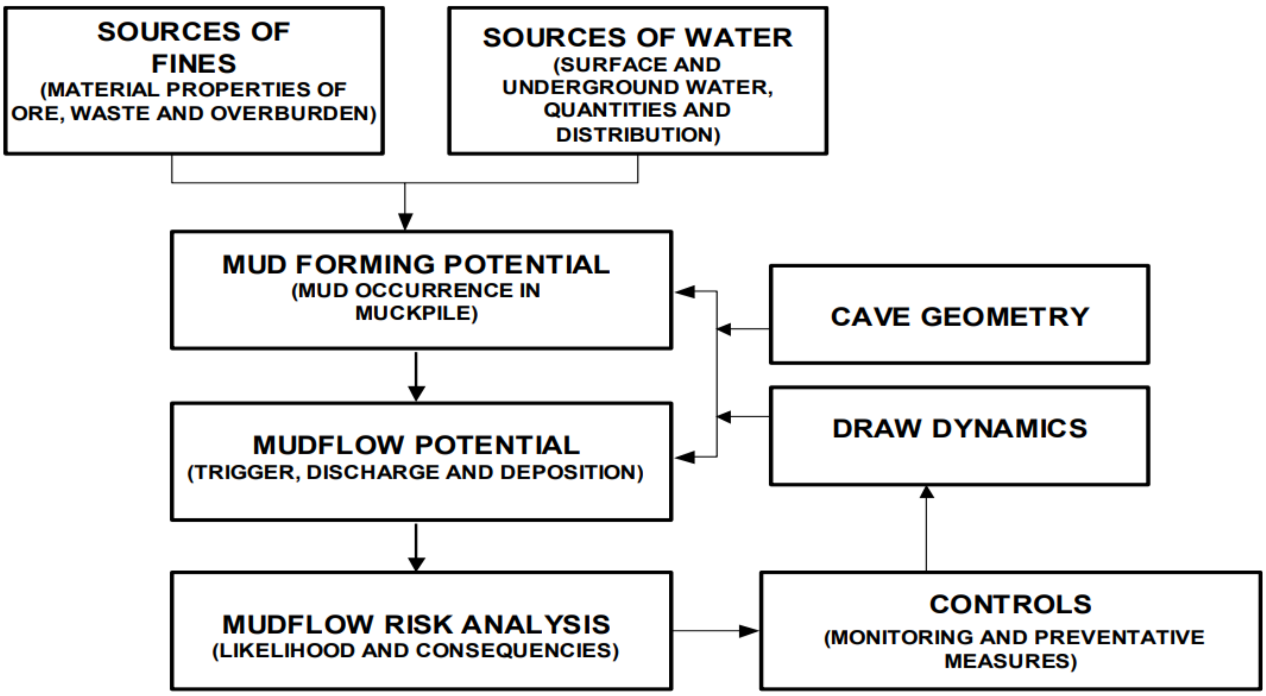

Figure 1 Mud rush risk framework (Jakubec et al. 2016)

Rock mass characteristics play a fundamental role in controlling susceptibility to mud formation. Variation in lithology, alteration, weathering, and structural fabric influences both the strength and fragmentation behaviour of the rock mass. Weaker lithological units such as clay-rich material, weak, altered and faulted zones are more prone to generate fines and weathering resulting in mud-forming material. Rock mass classification methods, such as rock mass rating and Q-system, can be used to identify weaker zones that may serve as sources of fine material within the cave column. These weak zones are often preferentially fragmented during cave propagation and become key contributors to mud rush susceptibility.

Fragmentation is the primary mechanism controlling the initial generation of fines in which the generation and accumulation of fines is prerequisite for mud rush. Without fines, water could simply drain through the coarse rock pile preventing the build-up of pore pressure for mud rush. As the cave develops, secondary fragmentation continues through gravity-driven interaction combining with stress redistribution process which led to more comminution and a continuous increase in fine material within the cave column. Studies at the Grasberg mining complex established that unsorted material containing greater than 20% sand-sized particles (<2 mm) becomes susceptible to flow if saturation exceeds 80% (Widijanto et al. 2012). In addition, field observations from several caving operations suggest that fines can migrate following draw patterns and cave movement.

In addition to fragmentation, material degradation contributes to the ongoing generation of fines. Degradation occurs through mechanical abrasion, wetting–drying cycles, and the chemical weathering process within the cave zone. Chemical weathering may lead to mineral alteration and clay formation, increasing the proportion of fines, plasticity, and water retention capacity. These processes are more significant within the weaker lithological units.

Water is fundamentally the primary driver of mud rush risk. Sources of water may include precipitation, surface runoff, groundwater inflow, and localised ponding at the subsidence zone (Jakubec et al. 2016). An increase of water content influences the stability of caved material by altering its mechanical properties, specifically by reducing shear strength and increasing pore pressure, which can lead to liquefaction. Fines can act as a sealant that reduces the permeability of the draw column, allowing water to accumulate and creating a matrix that, when saturated, can lose shear strength and liquefy. This transition is strongly influenced by material plasticity, which can be characterised using Atterberg limits. Materials with a higher plasticity index can retain more water and are more susceptible to flow under saturated conditions.

The transition from stable granular behaviour to flowable behaviour occurs when fines content, moisture conditions, and material properties reach critical threshold. At low moisture content, caved material behaves as a frictional granular medium. As moisture increases, cohesive and plastic behaviour may begin to develop. Under saturated conditions, materials may exhibit fluid-like behaviour, leading to slumping, continuous flow or a mud rush event. Experimental observations have shown that the onset of flowable behaviour is controlled by the interaction between fines characteristics and moisture content rather than by a single parameter (Castro et al. 2023). Similarly, drawpoint classification matrix, which is used to assess drawpoint material condition, adopts the combined approach of fines and moisture content rather than focusing on a single variable

Operational factors, such as draw control and draw rate, can act as both causative and triggering mechanisms contributing to mud rush (Ghadirianniari et al. 2024). Poor draw strategy influences both fragmentation rates and the redistribution of fines within the cave column, which, along with high extraction rates, may localise the comminution process (Varian et al. 2022). Non-uniform draw can introduce a localised accumulation of fines though fine migration. In addition, fine migration is commonly observed at the cave perimeter, where the cave boundary provides preferential pathways for the movement and accumulation of fine material.

3 Laboratory testing framework

There is no universal guideline in the mining or civil engineering industries for inrush material laboratory testing. The proposed framework utilises available literature and industry experience with modification to suit the caving operation while generally aligning with applicable ASTM standards for material testing.

The primary objective of the laboratory testing framework is to characterise the properties following the mud rush material generation with the geotechnical units to evaluate their potential for mud forming and flowability. The philosophy of the process is to understand:

- the content and distribution of particle sizes
- the flow behaviour of the finer fraction.

The initial step is a proxy to physical breakdown in the cave. Further downstream, the process uses qualitative indication of susceptibility to fines generation and flow capability. The process of laboratory testing is summarised in Figure 2. The ASTM standards referenced are used as a guidance rather than strict requirements as testing approaches may vary depending on site conditions and material characteristics.

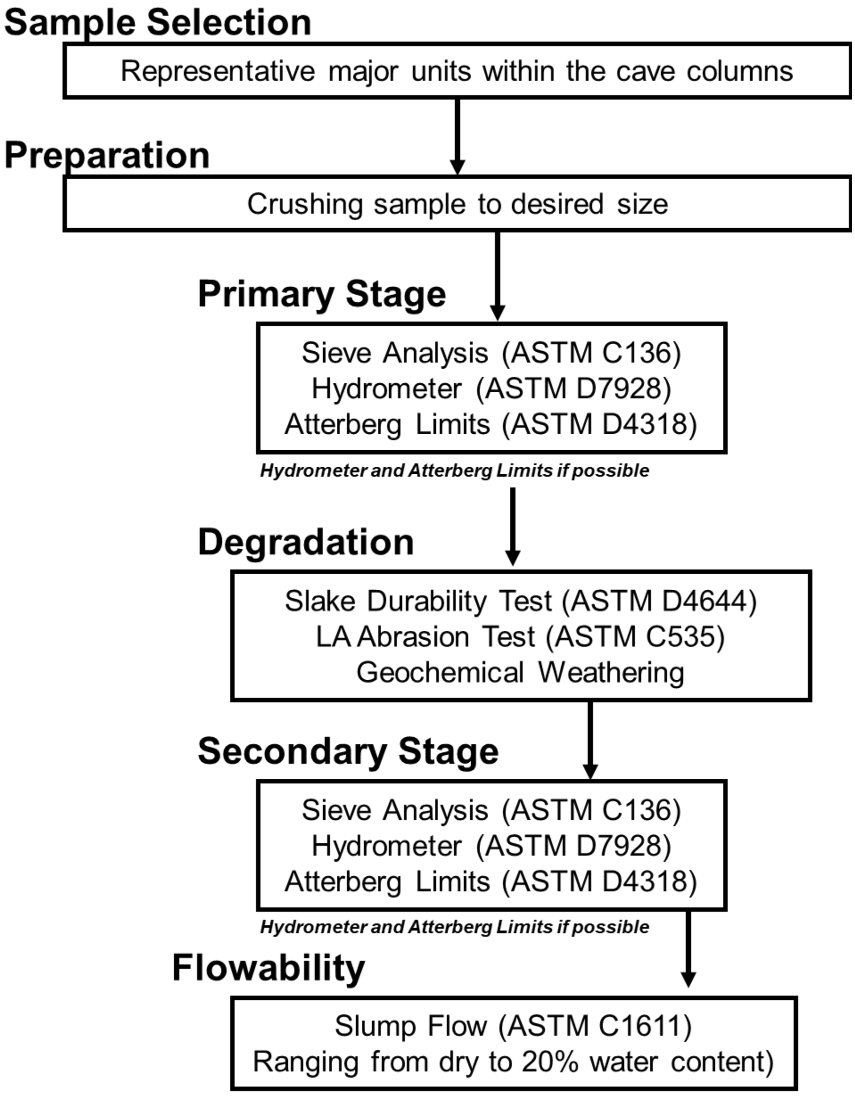

Figure 2 The laboratory testing framework to assess mud rush risk

3.1 Sample selection

Samples can be collected either from drillcore logging and/or drawpoint. Sample selection should aim to represent the range of lithologies and geotechnical units within the rock mass. A higher focus on representative sample selection should be given to geotechnical unit with a high potential for fines generation and degradation considering alteration, fracture density, intact rock strength and weak/clay zones. In addition, the samples should also be proportional based on the volumetric representation within the cave zone while also ensuring weak or any altered unit is captured during the selection process.

3.2 Preparation

Samples obtained from both drillcore and drawpoints are crushed to achieve a target fragmentation size distribution suitable for subsequent laboratory testing. The selected particle size distribution is not intended to directly replicate cave-scale fragmentation, but rather a representative laboratory-scale approximation of early-stage fragmented material within the cave environment through application of uniform physical energy. It is recommended to avoid over-crushing that may generate artificial fines and bias the downstream analysis of fines generation and flowability.

Sample size is selected based on both material characteristics and laboratory testing requirement. As a general guideline, the initial top size is approximately half drillcore diameter. However, weak or highly altered units may naturally break down into a finer fragmentation size during this stage. Maintaining a representative fragmentation size is important to reflect the early cave condition. The samples will eventually be more fragmented during the degradation stage. The selected fragmentation size therefore represents the maximum target top size rather than a fixed distribution. Appropriate fragmentation sizing also improves sample availability for downstream laboratory testing where the tests require specific particle size ranges with minimum sample mass.

3.3 Primary stage

The initial laboratory testing program of mud rush risk assessment begins in the primary stage, which mainly contains sieve analysis (ASTM International 2025b), hydrometer analysis (ASTM International 2021a), and Atterberg limit test (ASTM International 2018). The objective of this stage is to establish the baseline properties of the material prior to any further breakdown.

At the primary classification stage, particle size distribution (PSD) analysis was conducted to characterise the fragmentation. Based on the sieve results, the material was classified into gravel-sized particles (75 to 4.75 mm), sand-sized particles (4.75 to 0.075 mm), and silt-sized particles (0.075 to 0.002 mm). This classification provides an initial understanding of the relative proportions of coarse and fine fractions, which are influential to permeability, drainage, and fines mobility. The process included hydrometer testing to further classify the fine-grained fraction (silt and clay) that cannot be determined solely from sieve analysis. In some cases, there might be insufficient mass of material to conduct this test as fines below silt-size particle may not be available at the primary stage due to coarser fragmentation. Hydrometer testing can be skipped when there is no available sample at this stage.

Subsequently, Atterberg limits testing was carried out to determine the liquid limit and plasticity characteristics of the fines component. These parameters provide insight into the material’s consistency, plastic behaviour, and potential to transition into a flowing or mud-like state under saturated conditions, which is particularly relevant for assessing mud rush susceptibility during later stages of cave evolution.

3.4 Degradation

Following the primary material classification, samples were subjected to Slake durability test (ASTM International 2016), Los Angeles abrasion test (ASTM International 2024a), and geochemical weathering (ASTM International 2024b) to assess degradation behaviour. These tests were selected to evaluate material response to wetting–drying cycles and mechanical energy combining with the geochemical weathering process which reflects the degradation processes acting within the cave environment.

The test was performed over 2 cycles, with durability expressed as the Slake durability index (Id_2), based on the percentage of the original sample mass retained after 2 test cycles. Following each cycle, the retained material was oven-dried and weighed. Higher Id_2 values indicate more durable material, whereas low Id_2 values indicate a tendency for disaggregation into fines upon water exposure. The Los Angeles abrasion test was undertaken to assess the material's resistance to mechanical breakdown. The testing involves rotating the materials in a dry steel drum filled with steel balls, which causes impact and abrasion. Test results are reported as the percentage of material lost, with lower values indicating greater resistance to physical degradation. Los Angeles abrasion results indicate the rate of fines generation during draw and materials handling. Geochemical weathering testing provides an indication of the potential for chemical degradation, particularly in material susceptible to oxidation and mineral alteration. Although there is no set guideline on directly measuring chemical weathering on fragmented rock, related ASTM standards (i.e. ASTM International [2025a] for swelling clay, ASTM International [2019] for identification of altered clay-bearing minerals) can be adapted depending on the geological condition. When considered together, the degradation results provide a basis for assessing both the rate and extent of fines generation through the weathering process.

3.5 Secondary stage

Similar to the primary material classification, which includes sieve analysis (ASTM International 2025b), hydrometer analysis (ASTM International 2021a), and Atterberg limits testing (ASTM International 2018), this secondary stage was conducted following completion of the degradation tests. The objective of this stage is to characterise the post-degradation properties of the materials and for comparison with results of the primary (pre-degradation) classification.

This approach enables assessment of changes in PSD, fines content, and plasticity resulting from mechanical breakdown, wetting–drying processes, and chemical weathering. Such changes provide insight into the evolution of material behaviour as fragmentation and degradation progress.

The results of 2 clay units were excluded from the secondary classification hydrometer testing due to the unsuitability of the method for highly degraded fine material, which exhibited flocculation and non-uniform settling behaviour that would compromise test reliability and interpretation.

3.6 Flowability

Slump flow testing was undertaken as part of the laboratory testing procedure for the mud rush risk assessment to evaluate the flow behaviour of fines-rich material in the presence of water, under conditions similar to mud flow. Testing was conducted in general accordance with ASTM International (2021b) with adaptation from concrete tests with moisture contents ranging from oven-dry to 20% total moisture in 5% increments. Slump flow test results integrate the combined effects of fine content, clay mineralogy, and moisture content, and provide a practical indicator of flow susceptibility under a range of moisture conditions from dry to wet material. Materials exhibiting high slump values at relatively low moisture contents are interpreted to have an increased likelihood of higher mobilisation.

4 Discussion

The proposed laboratory framework has been applied across several mud rush characterisation studies at several caving operation with different geological settings and material types. While site-specific details and quantitative results are not presented due to confidentiality, the application of the framework has provided a consistent qualitative observation on mud-forming potential and mud rush susceptibility. Table 1 summarises the laboratory tests taken and the relevance to the mud rush mechanisms.

Table 1 Laboratory tests relevance to mud rush mechanisms

Laboratory test	Test objective	Inrush relevance
Sieve analysis	Identify fines distribution during the primary and secondary stages	Identify geotechnical units prone to fines generation
Hydrometer	Identify silt-size material that is not able to be captured during sieve analysis	Identify silt-size material distribution during fines generation
Atterberg limit	Identify material liquid limit and plasticity	Identify material transition under saturated conditions
Slake durability index	Identify material durability under wetting–drying cycle	Identify physical weathering once exposed to water
Los Angeles abrasion test	Identify material durability when undergoing mechanical breakdown	Influence of draw and comminution to secondary fines generation
Geochemical weathering	Identify material durability when undergoing chemical weathering	Potential of clay formation and weathering inside the cave column
Slump flow	Identify material flowability under different moisture contents	Material mobility with the increase of moisture content

The framework provides a more structured approach to characterise material behaviour related to mud rush potential by linking fragmentation, degradation process, increase in water content, and flowability. Application of the framework across different sites indicates that mud formation is controlled by interactions between fines, moisture content, and material plasticity. Samples associated with weaker geotechnical units including clay-bearing and weak zones consistently show a higher proportion of fines generation at both the primary and secondary stages with increased qualitative measurement from sieve analysis and Atterberg limit results. As a result, these units may represent key contributors to mud-forming material within the cave column, and management strategies need to be developed to address the high presence of the highlighted unit in the drawpoint. The degradation process of the laboratory testing framework highlights both physical and chemical weathering during comminution through mucking activity, exposure to water, and the geochemical process within the cave column. Material flagged as clay bearing and weak zone show higher plasticity and water sensitivity when comparing the outcome from the primary and secondary stages. Flowability testing provides a conceptual result on the laboratory-scale material flow by gradually increasing the material moisture content. As expected, low moisture content tends to hold the material together, while increasing moisture content material starts to slump.

These behaviours aligned with the mechanisms summarised in Section 2 which highlights the importance of identifying the weak geotechnical units to mud-forming potential. Overall, the framework provides a practical and transferable approach to add value from early characterisation studies on the inrush mechanism. In addition, outcome of the laboratory framework can be integrated into operating mines existing mud rush risk assessment to improve the evaluation of mud rush potential and spill probability. This approach enables the operation to be aware of mud rush susceptibility that is naturally inhered in caving methods.

5 Limitations

The framework is subjected to the limitation associated with a laboratory-based characterisation of the rock mass for mud formation and mud rush potential. The laboratory testing does not fully replicate the process within the cave zone. Hydrogeological processes including water migration and the weathering process may be simplified for the laboratory testing. Additionally, the framework relies on a qualitative interpretation which requires a good understanding of the rock mass condition.

6 Conclusion

This paper presents a standardised laboratory-based framework for assessing mud-forming potential in caving operations by integrating fragmentation, degradation, water sensitivity, and flowability to characterise material behaviour in relation to mud rush risk. The framework can provide a consistent approach evaluating the mud rush prone material with the established laboratory testing practices adapted from the ASTM standards. Although site conditions may vary, the principle of this framework provides an understanding of mud rush material characterisation in mud rush mechanisms. In addition, outcomes of the laboratory testing can be used as input for downstream mud rush prediction.

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