MUDRUSH RISK EVALUATION

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ABSTRACT

One potential hazard that should be evaluated during cave mining studies is mudrush. Mudrush is a phenomenon that can have very different origins, but produce the same results: injury, loss of life, damage to property, excess dilution, production delays, or mine closure. Although mudrushes are more common in cave mines than other mines, any mining activity that enables the accumulation of fine particles and water is susceptible to mudflow. This paper describes the process developed by the authors over the past decade to evaluate mudrush risk, specifically on caving and sublevel caving mines.

KEYWORDS

Cave mining, Mudflow, Mudrush, Mudpush, Risk, Wet muck

INTRODUCTION

There are several terms used in the industry and in available literature describing the sudden ingress of wet material into underground workings. The most common are “mudrush”, “mudpush”, and “mudflow”. All of these terms describe phenomena that can have very different origins, but can produce the same results: injury, loss of life, damage to property, excess dilution, and production delays or, in the extreme case, mine closure.

Two key characteristics of mudrush and debris flows are mobility and the unsorted nature of the material involved, i.e., particle sizes can range from clays to “car-size” boulders. Mudrush dynamics in underground mining are especially complex due to confinement and stress within the muckpile.

Butcher et al. (2000) recognized internal and external mudrushes based on the location of the materials’ source. External mudrushes are caused by the ingress of tailings materials into the cave. Internal mudrushes are those where mudrush is generated from the lithologies within the cave or subsidence zone.

The following terminology is used in this paper:

- Muck—caved or blasted material
- Muckpile—column of broken material inside the caved zone
- Mud—mixture of fines and water
- Wet Muck—material composed of unsorted solid particles (muck including mud) and water in proportions that can potentially flow by gravity, if undermined or disturbed (e.g., liquefied)
- Mudrush—uncontrollable ingress of wet muck into the underground workings
MUDRUSH EXPERIENCE

Mudrush occurs fairly commonly in mines; however, the majority of them are of little significance and are not life-threatening. Mudrashes that have killed and maimed miners are usually the subject of a detailed enquiry, which have often had significant legal and financial ramifications. As a result, the findings of the enquiries are rarely published in journals or at conferences. Authors of this paper have investigated the causes of mudrashes in a number of mines, and their experience, together with available literature, resulted in the following summary of cases.

Block caving and sublevel caving (SLC) operations are inherently susceptible to internal mudrashes because they have the potential to accumulate water (surface and underground), generate fines (the comminution process), and through production activities, provide disturbances as well as a discharge point. Block caving operations are also susceptible to external mudrush flows because the broken muckpile connects the surface (point of entry) with the underground excavations (point of discharge).

Although mudrashes are more common in caves than in any other mines, any mining activity that enables the accumulation of fine particles and water is susceptible to mudrush. There are cases of injuries and even fatalities from sudden ore pass discharges, the collapse and subsequent flow of unconsolidated or poorly consolidated backfill, and failing tailings/slimes dams.

Based on the mobility of the wet muck, two principal categories have been recognized: Fluid Muck and Viscous Wet Muck.

Fluid Muck

Fluid muck has a high water content (up to 50%), which has been recorded as flowing horizontally for great lengths up to 500 m. The depths of the debris deposits are shallow up to 1 m. The mud is uniformly graded and includes large rocks up to 3 m in size. The mudrush in this case resembles thin slurry and, generally, is seen more as a water discharge than a mudrush flow. It readily flows and reports to sumps and creates problems blocking pumps and screens. An example of the fluid mudrush is shown in Figure 1a.

Viscous Muck

Viscous muck has low moisture content (17–23%). It generally exhibits thixotropic properties and tends to be stiff. This material would not flow freely under gravity but, if stressed, under certain conditions it could be mobilized and “squeezed” out of the drawpoint. Such mobilized muck, despite the high viscosity, can be destructive and can extrude into any available opening. The extreme case of stiff mud protrusion from the drawpoint is illustrated in Figure 1b.
In 1994, when a tailings dam failed in the South African town of Merriespruit, 600,000 m$^3$ of material flowed through the town causing the death of 17 people, demolishing numerous houses, and damaging the environment over a widespread area. Strydom & Williams (1999) found the primary cause of the failure was insufficient freeboard to accommodate maximum precipitation over a period of 24 hours with a frequency of once in 100 years.

The cause of the disaster was attributed to unauthorized spilling of mine waste water over the dam, coupled with 32 mm of rainfall in a three hour period, which triggered the breaching of the wall. The moisture content in the slimes at failure was from 27 to 41%. Once the breach had occurred, large straining of the material in the drainage channel rapidly reduced its lateral confinement. The rapid changes in the stress condition contributed to liquefaction and the sudden flow of the tailings.

A review of the flow distances of failed tailings and slimes dams around the world showed they have occurred over distances as far as 24 km from a height of 44 m (a grade of 1:545), but this is the exception. Generally, flows were less than 5 km with an average of 3 km.

**Mufulira Disaster, Zambia**

In September 1970, 89 miners were killed at Mufulira, Zambia, due to an inrush 450,000 m$^3$ of muck into the workings. The muck originated from tailings dams, which (dating back from 1933) were located on subsiding ground above the workings. The water, impounded in the depressed crater of the tailings that had subsided, was seen as a major contribution to the inrush. Tailings and fines have the potential to flow and, once liquefied, can flow over large distances. The cone of depression that formed took a few years to eventually result in a massive flow. The concept of having a muckpile of near saturated fine material on top of a mine is analogous to the muckpile becoming saturated with fines and water over time.
Examples of Internal Mudrushes

South African Diamond Mines

Most of the mudrush cases occurred at mines that were employing the sublevel caving method or were in the process of converting from sublevel caving to block caving. Although caving principles and mud formation potential could be very similar for both methods, the draw control and cave interaction is more challenging for the sublevel caving method. In the case of block caving, draw control is easier to implement and manage.

Most of the diamond mines date back to the turn of the century and were mined in a number of ways. A number of mudrush flows have been reported in the South African press over the last 100 years and the most recent mudrushes occurred in the past several years.

General managers’ reports, which date back to the late 1890s, all point to water being the main driving force behind the mudrush flows with the presence of soft country rocks, which report to the muckpile as the main contributors to the muck. The rocks varied considerably in consistency and grading.

Freeport Mudrush Flow Experience

P.T. Freeport underground operations in Indonesia have also experienced mudrush flow problems, which have caused fatalities. The mine is located in mountainous terrain in the tropics and experiences very high annual rainfall ranging from 3,000 to 5,000 mm.

Muck from the IOZ contains 25–50% fines (< 2 mm). It was determined that muck containing more than 20% of fines could potentially flow, if saturated. The final saturation of the muck is 65–100%, and at least 80% saturation (corresponding to 8.5% moisture content) is required for the muck to flow. Observed outflows from the drawpoint indicated that drawbells were near saturation when each mudrush flow occurred. The relative density of the muck is approximately 80–90%. In order to flow, the material has to be loosely packed in the drawbell (less than 90% relative density).

Either dynamic triggers (blasting, equipment moving) or static ones (increase in pore pressure, mucking) could initiate a mudrush flow. The volume of the discharged mudrush is all within the drawbell.

In conclusion, the IOZ block cave mine is a “very wet” mine. The presence of fines in the muckpile exceeds 20% and makes it susceptible to form mud that could potentially flow. The observed triggers are all common to other “mudrush flow” prone operations. Details are reported in Hubert et al. (2000).

SLC Mines in China and Canada

At an iron ore SLC Mine in China, Hubei province, experienced a devastating mudrush in 2004, resulting in at least one fatality. An interesting characteristic was that iron ore rock mass is very competent and does not generate excessive fines and virtually no clays. In 1998, this region experienced extreme rainfall events and floods. Most likely, fines (and possibly clays) generated from the exposed crater “percolated” into the muckpile at that time and eventually created a “seal” that trapped saturated materials above the SLC. However, it was not until 2004 that approximately 14,000 m$^3$ of saturated debris entered the mine. In discussions with staff, it was apparent that, at the time of the event, drawpoints were overdrawn.

The most recent mudrush was reported from an SLC Mine in Canada. The mudrush risk assessment was conducted as part of the feasibility study and correctly predicted the mudrush potential risk. The mine had all the procedures in place and successfully and safely continues to operate with tele-remote equipment and strict operating procedures.
INVESTIGATIONS

A mudrush seldom occurs as the result of a single cause or fault. Therefore, any risk analysis has to take into account all of the contributing factors and their combinations. A failure of the “system” usually results when a combination of failures occur in such a way that the disturbing forces exceed the capacity of the system to resist those forces.

However, before assessing any risks to a mine, the following questions need to be answered:

- Is there potential to generate fines?
- Is there potential to accumulate water?
- Is there potential to form mud?
- What disturbance can mobilize and discharge the wet muck?

Figure 2 illustrates the mudrush risk assessment process.

Material Properties Evaluation and Testing

Firsthand experience and back analysis of mudrashes has allowed the authors to develop an understanding of the mechanisms that contribute to the formation and flow of mud. Original back analysis of the muds using both soil mechanics and geological testing provided valuable insights into what makes up the mud. In some cases, it was found that the mud was derived from country rock, a blend of ore and, in some cases, a blend of both. It was further found that the blends can vary significantly during the life of the mine. Extensive laboratory research allowed the blends to be recreated by mixing the samples of ore and country rock together.
Laboratory Simulation

The alteration of the ore and country rock occurs as a result of many mechanisms, which includes mechanical and chemical breakdown due to exposure to the atmosphere and water. In some cases, the breakdown occurs in a short time, but in other cases may take months or even years to occur while the material is mobile in the muckpile. Simulated mechanical and chemical weathering is carried out in the laboratory to age and weather the rock. A ball mill damage index is determined to provide an indication of the flow potential.

During the degradation process, the rock blend is monitored to identify its behaviour. The dramatic change in the gradings of the samples after the degradation is bench marked against "real" mud, sampled from various mudrashes around the globe. This process provides the mine with an indicator of which ore or country rock is at risk of generating mud.

Flow Potential of Mud

The flowability of the degraded materials is bench marked in the laboratory against the behaviour of known muds. A flow cone with variable aperture sizes was developed to accommodate the degraded material and the flow potential measured. The tests are carried out under a standard head at a range of moisture contents and aperture sizes to assess what the critical moisture range is likely to be for a mudrush to occur. During this test, the slumping potential and flow distance is related to known muds. An aperture ratio, determined from the flow cone size and maximum particle size, provides some indication of the likely size of the material that may flow from a drawpoint of a known size.

Studies and predictions that are carried out on new underground mines may take many years to be fully realised. Regular contact with mine investigators has assisted in developing confidence and calibration in the procedures presented.

Relationships with Water

Water and fine solid particles are the two most important elements contributing to mudrashes. Without water, there is no risk of a mudrush, even if all of the other criteria are present.

Water can have negative impacts at all stages of the mudrush cycle. For example, it accelerates weathering and thus speeds the mud-forming process. It is one of the triggering mechanisms for a mudrush and it serves as the main driver that causes the mudrush to flow. Therefore, it is important to examine all aspects, including the source and volumes of water entering the subsidence zone, the distribution and potential for accumulation within the muckpile, and the water's impact on flow-ability of the muck.

Early reports of mudrush flows were attributed directly to the presence of water. (The expression “a leaky drawpoint is a happy drawpoint” is recorded in a number of reports.) On some mines, drainage tunnels were constructed with the view to intercepting groundwater. Various reports attributed a subsequent reduction in the frequency of mudrush flow events to the effectiveness of the dewatering tunnels.

Other instances of mudrush flows were directly attributed to the falling of heavy rains shortly prior to the event. As the mine matured, the correlation between rainfall and mudrush flows diminished. This may be due to the retention time and storage capacity of the growing muckpile above the mine. Mudrush flows are seen to occur after a static period when the muckpile was not kept mobile.

MUDRUSH TRIGGERS AND BEHAVIOUR

Mudrush flows are fundamentally unsteady phenomena. Contraction and consolidation result in a change of pore pressure and thus alter the behavior of the flow. This fluid pressure (greater than hydrostatic pressure) can enhance flow efficiency and prevent consolidation. Unlike the surface debris flows that are
gravity driven, the flow behavior of mudrush could be complicated by disturbing forces that can easily exceed gravity (e.g., loading due to the collapse of arched material). The prediction of the mudrush flow behavior is further complicated by the fact that it usually changes mass and composition while in motion.

**Uneven Draw**

Production pressures for high ore grades could encourage the mine, preferentially, to draw certain areas of the mine. The effect is that zones of low stress and high voids are created in the zone of influence above the drawpoint. The fine fraction in the muck pile migrates toward this zone of low density material and fills the voids. This condition is even more prevalent when the draw in this zone is stagnant for some time. As the stress state changes in the zone, the fine fraction is subjected to confining stresses, which, when applied to a material with high moisture content, will result in a large increase in the pore water pressure with little stress applied to the rock. If the fine material has low permeability, it is unlikely that the pore water will dissipate freely out of the material. This cell of saturated, pressurized material can be simulated as a balloon filled with water and soil in suspension. If the balloon is breached, a catastrophic flow occurs. This concept is identical to releasing the confining stress of the cell. As the material is prone to liquefaction, it will flow with ease. The end result is a sudden ingress of mudrush into the drawpoint.

Correlation studies have indicated that, provided the muckpile is in a dynamic state and the material is being constantly drawn, the risk of mudrush flow is low. This happens because the constant movement of the orebody facilitates drainage and prevents migrating fines from settling and thus causes water to accumulate.

**Triggering Mechanisms**

Mechanisms triggering mudrush flow are acts of some disturbing force that mobilize the body of mud and discharge it into the underground excavations. A number of possible triggers include dynamic triggers—seismically induced liquefaction (by blasting or equipment induced vibration) and static triggers—excess stress (collapse of arched material or crater walls) and water that acts as a mobilizing force for mud, either by changing the material properties of the mud (described earlier) or by applying excess pressure. This can occur, for example, when the water level is rising in the drawbell or due to the sudden inflow of large quantities of water after heavy rainfall.

**Mudrush Flow Discharge and Deposition**

After the mud discharges from the drawpoint, the material will travel through the underground openings until all of the kinetic energy degrades. Typically, the coarser material is collected at the perimeter of the flow. Deposited coarse debris lacks high pore pressure and forms a “dam”. Freshly deposited mud flows may be initially dry and stiff at their perimeters, while the core of the deposit is still in a near liquefied state. In that respect, the stiffness and relatively high angle of repose at the face of the deposited debris flow may not represent the actual flow parameters of the total flow volume.

The travel distance of the mudrush flow depends on volume, velocity, physical properties of the material, and dynamics of the flow, as well as on resistance caused by the geometry and size of the openings. Because mudrush flows can exhibit both solid and fluid behavior, the calibration is complicated by the changing mechanisms of momentum transport and energy dissipation.
RISK ASSESSMENT

Following the assessment of the muck forming and wet mud flow potential, a qualitative risk analysis should be conducted where the following questions need to be addressed:

- What is the likelihood of mudrush occurrence during the life of the mine?
- What are the safety and economic consequences?
- What can be done to minimize the risk?

Because each company has its own risk assessment guidelines, we will not discuss the details of the risk assessment in this paper.

PREVENTATIVE MEASURES AND OPERATIONAL RISK ASSESSMENT

Preventative measures will help to ensure that the risk is managed.

Reactive Preventative Measures—Operational decisions that are based upon the results of a continuous monitoring program:

- Muckpile Monitoring, including fragmentation and moisture content.
- Surface Crater Monitoring, recording new failures, water accumulation and elevation profiles.
- Water Monitoring, including surface and underground inflow, pumping rates and ore moisture/tonnage.
- Geotechnical Monitoring, including changes in the tunnel/pillar deformation, etc.
- Operational Reports including production figures, secondary breaking reports and moisture.

Proactive Preventative Measures—To minimize the consequences of a wet muck ingress, measures should be implemented as part of the mine's standard operating procedures. These controls should be introduced as a matter of course in addition to the monitoring program.

Operational Mudrush Risk Assessment—The conclusions to be drawn from individual observations are, for example, water budget deficit could indicate water accumulation in the muckpile, etc. The drawpoints should be classified in different categories based on the amount of fines and moisture in the muckpile.

CONCLUSIONS

Block caving and sublevel caving operations are inherently susceptible to internal and external mudrushes because they connect the surface with underground and provide a potential point of entry for the water and mud. They also have the potential to accumulate water, generate fines and, through production activities, provide disturbances as well as a discharge point. Therefore, it is essential that the mudrush risk assessment forms an integral part of any block cave or SLC feasibility study.

Because of the complex nature of the caved materials, cave dynamics, and water distribution within the muckpile, it is very difficult to predict mudrush occurrences once mud has formed in the cave with any degree of certainty. However, draw control discipline, comprehensive monitoring, and standard operating procedures will minimize the risk.

There are a number of examples of caving mines that operate safely with high rainfall and mud forming potential, using tele-remote equipment and strict mudrush risk mitigation procedures.
REFERENCES


