Mud rushes and methods of combating them

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Synopsis

Mud rushes are hazardous occurrences that have occurred frequently in mines in South Africa, and have been the cause of numerous fatalities in the past. Mud rush incidents not associated with accidents are believed to be common occurrences that are not generally reported. Many such incidents are probably associated with the operation of chutes and box fronts. This paper describes the conditions necessary for mud rush occurrences, postulated mud rush mechanisms, and methods of combating the mud rush hazard.

Introduction

Mud rushes are sudden inflows of mud from drawpoints or other underground openings. Mud rushes can and have posed a major hazard to safety in underground mining. Statistics of accidents associated with rockpasses over the past ten years have been summarized by Stacey and Erasmus (2005). The rapidity of the mud inflow is such that escape of personnel in its path is most unlikely, with terrible consequences for safety. Mud rushes are also directly responsible for severe damage to infrastructure. Considerable violence, in the form of an air blast, is often associated with a mud rush. Such an air blast event can also be the cause of accidents and severe damage to mine infrastructure.

Published literature on mine mud rushes is very limited, despite the perception that mud rushes are a serious problem in the mining industry. Six well-documented incidents (not associated with rockpasses), where mining operations had suffered major in-rushes or continual in-rush problems, were identified in the literature. The recent disaster at Maroelabult Mine (Matthee, 2005) represents a documented case of a mud rush from a rockpass. It is probable that there is reluctance to publicize mud rushes in which accidents resulted, and there would similarly be little interest in writing up incidents for public consumption.

The following historical information, extracted from the literature, does not deal with mud rushes associated with rockpasses. It is included because it identifies important aspects that are relevant to all mud rushes. It also reinforces the information obtained from the Maroelabult enquiry.

Mud rushes associated with mining in South Africa were first observed at De Beers and Kimberley mines in the late nineteenth century, with many fatalities being attributed to their occurrence. In these events, the mud rush problem is ascribed to the breakdown of kimberlite and shale in the mine muck pile, with the addition of rainwater via the open mine (Hunt and Daniel, 1952). Since both kimberlite (Bartlett, 1992) and shale contain clay minerals, it can be assumed that these comminuted rocks, in combination with water, were the source of mud in the diamond mines. The sections and plans of Dutoitspan and Wesselton mines, presented by Hunt and Daniel (1952), indicate that the shale originated from the upper Karoo slopes, with the kimberlite being present in the muck pile, possibly due to under-extraction of the chamber. This under-extraction was caused by water-related ground control problems. Since chambering is a combination of shrinkage stoping and sub-level caving (Peele, 1942), with a muck pile being formed after chambering had been carried out, the possibilities of comminution of the shale and kimberlite rocks existed. In addition, the muck pile would also consist of a certain percentage of dolerite, attributed to slope failure, and this rock may not have been broken down during the mining and caving process.

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It would appear that the mud rushes were also related to active mining and drawing of the kimberlite, since mud pushes are described as occurring only at loading places (Hunt and Daniel, 1952).

The importance of the contribution of water in mud rushes is further described by Hunt and Daniel (1952). It was recognized in the latter part of the nineteenth century, during the mining at Kimberley Mine, that the mud rush problem could be partially combated by increasing mine drainage with the development of water drainage tunnels. These excavations were started in 1891, with the galleries being situated in the country rock outside the perimeter of the pipe. Water tunnels were developed below the base of the shale in the Ventersdorp lava, which is the main aquifer. These tunnels were only partially successful since they did not prevent rain water from reaching the muck pile. Much water still ran down from the lava/shale contact into the muck pile.

The importance of drainage galleries as a method of mud rush prevention was recognized as early as 1899 at Wesselton Mine. When underground mining began at this mine, it was thought that a far greater mud rush risk existed, because mine water pumping volumes were greater and the main shale/lava contact was deeper. The importance of the main shale aquifer, and the need to dewater it, were recognized from the commencement of mining. Hunt and Daniel (1952) describe the development of the first water tunnel at this mine in 1899. However, this did not stop the occurrence of mud rushes, with 20 lives being lost to mud rushes between 1919 and 1950. In one instance, 12 lives were lost. As a result of this, it was decided to increase the groundwater drainage capacity of this mine by developing a series of new tunnels.

At Dutoitspan Mine, the development of a drainage gallery system started in 1908, with the need to prevent muck pile water ingress being recognized earlier. Two drainage tunnels were initially developed 20 m and 45 m from surface, and it appears that these tunnels were relatively successful in reducing the frequency of mud rushes.

The water drainage tunnel systems described by Hunt and Daniel (1952) appears to have been the first line of defence in the prevention of mud rushes. A further measure included the development of drawpoints located at the pipe contact. These excavations were used to extract wet ground and prevent the formation of underground mud. It is also probable that this drawing may have increased the muck pile porosity, thus enhancing drainage. Reference is made to the ability of weathered kimberlite to hang up, by acting as a plug of mud. From this, it can be hypothesized that a weathered kimberlite mud plug could occur in the muck pile above the workings, reducing drainage and increasing the potential for mud formation.

The need to evacuate personnel rapidly is mentioned by Hunt and Daniel (1952), and a system of guards and air whistles was introduced at Wesselton Mine in the 1950s. Such precautions were taken to prevent underground workers from being cut off in adjacent excavations by mud rushes.

Jennings (1978) documents investigations relating to the failure of the No. 1 slimes dam at Bafokeng Mine on 11 November 1974, which resulted in a mud rush into the underground workings. It was concluded that the dam wall failed with a flow slide mechanism, triggered by a piping failure through the dam wall. Once the wall had broken, the retained slimes became fluid and flowed into the Bafokeng shaft. The classic bottle-shaped scar associated with flow slides was observed at the dam breach area. The major factors contributing to the failure were:

- the layering of coarse and fine particles, which could have facilitated piping
- the use of the slimes dam as a storage facility for rain water, leading to increased pore water pressures
- construction techniques that were applicable to gold tailings and not platinum tailings dams.

Midgley (1978) reports that the dam failed after a period of intense rainfall—75 mm over a two-to four-hour period the night before. This again emphasizes the role of water in mud rushes. A scrutiny of the diagrams from this paper shows that the dam was situated in close proximity to the shaft. This indicates that a potential mud rush hazard always existed.

Rudd (1978) states that the slimes dam failed very quickly, destroying mine buildings and winding houses and flooding the shaft with slimes. Twelve men lost their lives. It is estimated that 3 million m^3 of slimes escaped. This indicates the hazard potential of a mud rush caused by a slimes dam failure.

Fleischer and Sandy (1976) present the results of an investigation into an in-rush of tailings into the Mufulira Mine on the Zambian copperbelt in 1970. In this mud rush 89 people were killed when workings were engulfed by 450 000 m^3 of slimes. The report also deals briefly with the factors that led up to the mud rush. The mine used slusher block caving and open stoping without mud rush incidents being recorded. The main tailings dam, which failed, was present above the mine workings for many years. However, when the mining method changed to sublevel caving, the situation changed, with higher extraction rates occurring. Although not stated in the report, it is possible that isolated draw occurred. This in turn led to the in-rush of tailings. It was further thought that the tailings in some parts of the dam may have been of a finer grade with greater moisture content, and thus with a greater ability to flow.

Fleischer and Sandy (1976) hypothesize that a clay layer below the dam may have acted as flexible base and may have accommodated a certain degree of ground deformation in previous years associated with the block caving. The geotechnical investigations that were conducted on the failed tailings dam, to stabilize the slimes in order for operations to resume, are also described. It was found that tailings’ flow would not occur if moisture contents were low enough. Tailings would consolidate if dewatered sufficiently and would form a dry plug with a limited mud rush potential.

Neller, Oliver and Sandy (1973) describe the associated problems attributed to the major mud rush at Mufulira, namely the threat of mine flooding caused by the destruction of mine pump chambers. This threat was overcome by the design of a temporary mine pumping system using mobile submersible pumps. Additional problems mentioned by the authors were the extensive damage to mine infrastructure and the problems of rehabilitation.

The threat of a mud rush due to tailings not only comes from slimes dam, but also can be ascribed to the failure of underground backfill. Bryant *et al.* (1994) describe an incident that occurred during mining at Carolusberg Deep Mine. This mine used vertical crater retreat (VCR) stoping to extract a pipe-shaped copper orebody. The orebody was mined with 20 m x 20 m VCR stopes, which were then post-filled with a mixture of tailings, cement and blast furnace slag. The mining sequence started with coning of the panel and then mining by VCR blasting. The panels were then backfilled, with mining of the adjacent panels not beginning until the backfill had reached its 45-day compressive strength (normally 1.5 MPa). Other mining rules were that no panel would be mined if three sides of the stopes consisted of under-strength fill. The paper describes the events that led up to the failure of the fill, the main aspects being:

- fill dilution of ore from the current operational stope
- noticeable slumping of fill on the upper levels.

The authors give no reason why the backfill failed. The consequences of the failure were the death of four mineworkers, and the total inundation of two production levels, the ramp system for five levels and the main haulage.

The literature on mud rushes associated with box-holes, ore passes and chutes is almost non-existent. Hang-ups in passes and box-holes, and blockages at chutes are often occurrences that may result in mud rushes. The presence of fines, which produce 'sticky' material, promotes conditions that are favourable for the formation of hang-ups and blockages. The 'sticky' material is also the mud that is then available to flow in the mud rush. The sources of the 'mud' include those identified for major mud rushes, but can also be the accumulation of fines produced by comminution of rock, and backfill used in the mining operation. Similarly, sources of water include rainwater and groundwater, but more commonly would be drilling and operation water and water from leaking or burst pipes.

These types of mud rushes usually occur as a result of bad mining and operational practices. Unlike the major mud rushes, which have been described above and in which the location of and potential time of occurrence of the hazard is unknown, the potential hazard with box-holes, passes and chutes is usually known because of the hang-up, blockage or other conditions. The actual hazard is the mud rush that can occur when the chute is opened or the hang-up is cleared. To minimize the hazards in these cases, hang-ups and blockages should be prevented by avoiding the tipping of oversized and foreign material, keeping the material in the pass or box-hole moving regularly, clearing accumulations of sticky material (pagging) regularly, and preventing water from entering passes and box-holes. In essence, these actions represent good management of the facilities. Special chute designs and chute operating procedures have been developed to minimize the mud rush hazard at these locations (Prins, 1995).

The general rockpass issues presented above are all relevant to the accident at Maroelabult Mine that occurred in December 2004 when a mixture of mud and water flowed from a rockpass into a decline shaft under construction, inundating seven workers at the face of the shaft. Five other workers were injured in the event. The report of the enquiry into the accident (Matthee, 2005) indicated that water was allowed to accumulate in the rockpass from which the mud rush occurred. There was no control mechanism in place to prevent the mud rush from occurring. Blockage of the rockpass was observed shortly before the failure, but clearly the observers did not realise the importance of such an observation. The mine standard required a drainpipe to be installed at tipping areas to divert water that could otherwise enter the passes. These pipes were reported to be frequently out of place or badly installed, which clearly affected their ability to drain the water away satisfactorily. The findings of the enquiry indicated a system failure of the risk management system. The management of risks associated with unsatisfactory drainage measures, absent control mechanisms, and non-reporting of blockages in passes was apparently inadequate.

In summary, mud rushes have affected mining operations in South Africa for over 100 years, with many fatalities being attributed to them. Few detailed case histories on mud rushes exist. However, the reviewed literature suggests that these events are related to:

- comminution of rocks containing clay minerals
- failure of slopes that comprise clay minerals
- failure of tailings dams associated with subsidence and/or the drawing of ore
- liquefaction of tailings or backfill with direct flow into underground workings.

There is strong evidence that the presence of water in general, including rain and/or groundwater, has a major influence on the occurrence of mud rushes. In this respect, the paper by Hunt and Daniel (1952) shows the efforts made to reduce the groundwater regime and hence its effects on the occurrence of mud rushes. The experiences from Beattie Mine show that underground workings are threatened by mud rushes due to open pit mine slope failures, provided that connections exist between the pit and underground excavations. From the information reported by Hunt and Daniel (1957), and that contained in the Mufulira Mine disaster report, the in-rush of mud or slimes corresponds with the drawing of ground and the change of mining method.

Sources of mud and environment for mud rush occurrence

From the review of literature and mud rush accident reports, sources of mud that have been involved in mud rush occurrences are the following:

- readily weatherable materials such as shale and kimberlite, which occur in the ore and country rocks
- tailings impoundments, which are located on surface above or adjacent to mine workings
- backfill placed in underground stopes for support or disposal purposes
- in the case of box-holes and passes, mud and fines, from whatever source, that can form 'sticky' material.

From the historical information mentioned earlier, it can be deduced that four elements are required for a mud rush to occur:

- potential mud-forming materials must be present
- water must be present
- a disturbance of the mud, in the form of drawing or other mining activity, must occur
- discharge points must be present through which the mud can enter the mine workings.

Evidence from mud rush occurrences suggests that all four elements must be present at once for a mud rush to occur. The implication is that, even if only one of the elements is absent, a mud rush will not occur.

Mud rush mechanisms

There is no single mechanism for the occurrence of mud rushes in mines. Mud rushes can be classified as external mud rushes or internal mud rushes.

- External mud rushes result from mud generated externally by the deposition of tailings and mine backfills. In-rushes of material from slope failures are also classified under this heading. External mud rushes are those in which the mud is produced externally to the physical underground environment
- Internal mud rushes involve mud produced by the comminution of shale or other clay-forming country rocks, and clay mineral rich ores, within the cave muck pile. Fines that accumulate as a result of the mining process are also involved in the internal process. Mixed mud forming materials are also grouped in this category—even though some material is formed outside the underground environment, this material mixes with internal mud.

External mud rushes

External mud rushes are produced from three main sources:

- *In-rush of tailings or slimes*—the inflow of tailings or slimes can occur directly, or indirectly as a result of dam wall rupture, from which the material can flow unaided towards a shaft, adit or open bench, resulting in an in-rush of tailings underground
- *Failure of placed backfill in underground stopes*—this type of failure could occur due to the placement of poor quality backfill, during the filling if a barricade ruptures, and once the fill has been placed
- *Mud rushes due to open pit slope failures*—in cases in which underground mining of an orebody has been preceded by open pit mining, the influx of mud into the workings is due to the failure of an open cut slope directly above underground mines workings opening some way to the surface mining, resulting in the in-rush of slope material to the underground workings.

Internal mud rushes

Internal mud rushes have been experienced for approximately 100 years at Kimberley mines. The mud is formed internally during drawdown of the waste capping above the orebody. Mixed mud rushes are included in this classification, due to the mixing of internally and externally generated mud materials within the muck pile. The proposed internal mud rush mechanisms are given below.

- *Muck pile/waste capping mud rushes*—the proposed mechanism for a diamond mine, in which initial open pit mining was succeeded by underground cave mining, is shown in Figure 1. Although this mechanism is illustrated for a diamond operation, it is conceptually applicable to other operations as well
- *Secondary waste capping/muck pile mud rush mechanisms*—the above mechanism may be regarded as a 'major' mechanism. However, there are two other secondary internal mud rush mechanisms. These are, firstly, rapid muck pile compaction, illustrated in Figure 2, which can be seen as the mechanism responsible for mud pocket discharge; and reduced muck pile/waste capping drainage, the mechanism of which is shown in Figure 3.

Mixed mud rushes can be ascribed to the creation of mud from a combination of the above sources.

Mud rush mechanisms from box-holes and rockpasses are straightforward. The 'sticky' material formed from the fines and water adheres to the sides of the box-hole or rockpass, and to the box or chute structure. This restriction impedes the flow of material and causes further agglomeration and ultimately a blockage. In addition, sticky material particles may adhere together to form, effectively, much larger particles. These may be large enough to lead to hang-ups in box-holes and passes. Once a blockage or hang-up has occurred, rock, further fines and water can accumulate above the restriction, providing a driving force for a mud rush, which occurs when the chute is open or some disturbance of the blockage material occurs.

Trigger mechanisms and warning signs

Only two possible mud rush triggers exist—disturbance and water. This is because these two factors control the discharge process of the mud rush. Disturbance creates the conditions necessary to allow free mud discharge, and water acts as a mobilizing force for the mud, either by changing the material properties of the mud, or by applying a pressure, due to an increasing head of water.

Disturbance

In the case of underground stopes, the following are considered to be warning signs (i.e. possible disturbances) for mud rushes:

- the poor design of stope, back, crown pillars and sidewalls
- the collapse of open stope rib pillars leading to back/crown pillar failure and surface subsidence
- the ingress of groundwater into the stope, weakening the rock mass.

In the case of box-holes and rockpasses, the disturbance is generally the opening or movement of the chute or box front.

Water

It is clear that water has had a role in mud formation and the in-rush triggering process. The following are considered to be possible mud rush warning signs:

- Lack of a correctly designed mine drainage system
- Poor maintenance of the mine drainage system. In this respect, particular note must be taken of the following:

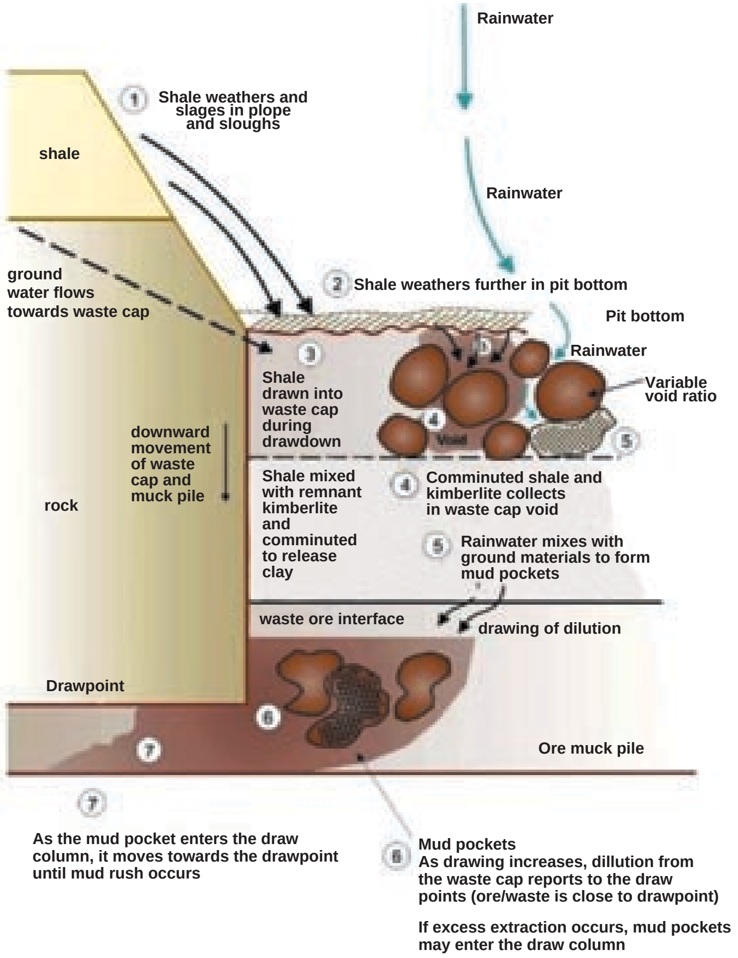


Figure 1—Muck pile mud rush

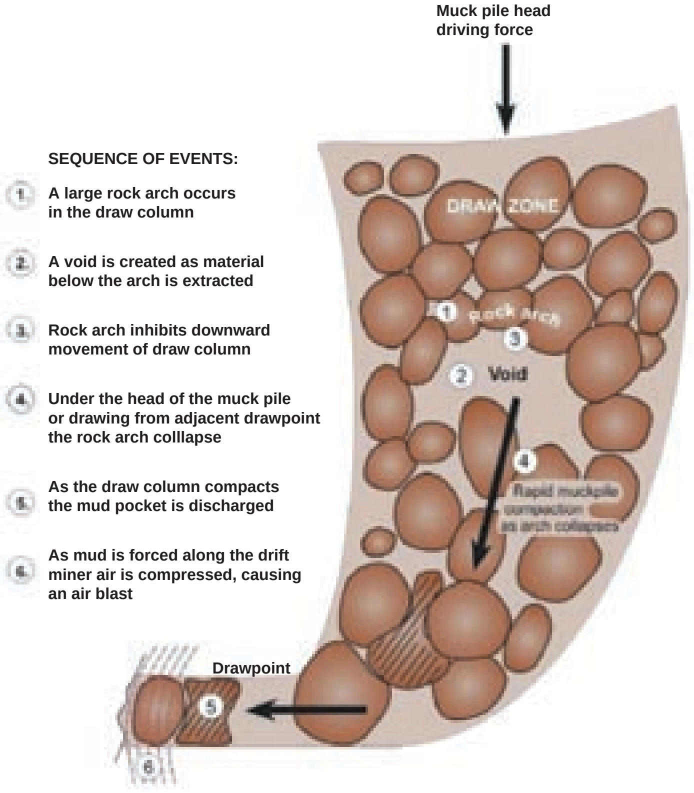
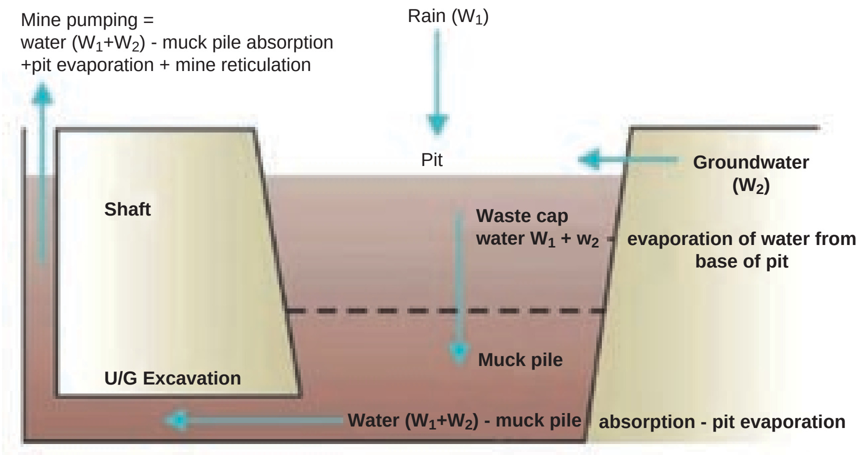


Figure 2—Secondary mud rush mechanism

Beginning of mine life



Reduced muck pile / waste cap drainage

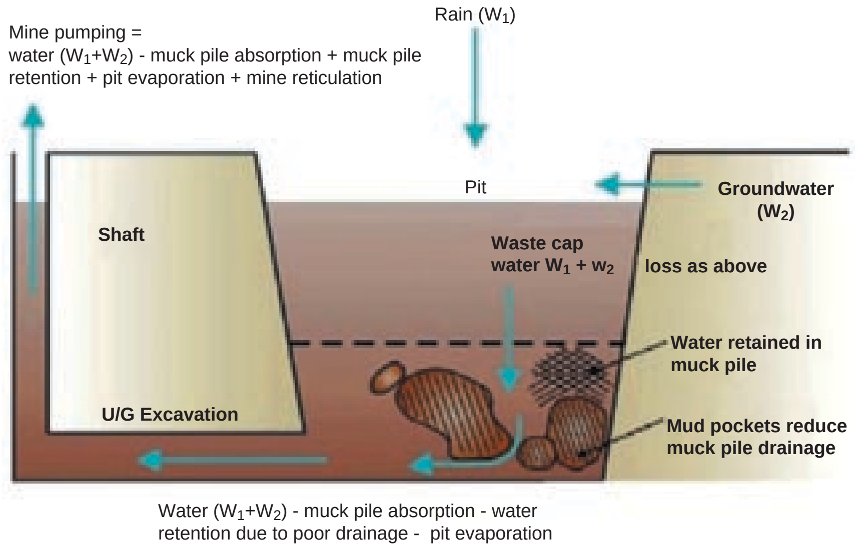


Figure 3—Reduced drainage from muck pile/waste capping

- if the mine drainage system consists of a network of drainage galleries: the collapse of these tunnels, and the calcification and blockage of drain holes and underground drains
- if mine dewatering is achieved by the use of borehole pumps: the vandalism and theft of pumps, and the collapse of dewatering boreholes
- blockage of surface drainage trenches by undergrowth, and their collapse
- surface ponding

decreasing mine pumping rates over time
small underground floods and mud rushes
the increased presence of water underground.

With regard to box-holes and passes, which contain material and in which there is water entry, a warning sign will be the absence of water draining from the chute or box front. The implication is that a blockage has occurred, allowing water and material to build up behind it.

Risk assessment

As part of their requirement to identify hazards in terms of the Mine Health and Safety Act, mines must address the potential for mud rushes. The primary risks in the occurrence of mud rushes are:

the accumulation of water
the accumulation of mud-forming minerals, both internally and externally
the proximity of the mud to the drawpoint or discharge point
the freedom for the mud to discharge.

If such a risk assessment identifies that a significant mud rush hazard exists, the mine should be classified as a mud rush prone mine. The commonly observed condition of rockpasses and box fronts in many South African mines indicates that most mines would have a significant probability of mud rush occurrence. It is to be noted that the enquiry into the disaster at the Maroelabult Mine indicated a failure of the risk assessment system with regard to drainage of water and a control mechanism.

Preventive measures

Implementation of preventive measures will reduce the risks of mud rushes.

General preventive measures

In mining operations in which backfill is used as regional support (cut and fill, open/VCR stoping, post-filling and post-pillar mining operations), fill quality is vital:

- backfill should be designed according to best current practice
- a backfill quality control programme must be implemented, where acceptability of fill strength is judged according to established concrete practice statistical analysis techniques
- a mine dewatering system and other measures must be implemented to prevent the ingress of groundwater into filled stopes. All mines using backfilling must have a system of preventing fill decantation water from accumulating in stopes and other workings
- backfill barricades should be designed with a sufficient factor of safety to prevent backfill runaway.

The hazards associated with blockages and hang-ups in chutes, box-holes and rockpasses should be prevented by the following:

- minimizing the quantity of water that flows into these excavations
- correct design of box/chute fronts and chute operating systems
- draining of water from behind box front structures
- regular removal of pagging from the surface of the box-hole and pass, and from the surfaces of the box or chute front structure
- regular drawing of material to ensure that the rock column is kept moving and does not consolidate.

At all mud rush prone mines, methods should be in place for the sealing of old workings and abandoned drawpoints from where mud discharge could occur. Methods of slowing or preventing the flow of mud to other operational levels via mud transport excavations, such as shafts, box-holes, passes, haulages, etc, must be determined and implemented. Special note should be taken of the need to secure those passes and shafts which may facilitate mud flow to operational workings.

Procedural measures for the prevention of mud rushes

The first procedural step is to classify mines as mud rush prone or non-mud rush prone operations, based on a risk assessment as indicated above. Should a mine be classified as a mud rush prone mine, the following measures should be implemented:

- the compilation of a mandatory code of practice for the prevention of mud rushes, as provided for by the Mine Health and Safety Act. This code of practice should be reviewed independently on an annual basis
- a set of underground mud rush precautions should be compiled
- the appointment of a competent person to be responsible for mud rush control
- mud rush incidents should be recorded in the SAMRASS database.

Compilation of underground mud rush precautions

At every mine where a historical, major mud rush hazard or potential mud rush hazard exists, as determined by a risk assessment, a set of underground mud rush precautions should be compiled. These precautions should be focused on the evacuation and identification of workers in a mud rush hazard area. The following must be included:

- a record book or other means of recording the number and names of personnel working in the hazard area. This book must be kept in a prominent position at the entrance and exit of each area. It must be signed by all personnel entering, working in, visiting and leaving the area. The position should be identified by a flashing light and signs
- a mud rush warning system, consisting of sirens or alarms, should be installed in the hazard area. These alarms must be sounded in the event of a mud rush
- an evacuation procedure, showing the means of escape from the affected area and the further actions to be taken if deemed prudent
- a notification procedure to ensure that the responsible officials are informed of the in-rush as quickly as possible
- a closure procedure for any mine services that may hamper rescue efforts.

Copies of the precautions must be placed at the entrance and exit of all potential in-rush areas. These procedures should be communicated to all personnel concerned, on a monthly basis, at the working place.

Recording of mud rush incidents

Mud rush incidents should be included in the list of reportable incidents. They should be reported to the Department of Minerals and Energy, and recorded in the SAMRASS database of accidents and incidents. The following information should be forwarded to the Department of Minerals and Energy for inclusion in the SAMRASS database:

- date and time of in-rush
- location of mud rush (location indicated on a plan)
- how far the mud pushed and the quantities discharged
- percentage extraction for the discharge drift and the drawpoint
- mine pumping and rainfall records.

Conclusions

Although this paper has dealt largely with mud rushes that have not been associated with rockpasses, the following general conclusions relevant to rockpasses can be drawn:

- for a mud rush to occur, four elements must be simultaneously present. These are the occurrence of potential mud-forming materials, water, a discharge point into the mine workings (the chute, box front or pass opening), and a disturbance of some form (such as opening the chute) control of water entering rockpasses is critical to the prevention of mud rushes

management of rockpass operation will assist in minimizing the occurrences of hang-ups and blockages, and therefore the prevention of mud rushes

remote operation of chutes and box fronts will promote safer conditions in the case of mud rush occurrences.

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