There are several geological hazards that are encountered during the life of a quarry or open pit mine. Most of these hazards are included in a mine’s Ground Control Plan (GCP). The GCP ensures adequate geotechnical planning throughout the life of a mine, safe mine operation, and aspects towards final reclamation. Some measures of consideration in the GCP should include geological structures and their influence on wall stability, strength of the rock mass, rain or water inflow issues, surface drainage, mine dewatering procedures, geometry of the pit, pit wall stability, and appropriate drill and blast procedures for final walls. Additionally, when appropriate, the application of rock reinforcement and safety precautions are specified for working near highwalls and methods of open pit wall monitoring.

Engineering

The first step towards preventing wall instability and rockfall hazards is to begin with sound engineering and planning to ensure the long term stability of highwalls. Equally important is the need for ongoing refinement, based on geological changes within an active mine. As mining advances and mine design standards undergo operational changes, it is crucial any geotechnical assumptions be reviewed and modified by an experienced professional engineer or geologist to continually ensure the integrity of the final highwall design and reduce the likelihood of highwall instability and rockfall hazards. It is important to re-evaluate modes of failure potential with relevant geological characteristics such as discontinuities (spacing, continuity, shear strength), bench orientations relative to the highwall face, and bench properties that contribute to rock mass behavior as new geological information becomes available.

Communication

Regularly informed ground control meetings with mine personnel to formally review changes in geological conditions and observed ground control issues helps to develop early recognition protocols. It is far more effective to make required modifications to current mine operational practices (i.e., blast size or reinforcement) and mine plan changes prior to highwall failures because remediation to a hazard is commonly less expensive before a failure. Geotechnical engineers and geologists can design overall slope angles and bench configurations to minimize extensive loss of catch bench width and thus minimize rockfall hazards. Train all onsite mine personnel in recognizing hazardous highwall conditions and environmental factors that decrease highwall stability. Highwall investigation techniques and protocols serve as our best method to minimize hazards before they become an issue. It should be noted that unexpected rockfalls that do not exhibit early signs of displacement are commonly not identified by individuals as a hazard. A heightened awareness and close monitoring of environmental and site changes throughout the year, especially during spring and fall rains is invaluable. Additionally proactive steps can be taken to reduce the chance of surface ground failures and rockfalls.
Causes of Hazards

Everyone needs to be mindful of how most rockfalls hazards are induced and simple changes have a lasting impact to improve long-term stability of highwalls and minimizing operational downtime.

1. Planes of weakness such as joints, faults, mud seams, and changes in face orientation against the geological structure. Examining rock slopes and comparing the orientations of the discontinuities to the orientation of the highwall is referred to as a kinematic analysis. A kinematic analysis identifies which modes of failure have a kinematic potential of occurring, and is most commonly done with a stereonet.

2. Equipment or mining activity working on a bench above. Mining activity above an active area of a mine or quarry can initiate rockfall instability from a pre-existing condition. Keep drills and other mobile equipment away from highwall faces or highwall hazards by positioning them in safe locations. Be mindful of loose debris at the crest areas as they tend to dislodge materials.

3. Water issues (e.g. precipitation and ground water). As open pit wall failures often occur after rain events, it may be necessary to develop an understanding of the mechanisms of infiltration of surface water into the rock mass. The hydrogeological environment of an open pit needs to be understood to an appropriate level to ensure adequate provisions are made for the removal of rainfall and groundwater inflow as the mine continues to expand. Some of the more significant effects of water can have a negative impact on the general integrity of pit walls.

4. Freeze thaw cycle and erosion. We see this in coal mines more frequently as coal seams erode at a much higher rate sometimes referred to as differential weathering. Also when water freezes during typical freeze / thaw cycles it expands and at times can exert pressures in excess of 38,000 PSI on those surfaces. Some of the more significant effects water can have on the general integrity of pit walls include:

   - Increase in pore pressure within the rock mass (which reduces shear strength),
   - Softening of infill or rock material (particularly clays),
   - Slaking of soft rock due to wetting and drying cycles,
   - Freeze / thaw cycles (when water freezes it can induce significant expansion pressures on joints and cracks)
   - Erosion of weaker bands of rock by water seepage or run-off,
   - Reduced blasting efficiency, and
   - Corrosion of ground support and reinforcement.

5. Poor or insufficient drainage control. The hydraulic forces caused by water contained within the slope will expedite the deterioration of the rock structures or blocks. An effective tool to alleviate these external forces is to assure proper drainage of the rock slope. Finding the source of the water can be a very difficult task, but it is important to make every attempt to drain the slope of any possible water accumulation. It is necessary to undertake adequate investigation of the range of geological conditions, and characteristics of water flow throughout the site. Dewatering / depressurization programs can be implemented so that the required levels of depressurization can be achieved.
6. Tree and vegetation along the highwall (e.g. Root jacking). Vegetation and tree growth can develop relatively quickly and needs to be maintained for a variety of reasons. As trees take root, their roots can work their way into minor cracks, later expanding and destabilize blocks.

Figure 1. Loose material at upper crest detected during a site inspection.

7. Excessive blast damage. Design modification must be undertaken to continually improve the integrity of the final highwall design. Sound blasting practices to minimize the negative impacts of overbreak and excessive vibration can aid in maintaining the design integrity throughout the mine life. Mines must incorporate a method of wall control blasting such as pre-splitting or cushion blasting, which buffers the production blast from negatively impacting the walls, thus creating a more competent highwall and catch bench. This practice provides an effective means to maintain the integrity of the final wall.

**Rockfall Mitigation Techniques**

Rockfall mitigation techniques have been used with several ground control related issues and continue to incorporate and develop appropriate remediation measures. This is important because the consequence of a highwall failure can pose hazardous conditions and threaten the long-term viability of an operation.

Several methods exist to reduce the hazards related to ground instabilities from a highwall, including scaling, provision of adequate catchment area, and ground reinforcement. Scaling is an operation where rocks on the highwall are checked for stability with a miner’s bar and what is commonly referred to as air bags. These air bags were originally developed for the Fire and Rescue industry as a means of lifting heavy objects using air pressure to inflate these bags. There are several different sizes that can be utilized in the scaling operation and the amount of force exerted ranges from 5 tons of pressure to 90 tons of pressure. If loose blocks are encountered, they can be removed from the highwall under a controlled environment. (Figure 2).
Below is a summary of Rockfall mitigation techniques with a general rating of their cost of implementation and overall effectiveness for maintaining long term stability.

<table>
<thead>
<tr>
<th>Rockfall Mitigation Techniques Ranking</th>
<th>Cost of Implementation</th>
<th>Overall Effectiveness</th>
</tr>
</thead>
<tbody>
<tr>
<td>✓ Adequate Catchment area and berms</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>✓ Catch Bench Maintenance</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>✓ Highwall Scaling (Hand / Mechanical)</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>✓ Zone dewatering and drainage diversions</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>✓ Tree and vegetation removal along slopes</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>✓ Highwall Buttress</td>
<td>Low - Medium</td>
<td>Medium</td>
</tr>
<tr>
<td>✓ Mesh / Drape Fences</td>
<td>Medium</td>
<td>High</td>
</tr>
<tr>
<td>✓ Protective Blasting Techniques</td>
<td>Medium</td>
<td>High</td>
</tr>
<tr>
<td>✓ Polyurethane Resin Injection – Rock ‘Gluing’</td>
<td>Medium</td>
<td>High</td>
</tr>
<tr>
<td>✓ Shotcrete or Gunite</td>
<td>Medium - High</td>
<td>High</td>
</tr>
<tr>
<td>✓ Highwall Drilling and Reinforcement</td>
<td>Medium - High</td>
<td>High</td>
</tr>
<tr>
<td>✓ Rockfall Barriers and Retaining walls</td>
<td>Medium - High</td>
<td>High</td>
</tr>
</tbody>
</table>

A common approach to dealing with rockfall hazards is to provide an adequate catchment area at the base of the highwall. An experienced geotechnical engineer or geologist can assist in providing requirements of an adequate catchment area with tools such as the Catchment Area Design Guide (Pierson, Gullixson, & Chassie, 2001). Berms must be properly sized and located to contain failing
material. When measures are needed to handle rockfall hazards beyond scaling and providing an adequate catchment area, many other remediation tools are available. These include the use of dowels, tensioned anchors, draped mesh, pinned mesh, rockfall fences, hybrid systems, and berms. Selecting a ground reinforcement method relies heavily on a good working knowledge of the local ground conditions in determining the most effective design.

Figure 3. Mesh and bolting installation using a GeoStabilization International wagon drill.

There are several variations in mesh designs providing different load capacities (Figure 4). Their application includes areas of highly weathered rock near high traffic areas such as access ramps and portals. This provides an adequate measure to reduce the risk to mine personnel and infrastructure by controlling rocks as they fall from a highwall. Control of the rockfall reduces its energy and contains the rocks to a catchment area where they can be collected and removed in a safe manner; minimal maintenance is required if designed properly. The type of material used for the mesh design should be scrutinized to make sure that it can manage potential rockfalls without tearing and creating gaps in the system.
Flexible rockfall barriers, also called rockfall fences, contain falling rocks from moving into protected areas. These systems can be installed easily and quickly but regular maintenance will be required depending on the frequency of the rockfall events. There are two predominant types of rockfall barriers on the market, standard flexible barriers and hybrid barriers (Figure 5). Standard rockfall barriers are designed as flexible systems that dissipate the energies and immobilize the blocks upon impact. The drawback of this type of system is that once the barrier has been impacted and the falling rock immobilized within the system, the ability to contain and immobilize future rockfalls is diminished. The only way to assure that the system will continue to work as designed is to remove the rock that is contained in the system, replace any damaged parts and reset the system. With hybrid flexible barriers, the net is not attached to the bottom cable and the netting is extended out downhill to allow the system to capture the falling rock, dissipate the energies and then release the rock.

Maintaining catch benches and cleaning them of excessive debris is required to maintain its overall ability to control and minimize the hazard associated with falling debris. If a catch bench is not regularly
maintained, it increases the risk of rockfalls by creating launch features that project the falling rock onto working areas. This increases potential damage to mine infrastructure and even personnel (Figure 6).

Figure 6. Full catch benches (Michalek, 2001).

In addition to control of rockfalls, ground reinforcement methods can be effective engineered solutions to safely access sensitive areas of a mine and reduce the risk within open pit mines. The GCP incorporating reinforcement continues to evolve as plausible economic options. Some rock and soil mass reinforcement techniques include rock anchors, dowels, cable bolts, tiebacks, and shotcrete.

The two types of rock bolts commonly installed are dowels, which are fully grouted anchors without any pre-tensioning, and post-tensioned anchors. The advantage of using dowels is that the anchor will go into tension at the appropriate time and with appropriate tension if the structures are under stress due to hydraulic pressures, freeze and thaw cycles, blast vibrations, or other outside forces. In order for a rock dowel to become mobilized, there first has to be a minute amount of movement. If the block is stable enough to drill into and install the anchors, the dowel method is an effective technique to assure long-term stability of the structures. Tensioned anchors can be installed where the rock blocks have previously moved or structures are undercut and additional forces are needed to be applied to counteract gravitational forces.
Monitoring Systems

There are many new technologies emerging. Technologies such as remote sensing should not replace basic geotechnical methods of investigation, but should be used in combination with tried and true methods. An active attention to early warning signs from highwalls such as tension cracks, loose material, or abnormal water flow can signal a greater geohazard event is imminent.

Most highwall monitoring systems measure the relative displacements to monitor slope behavior and maintain a safe operation. Highwall surface monitoring systems can include radar systems, robotic total station systems, and surveying target prisms. Subsurface measurements can incorporate inclinometers, time domain reflectometry, and borehole extensometers to collect data on rock mass displacement. Some of these monitoring methods can be difficult to implement with limited access along the highwall. As mining advances it is imperative that this monitoring system be relocated to those areas of concern.

There is a growing trend for radar monitoring systems at mine sites to identify specific areas of instability along highwalls, waste dumps and tailings dams. They can be incorporated to understand those factors that are influencing slope movement throughout the year, including weather events and mining activities (i.e. drilling, blasting or haulage). Monitoring can also be used to evaluate the effectiveness of a newly constructed buttress, dewatering key zones or the impact of a drainage diversion against its overall effectiveness on reducing slope movement.

Wall failures do not occur without warning if the failed area is being well monitored. Early detection of wall failure allows mine operators to plan and implement appropriate actions with sufficient notice such that the effect of the failure on mine safety and productivity is minimal. Where safe foot access cannot be maintained or guaranteed, monitoring equipment that can be operated remotely should be installed on the respective slope faces or crests. Visual monitoring alone is acceptable until the pit wall expresses one or more signs of potential instability.

Each site must have its own monitoring strategy, matched to local ground conditions.

Visual signs that allude to incipient failure of pit walls include:

- formation and widening of tensile cracks,
- displacements along rock defects in the batter face,
- bulging of the slope face or toe,
- raveling of rock within the slope,
- increased water seepage,
- bending of reinforcement or rock support elements, and
- rock noise and ejection.

Miners must inspect their working place before starting work and be aware of any changes in conditions. Any unsafe condition must be reported and corrected. Cracks, cavities, and other unstable areas should be identified, marked, and avoided. Records of visual observations made during regular inspections of pit walls, play a very important part in building up a history of ground behavior for assessment of pit wall conditions.
Conclusion

There is a balance between safety and the economic viability as mines get deeper and continue to experience slope stability issues throughout the mine life. Engineering controls are an effective means to guard against rockfalls, unstable ground, and challenging geologic conditions. Continually assessing mine designs along with operational planning can have a significant and positive impact on highwall safety by reducing potential hazards. Using engineering controls such as slope reinforcement, adequate blast vibration limiting techniques and rockfall containment systems can be a viable solution to safeguard your operation.

References


Watts, C. F., & Woodard M. J. (2014). Practical rock slope engineering short course, Queen’s University, Kingston, ON.