Case Study: Investigation, Analysis and Mitigation of Rock Instability for a Potential Slope Failure in Highly Weathered Granite at Pinto Valley Mine in Arizona

ABSTRACT: In the mining and civil engineering industries, slope stability issues have become essential problems to avoid ensuring site safety, maximum ore extraction and limited interruptions in production. Slope failures in mining operations are a cause for concern when dealing with potential safety hazards, accidents and injuries for mining personnel and damage to equipment. Predicting, monitoring and investigating slope failures are pertinent for safe working conditions and should be inspected continuously. A high wall composed of a small top layer of alluvium underlined by highly weathered granite at the Pinto Valley Mine in Arizona expressed warning signs such as rockfall, talus/debris retained on lower benches, tension cracks and displacements on the slope stability radar (SSR) during production adjacent to the slope. Detailed inspections, monitoring and mitigation were immediately initiated following these signs of instability.

If the area of interest is not critical to production, the easiest plan of action would be to leave the material in place and let the slope fail naturally as long it will not cause any safety hazards; however, this is not the case for failure researched in this paper. Mine blasting and production need to continue below the failure due to high grade ore in the vicinity. This can only happen if the failure mechanism is well understood and the rate of displacement is low. This study was performed to understand the mechanisms that triggered the failure, the rock conditions before and after the failure and to show how to proceed with controlled mining procedures in organized manner. This study will show observations before, during and after the slope instability as well as successful mitigation efforts and analyses. This study will provide results and conclusions of the slope failure in order provide data, recommendations and information to engineers and geologists for potential slope failures in the future.

Keywords: Slope stability, slope monitoring, radar, rock mechanics, case study

1. INTRODUCTION

Slope stability plays an important role in rock engineering. During the design, construction and post design phases of rock slope stability, engineers and geologists need to pay close attention to the rock conditions within the rock slope to prevent slope failures, protect employees and maintain economic profit. Slope geometry, material properties, and insitu stress conditions need to be investigated in order to understand the potential for rock slides, wedge failures, and other instabilities.

The following need to be taken in consideration when designing, constructing, mining and monitoring highwall rock slopes in open pit mining. (after Stacey, 2012)

Safety and Social:

- Loss of life or injury
- Loss of worker income
- Loss of worker confidence
- Loss of corporate credibility, both externally and with shareholders

Economic:

- Disruption of operations
- Loss of ore
- Loss of equipment
- Increased stripping
- Cost of cleanup
- Loss of markets

Environmental and Regulatory:

- Environmental impacts
- Increased regulations
- Closure considerations

This case study will examine an observed and monitored slope failure to provide the engineering community with an insight of how mitigation, observations, analysis and monitoring efforts were implemented to prevent injury and a cease in operations.

The Pinto Valley Mine is located near Miami, AZ, United States and is owned by Capstone Mining. Pinto Valley is located within the Globe-Miami Mining District of Arizona, which was continuously mined from 1880's until the present. The pit of the Pinto Valley has a "L" shape and is prone to unusual geological conditions and areas of low strength unstable material. This case study observed and monitored a slope failure that occurred in late October of 2019 at the crest of a highwall in the southside of the Jewel Hill 2B region at the Pinto Valley Mine. Figure 1 below exhibits the pit map where the slope failure took place.

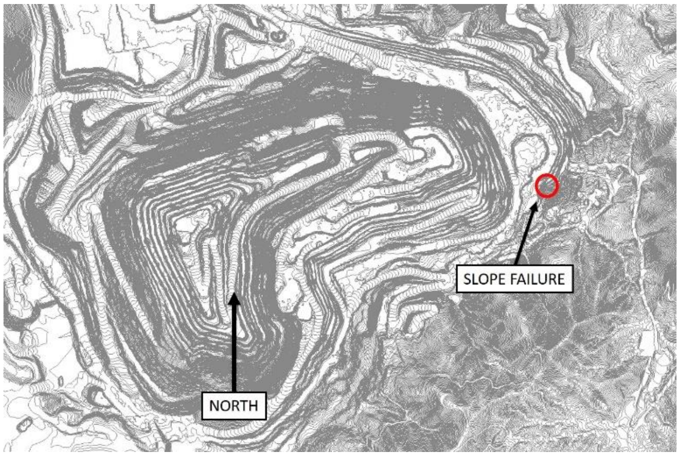


Fig. 1. Pit map showing location of slope failure.

2. GEOLOGICAL BACKGROUND AND MATERIAL PROPERTIES

Pinto Valley Mine lies within the Globe-Miami Mining District in the mountain physiographic province of Central Arizona. The northwest-striking regional faults in the mine area, such as the Gold Gulch, are also located in the southern most extension of the Basin and Range Province. Rocks in the area range from Precambrian to recent, with the main ore host rock being the Lost Gulch Quartz Monzonite. There are three major structural blocks in the district. Pinto Valley lies in the western most Inspiration block. Further, the mine lies within the Castle Dome Horst, which is an elevated block of the Lost Gulch Quartz Monzonite.

The slope of interest is located at the east side of the Pinto Valley mine within the Martin limestone and ruin granite geology region. The Martin limestone consists of five members ranging from a basal conglomerate to limey shale. The ruin granite is mostly very strong material; however, the slope of interest contains very highly weathered granite.

The slope of interest is located at an important section of the mine. Mining and blasting are within in the vicinity of the toe of the high wall. The slope failure height was approximately 27.4 m (90 ft) in height. The slope is adjacent to the mine property with forest service land. Rainfall was not observed for at least 2 weeks prior to the failure. The following sections will exhibit observations, mitigation efforts and conclusions of the Jewel Hill slope failure at the Pinto Valley mine.

3. SITE INVESTIGATIONS AND OBSERVATIONS

Displacement monitoring and looking for potential failure conditions are pertinent when production is in progress in an open pit mining operation. Different modes of failure and deformation mechanisms can exist within a slope. There are several items to beware of when investigation slope conditions.

Items to pay close attention to when investigating rock and/or slope instabilities

- Tension cracks at crest;
- Transverse and longitudinal cracking in slope
- Highly weathered or altered material
- Faulting
- Rockfall.
- Debris/talus retained on benches
- Wall seepage;
- Poor drainage
- Unfavorable orientations of rock structures of potential wedge failures
- Known areas of rocks with weak strengths
- Overhanging rock that might topple
- Cracks that look to be growing and/or widening

The following subsections will explain the behavior and observations obtained prior to failure, during failure and post slope failure conditions.

3.1. Prior to Failure

Surface and slope monitoring systems are essential in observing and interpreting potential slope movement, failure scenarios and estimating if and/or when a slope will fail. Some of these methods to monitor high wall slopes are the following:

- Photogrammetry
- Survey or prism system (total station)
- Global positioning system (GPS)
- Slope stability radar (SSR)
- Light detection and ranging (LIDAR)
- Interferometric synthetic aperture radar (InSAR)

Before the slope failure took place, continuous small amounts of displacements and velocities were indicated by the slope stability radar (SSR) located across the pit from the failure. The SSR (Groundprobe, 2019) monitoring system contained different alarms set to alert mining personnel of critical and/or potential movement of high walls in the Jewel Hill area. (Figure XX and Figure XX). These alarms are divided into three types that included user (issues with SSR monitoring data), geotechnical (alert relating to geotechnical issues and first warning indications of movement), and urgent alarms (critical displacement and velocities indicating a failure could be possible). Section 4 of this paper will explain in further detail of patterns and data from the SSR to shown possible failure situations in the area. Figure XX and XX show the slope prior to failure.

Fig. 1. Groundprobe SSR used to monitor pit high walls

Fig. 1. Image used by SSR with slope of interest in red

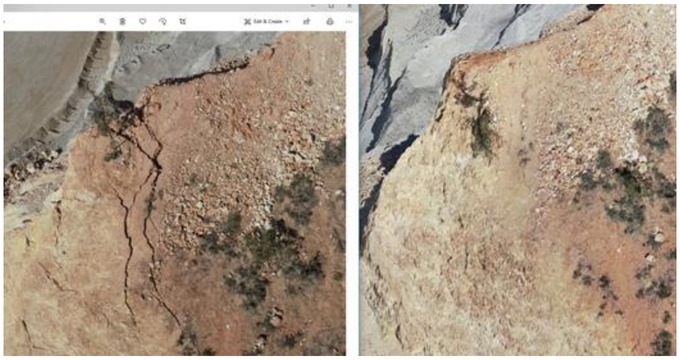
Tension cracks were observed at the crest of the top of the three benches of the failure. These cracks were noted and relayed to mining personnel that potential movements are in progress. Minor, continuous rockfall was also observed prior to failure.

Fig. 1. Slope of interest before failure and excavation (looking south)

Fig. 1. Slope of interest (looking south)

3.2. During Failure

The slope finally failed in the late evening of 30 October 2019. Mining personnel indicated larger amounts of the rockfall began during the previous evening until the slope failed due to being severely weathered and having low rock mass properties. Several alerts were emailed from the SSR indicating urgent and geotechnical issues are in progress. The mine drone was flown above the failure and exhibited all inclusive images. Figure XX shows the drone photo of the failure from above and Figure XX shows the failure close up at the haul road. Figure XX shows the tension cracks at the crest of the benches prior to failure.



3.3. Post-Failure

Once the failure reached equilibrium, mining personnel and engineers investigated the area to ensure no further movement would progress. The failure looked to be a circular failure as well as being severely weathered and having low rock mass strength.

Fig. 1. Intact rock at center of failure rock mass on slope

4. DATA AND MONITORING INTERPRETATIONS

After the slope failure in Castle Dome section of the pit occurred, joints and the slope were mapped for dip and dip direction orientations. The orientations and material properties were input into the computer program Swedge (Rocscience, 2019) in order to compute a kinematic back analysis to determine what approximate material properties and orientations were during the failure scenario.

SSR data from displacements, velocities and inverse velocities were reviewed and interpreted to determine when the failure occurred and if an estimated prediction of the failure could have been more understood. The following two sections will look at the back analysis and SSR data in further detail.

4.1. Slope Stability Radar Data

The slope stability displacement, velocity and inverse velocity were continuously analyzed and monitored using the SSR and SSR viewer (Groundprobe, 2019). The SSR was essential when estimating and predicting if and when a slope failure will occur. The slope failure in the Castle Dome section of the Pinto Valley mine is no exception.

The SSR viewer was utilized to obtain data and interpret slope patterns from the displacements, velocities and inverse velocities of the slope failure. The figures below exhibit the plotted values of the SSR pixels approximately one week before failure, during failure and one week after the failure. Each plot is labeled with 1, 2 and 3 corresponding to patterns that led to failure, shows when the actual failure occurred and the slope reaching equilibrium after the failure.

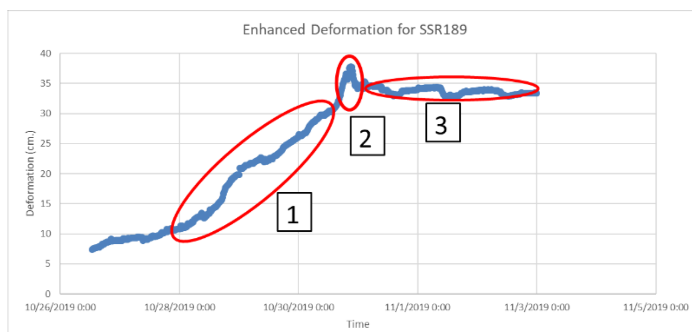


Fig. 1. Enhanced deformation for slope failure from the SSR

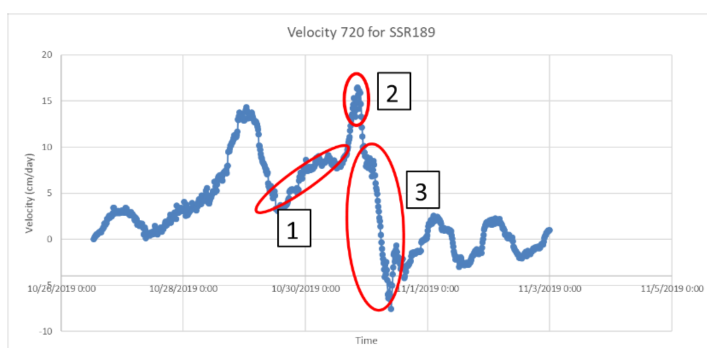


Fig. 1. Velocity data for slope failure from the SSR

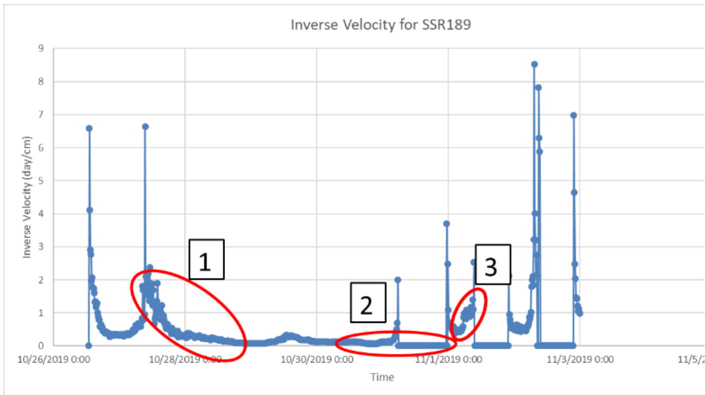


Fig. 1. Inverse velocity data for slope failure from the SSR

5. DISCUSSION AND MITIGATION EFFORTS

Before the failure, mining personnel were made aware of the possibility of a failure due to SSR data patterns, tension cracks at the crest of the slope and some rockfall/raveling. Since the slope is about 50 m from a contact with fault zone, there is a possibility of weaker rock mass due to the proximity to the fault. Rainfall was not observed for at least 2 weeks prior to the failure. A piezometer drill hole just to the east of the failure indicated no pressure head at the elevations where the failure took place. It also should be noted a small old drainage drift is located just to the south of the drift. The high walls at this drift exhibit signs of seepage. Although it is unlikely the seepage from this drift played a role in raising pore pressure at the slope failure, this should still be considered a potential cause. Figure XX shows location of slope failure and seepage area.

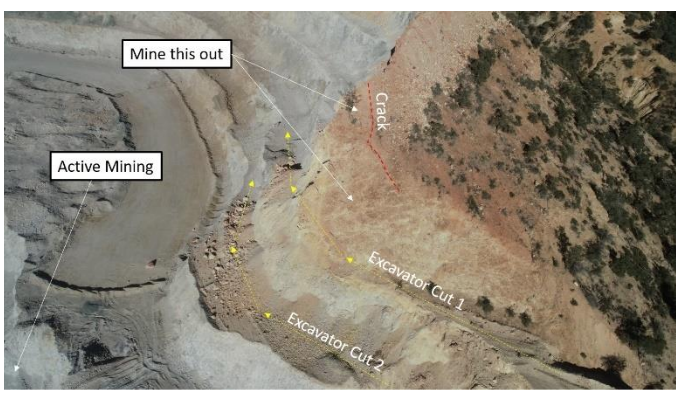
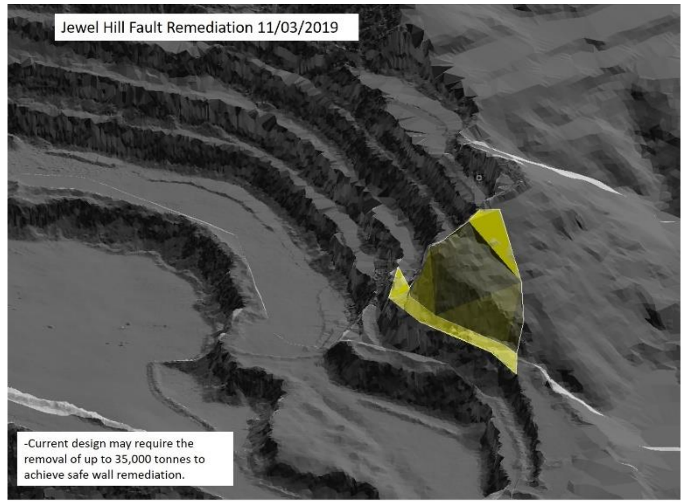


Fig. 1. Plan to excavate out remaining unstable ground



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Prior to and during slope failure, mining personnel bermed off the area and the haul road was temporary closed with limited access until mitigation efforts were completed. Once the slope reached equilibrium and slope movement was determined to cease, the haul road was opened to one-way traffic. The talus and debris were cleaned out by dozers and the remaining intact rock between the two wedges was excavated by a large track excavator to ensure no failure would propagate. The slope will be continuously monitored and investigated to ensure no movement will be encountered.

Pinto Valley mining and operations personnel and engineers discussed mitigation efforts to get rid of the unstable slope area. The following tasks were implemented:

- Track Excavator created a safe ramp to excavate unstable rock (Photo 5).
- No mining personnel were allowed below slope to ensure no one was injured during excavation of unstable slope.

- Area below still bermed off where mining is taking place and haul road traffic was reduced to one lane for safety precautions.
- Slope was excavated into stable ground, beyond the last signs of tension cracks.
- Area will be closely observed.

Mining personnel and engineers discussed status of slope failure and safety concerns with the Pinto Valley operations and technical mining services. It was determined the slope failure area would be bermed off at the toe and no personnel allowed to enter without permission from the mine superintendent and geotechnical engineer. It also was recommended to install more survey prisms in order to monitor the slope region.

Unstable ground conditions are to be discussed with operations and mining personnel during monthly and yearly site-specific meetings. During these meetings, personnel will be informed of certain key aspects of what to look and observe for unstable ground when working in the pit.

6. CONCLUSIONS

In summary, this paper was created from a general interest and professional experience for slope stability conditions in an open-pit mining scenario. The findings in this paper were used to exhibit successful methods, observations and mitigation methods. and may be advantageous in different mining scenarios. These key points are recommendations by the authors:

- Inexperienced or untrained personnel should receive training for dealing with unstable slope conditions and safety procedures if there is even the slightest probability that unstable conditions will be encountered;
- Always be aware of your surrounding and be conscious of unstable ground;
- Site investigation personnel should pay close attention to the local geology and ground conditions revealed by exploratory borings, observations and data patterns;
- Hazard maps should be constructed to indicate locations of potential unstable slopes and high walls;
- Follow all mine procedures and rules implemented for safety
- Follow MSHA rules and wear PPE at all times
- Ensure operation mining personnel are aware of conditions that will produce unstable ground conditions and should report these to their supervisor immediately
- It would be beneficial to analyze the interaction of joint structures and the adjacent geological material using 3D numerical modeling
- Modeling can be used to estimate and for show if rock mass properties and slope angle recommendations are correct, adequate and will have the potential to succeed

The paper was constructed to help mine planners, engineers, mine operations personnel and geologists better understand potentially unstable ground and how to determine which numerical, mitigation, monitoring and construction methods are the most appropriate for critical unstable slope situations as well as safe methods to continue mining safely. The methods discussed have shown great potential towards safe working areas in poor, unstable ground conditions when implemented successfully by mining crews.

ACKNOWLEDGEMENTS

The authors would like to show appreciation for all the Capstone Pinto Valley mining engineers and operations personnel that helped capture valuable information needed to construct this study. Without their efforts, mitigation steps, photos and personnel safety would not have been possible.

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