Paper No. 15

ISMS 2016

Lessons in slope stability management from Kinross' Tasiast mine, Mauritania

Korhan Tasoren [a, *], Gillian Gardhouse, P.Eng. [b], Dr. Jerry Ran, P.Eng. [c]

[a] Senior Geotechnical Engineer, Kinross Tasiast Mauritanie Limited SA, Nouakchott, Mauritania, BP 5051
[b] Senior Geotechnical Engineer, Kinross Gold Corporation, Toronto, Canada, ON M5J 2V5
[c] Geotechnical Services Director, Kinross Gold Corporation, Toronto, Canada, ON M5J 2V5

ABSTRACT
The continued monitoring and optimization of a mining operation are essential extensions of a feasibility study. While the ultimate goal is to mine to the planned design in a safe and economic fashion, such efforts are challenged on a daily basis by changing ground conditions. Success in a dynamic mining environment requires a strong understanding of historical instabilities and wall control blasting, along with well-defined near wall excavation and clean-up procedures, and an advanced slope monitoring system. This paper presents several cases describing different modes of slope failure experienced at Kinross' Tasiast mine site, and the operational and design measures implemented to manage and monitor these instabilities. Routine data collection practices and blasting designs that have been introduced to minimize wall damage and steepen slope angles are also discussed.

1. INTRODUCTION

The Tasiast mine (Tasiast) is an open pit gold mining operation that is owned and operated by Kinross Gold Corporation. The mine is located in northwestern Mauritania, approximately 300 km north of the capital city of Nouakchott (Figure 1).

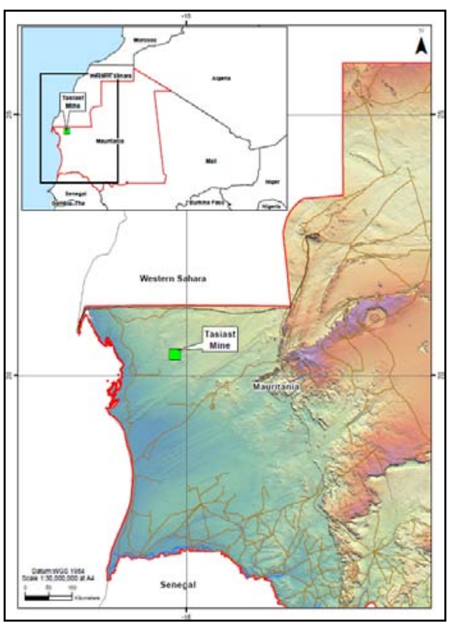

Figure 1: Location of the Tasiast mine site.

Today there are two active mining zones at Tasiast: the Piment Zone and the West Branch Zone (Figure 2). The Piment Zone hosts eight small, narrow pits. The largest of these pits is known as Piment Central and is 0.9 km long and 0.5 km wide, with a depth of 0.2 km. Mining commenced at Piment in 2007 and commercial production was reached in 2008. To the south of the Piment zone is the West Branch Zone. The West Branch pit is the largest of the four pits located in this area. In 2009, the mineralized Greenschist Zone was discovered at West Branch, prompting additional exploration and study to support an expanded project. A feasibility study was subsequently completed in 2014. The final pit shell in the current design measures 1.8 km long by 1.4 km wide and is approximately 0.5 km deep. The pit is now in the first phase of operation.

Since extraction began in 2007, a number of minor slope failures have occurred at Tasiast. Back analyses were performed in some cases, and slope designs and implementation procedures were optimized to minimize blasting damage and monitor slope movements.

This paper presents typical slope failure modes observed at Tasiast, results of the corresponding back analyses, and lessons learned in slope stability management.

2. MINE GEOLOGY

At Tasiast, gold mineralization at the regional scale occurs in two parallel trends: the Piment Zone, with a strike length of 4.5 km, and the Greenschist Zone, with a strike length of approximately 1.5 km.

*Corresponding author – korhan.tasoren@kinross.com : 00 (222) 44441573

Both zones are characterized by oxidized and transition materials to a depth of 50 m to 100 m, which are then underlain by fresh rock. The dominant and controlling structure of the eight to ten sets of identified geological discontinuities and features is the foliation, which dips toward the hanging wall of the deposits (east).

Groundwater flow occurs in the oxidized zone and into the transition zone. Following the start-up of mining, local scale flow shifted the hydraulic gradient toward and into the pits. Below the transition zone, there is virtually no groundwater movement due to the low hydraulic conductivity of the fresh bedrock. There is no regional-scale groundwater flow in the Tasiast area (SWS, 2014).

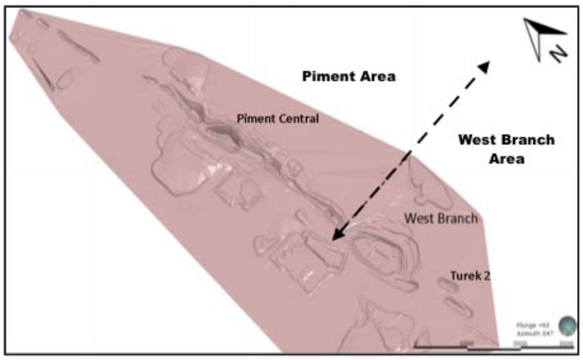

Figure 2: Mining area layout showing studied pits.

3. GEOTECHNICAL DATA AND PIT DESIGN

The latest geotechnical study and pit design for West Branch were completed in 2014. In addition to previous geotechnical investigation programs, the 2013 drilling campaign consisted of eight dual purpose geotechnical and hydrogeological holes totaling 4,609 m. Oriented core logging, field and laboratory testing, borehole televiewer surveying, and pit mapping methods were also used to collect geotechnical data. Golder Associates, the consulting firm behind the 2014 geotechnical investigation, selected Cai's Geological Strength Index (GSI) for rock mass classification purposes.

The West Branch pit is divided into four geotechnical domains based on geological, structural and rockmass similarities, as well as wall orientation due to the nature of the foliated/bedded host rock (Figure 3). Each domain is sub-divided into oxide, transition, and fresh categories based on the intensity of weathering. Two different rockmass qualities have been identified within the transition zone and subsequently categorized as the upper and lower transition zones for geotechnical slope design purposes.

Slope stability analyses completed for West Branch were based on the developed geological, structural, rockmass quality, and hydrogeological models. Two numerical modeling methods (Limit Equilibrium and Finite Element) were used to establish slope angles and obtain the corresponding Factor of Safety values for the slopes. Recommended slope design parameters are shown in Table 1.

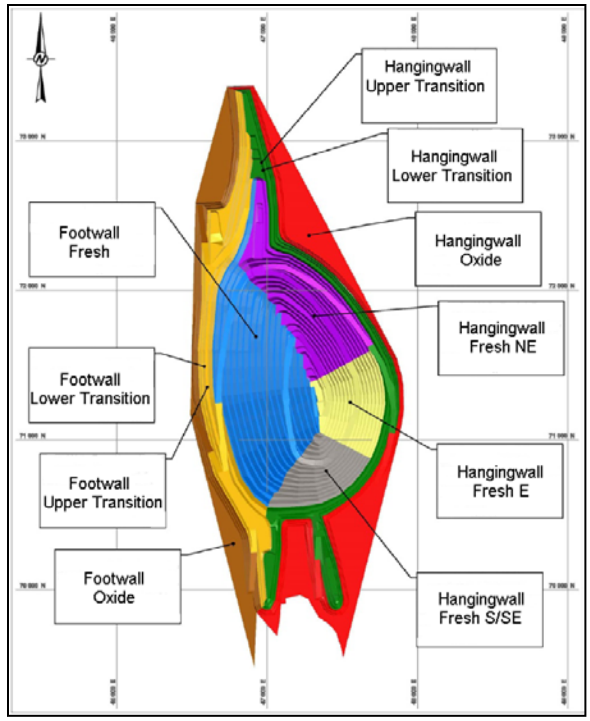

Figure 3: West Branch open pit geotechnical sectors. Modified from Golder (2014).

Table 1: West Branch slope design recommendations.

Sector	Depth (m)	Bench Face Angle (°)	Bench Height (m)	Berm Width (m)
HW oxide	0-30	60	10	6.5
HW transition	30-100	65	10/20	6.5/8.5
HW fresh	>100	75	30	10.5
FW oxide	0-30	45	10	6.5
FW transition	30-100	45	10/20	6.5/8.5
FW fresh	>100	45	30	10.5

4. HISTORICAL SLOPE FAILURES AND DESIGN IMPLEMENTATIONS

Pit slope stability is an important aspect of providing a safe and productive working environment at a mine site. Slope failures have historically occurred in the upper zones of operating pits at Tasiast. Circular, planar, wedge, and toppling failure modes have been observed and are generally attributed to the weak rockmass and excessive blasting damage. Although none of these failures were large in scale, the insights gained can be used to make operational and design improvements.

4.1 Piment Central Pit Rockfall Incident

A loose rock fell 50 m from a bench crest to the pit floor on the hanging wall side of the Piment Central Pit during a night shift. The slope monitoring radar was able to detect the movement, which was caused by crest damage, but was unable to send an alarm to the site geotechnical team because the movement was sudden rather than progressive (Figure 4). The radar data indicated that the loose rock had a mean displacement of 1.10 mm and a velocity of 2.5 mm/h (Figure 5).

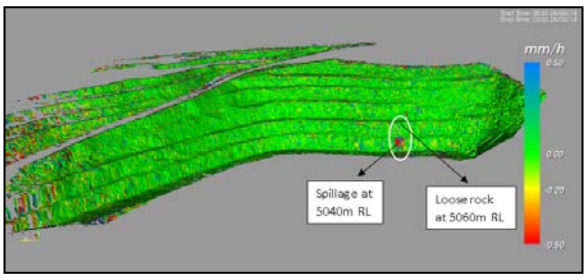

Figure 4: Slope monitoring system screen shot of the movement area during the event.

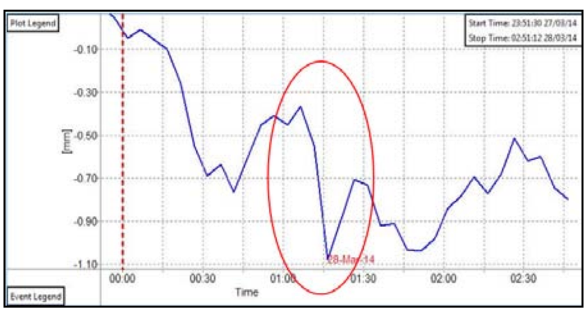

Figure 5: Displacement graph of the event.

RocFall software (Rocscience) was used to back analyze the rockfall event and calculate the displacement. The weight of the rock mass was estimated to be 200 kg. A face profile was created using AdamTech photogrammetry software. The actual distance from the toe at the pit bottom to the final resting location of the spilled rock was measured at 10.75 m in the field and calculated at 10.015 m by the RocFall model, demonstrating that the model is an adequate representation of the event (Figure 6).

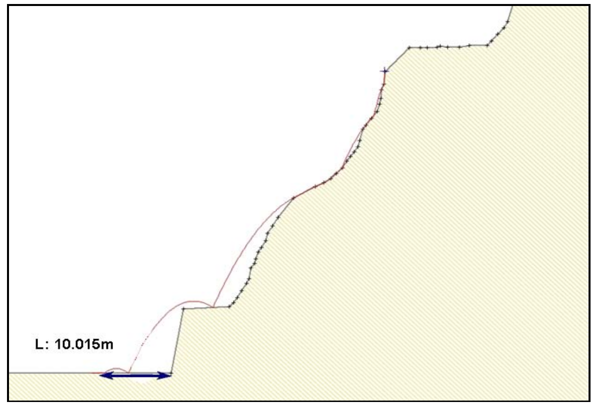

Figure 6: Back analysis of the rockfall incident using RocFall software.

The root cause of the failure was the presence of loose rocks on the broken crest due to blasting damage, excessive sub-drilling, and poor face clean-up practices. The geological characteristics of the region adjacent to the blast and further up the slope dictate the potential for blast-induced damage (Read & Stacey, 2008). The hazard area was identified, a high windrow was built along the ramp 10 m away from the toe, and a 15 m standoff distance procedure was put in place for the rest of the pit to prevent similar incidents. A 20 m vertical mid-bench presplit blasting design was applied to the pit hanging wall to reduce production blast damage to the face, since a proper trim blast could not be implemented in such a narrow and small scale mining environment. Significant improvements have been observed in the condition of the face and in pit design compliance since implementing the pre-split design (Figure 7).

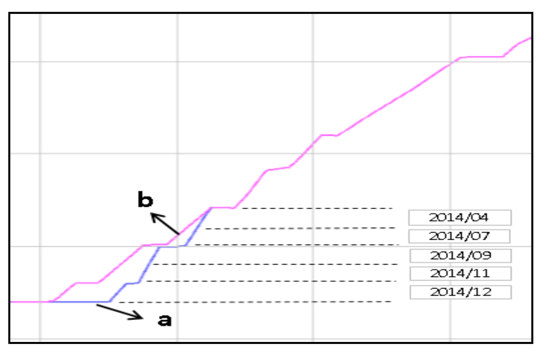

Figure 7: a) Actual pit wall design after implementing pre-splitting procedures; b) Predicted pit wall without wall control blasting.

4.2 Planar Failure at West Branch Footwall

The West Branch footwall design bench face angle (BFA) was limited to 45° to avoid undercutting the foliation, which dips at 42° to 46°. The foliation strikes 350° and has an average spacing of 2.5 m. Previous blast designs used in the early stage of the project did not consider these design limitations, which led to excessive damage in the oxide and transition zones on the footwall. This was exacerbated by the use of standard full depth vertical blast holes near the wall.

Several small, bench scale planar failures were experienced as a result of damaged or narrow catch berms, and broken toes. The typical failure dimension was limited to 20 m long by 2 m wide by 30 m high due to the condition of the rockmass and the intersection of joint sets.

To prevent blast damage, a modified trim blast design was applied to the area near the footwall (Figure 8). Two stepped holes were introduced to break the rock along the foliation surface and achieve the pit design. This approach resulted in smooth face conditions along the foliation plane and improved pit design compliance on the footwall.

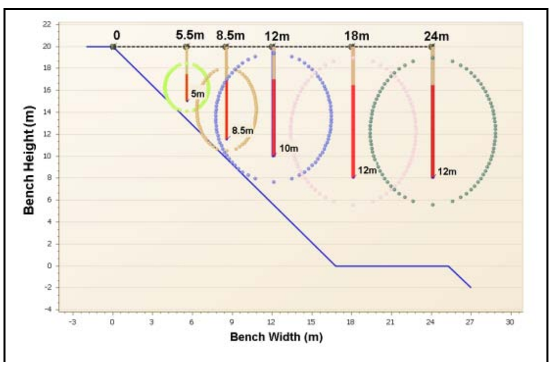

Figure 8: An example of a modified footwall trim blast design.

4.3 Turek 2 Pit Rockmass Failure

The Turek 2 pit is one of the oxide satellite pits that will eventually become part of the West Branch pit as mining progresses. The Turek 2 pit has 10 m high benches with 6.5 m wide catch berms and a 65° BFA. It is 45 m deep. Approximately 400 tons of material fell several benches to the bottom of the pit, resulting in a failure area 25 m long, 3 m deep and 25 m high. A 75° foliation angle was measured on the pit face where the failure occurred.

Back break was observed on the catch berm parallel to the strike of the foliation after production blasting. No consideration for wall control had been included in the blast design, such that a high energy charge was used in soft rock, causing damage to the final wall. Rainfall flow marks were found on the top of the pit in the failure area during the incident investigation. Over-digging was observed on the face, resulting in a very narrow catch bench berm. Together these factors contributed to the failure.

SLIDE v5.0 software (Rocscience) was used to back analyze the failure. Inputs included a high resolution photogrammetry face profile (Figure 9), steep transient water table profile behind the face, and density, cohesion, and friction angle values. Different combinations of the input parameters shown in Table 2 were analyzed to simulate conditions similar to those of the failure. The SLIDE v.5.0 results are shown in Figure 10. All of the condition combinations suggest a Factor of Safety (FOS) of 1.0 (Table 3).

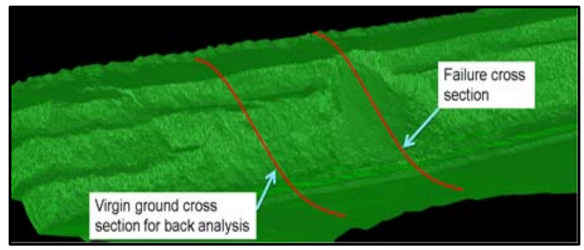

Figure 9: Photogrammetric surface of the failure area.

Table 2: Back analysis results using different combinations of conditions.

Unit Weight (kN/m^3)	Friction angle (degree)	Cohesion (kPa) Wet	Cohesion (kPa) Half Dry	Cohesion (kPa) Dry	FOS
23	30	31	25	19	1.0
23	32	27	20	14	1.0
23	34	24	15	9	1.0
23	36	20	11	3	1.0
23	37	17	8	0	1.0

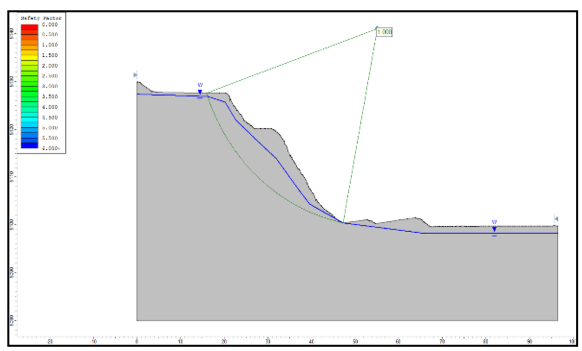

Figure 10: SLIDE v5.0 section of the hanging wall.

The pit design was reviewed and modified after the failure. A 15 m wide catch berm was left on the hanging wall, and a radar system was set-up to detect any further movement. A similar type of movement was observed by the slope monitoring system on the northern side of the failure (Figure 11). Blasted material was left as a buttress to prevent excessive movement along the face. Only a toe charge was applied to the first row of the production blast to further reduce vibrations and related damage.

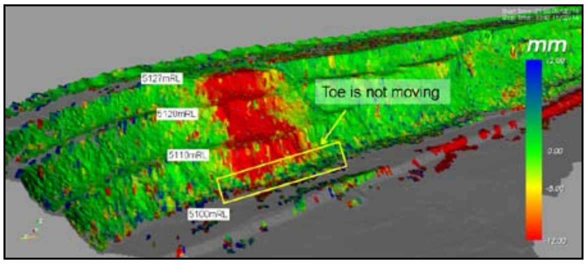

Figure 11: Movement at the northern side of the failure.

The following rockmass characteristics were determined as a result of the back analysis: the cohesion is 19 kPa, the friction angle is 30° and the unit weight is 25 kN/m^3 for similar types of material. The effect of weathering in the oxide zone was greater in the hanging wall of the Turek 2 pit than in the West Branch area. Based on this, the Turek 2 pit geometry was modified to 10 m high benches with 7 m wide catch berms and a 55° bench face angle.

4.4 Summary of Failures

Table 3 summarizes the different failures, actions and outcomes discussed in this section.

Table 3: Summary of the failures and the actions taken in response.

Pit	Area	Summary
Piment Central	Problem & Cause	Rockfall due to broken crest resulting from excessive sub-drilling and poor face clean-up practices
	Analysis	Review of monitoring data Back analysis to calculate displacement
	Solution	Implemented mid-bench pre-splitting Built windrow appropriate distance away Implemented standoff distance procedure
	Result	Improved face condition Increased compliance to design
West Branch	Problem & Cause	Planar failure due to incompliance with pit design dimensions
	Analysis	Blasting design review Pit design review
	Solution	Two stepped blast hole design applied
	Result	Smooth face conditions along the foliation plane Improved pit design compliance
Turek 2	Problem & Cause	Rockmass failure due to excessive blasting damage and rainfall infiltration
	Analysis	Field investigation Photogrammetry survey Back analysis Review of monitoring data
	Solution	Revised pit design based on the back analysis results Enlarged catch berm Modified blasting design
	Result	Planned pit production completed without safety issues or ore loss

5. ONGOING DATA COLLECTION AND MONITORING

Ongoing geotechnical data collection at Tasiast consists of face mapping, application of photogrammetry techniques for measuring structures (Figure 12) and bench configurations, pore pressure measurements from twelve vibrating wire piezometers around West Branch, and wet blast hole and grade control hole mapping, where available, to support pit inspection and operation.

Recently, data from face mapping and structural measurements were used to update the structural and geotechnical models. The geotechnical model was subsequently used in a fragmentation study to better understand the effects of energy distribution across major and minor joint sets. This is significant because blasting loosens existing structures to liberate rock blocks and create new fractures within the intact material (Kanchibotla et al., 1999). Rockmass elasticity parameters and the intensity of structures (in-situ block size) are known to have significant influence on the efficiency of blasting at Tasiast. As a result of the study, fragmentation was improved in the ore zone, and the cost of drilling and blasting was reduced while maintaining the quality of fragmentation in the two main rock types.

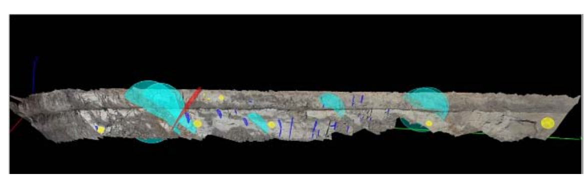

Figure 12: Structural measurements obtained along the West Branch footwall using photogrammetry.

The control and management of water is a fundamental component of most successful large open pit mining operations (Beale & Read, 2013). Pore pressure data obtained from vibrating wire piezometer holes and mapping of wet blasting or grade control holes assist groundwater studies and provide guidelines for pit dewatering activities on a daily basis (Figures 13 and 14).

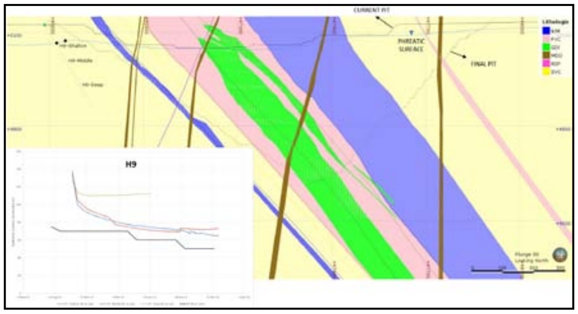

Figure 13: Cross section of vibrating wire piezometer hole.

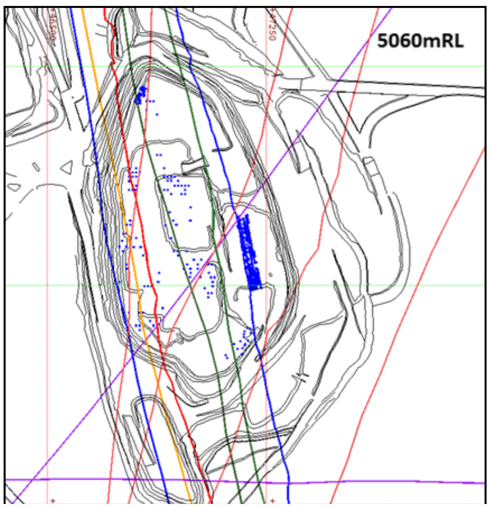

Figure 14: Plan view of West Branch major structure and wet drill hole mapping correlation.

The Tasiast mine currently has two synthetic aperture slope monitoring radar systems. These systems have been used for tactical and strategic monitoring in different pits since 2013 (Figure 15). Parameters for alarm set-up include area (m^2), velocity (mm/hour), and time interval (hour or day). These parameters must be low enough to provide an early warning when a slope is starting to move, but also high enough to prevent false alarms. The system collects continuous data in three minute scan intervals and backs up historical files to an external storage unit for further analysis. Interpreted data are transmitted to the Guardian slope monitoring software in the office to be filtered based on site thresholds. Any type of movement above the set thresholds triggers the alarm, prompting the software to send email and SMS alerts to relevant personnel. The site slope movement action plan is summarized in Figure 16.

Figure 15: IBIS-FMT slope monitoring radar in action.

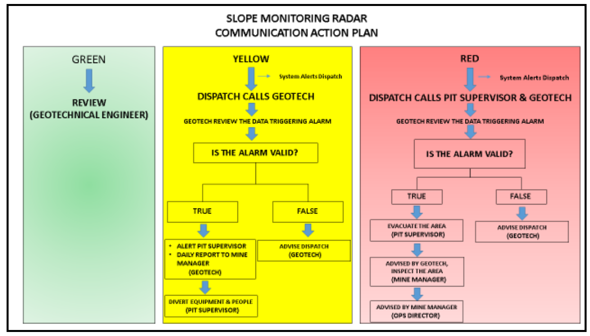

Figure 16: Summary of the slope movement action plan.

6. CONCLUSIONS

Bench excavation at the Tasiast mine site is controlled through a variety of measures, including the use of appropriate equipment, standard operating procedures, and marked lines or pegs, in order to minimize face damage and crest loss. When there are localized failures, wider catch benches and safety berms are commonly used to protect personnel and equipment. Areas of concern related to slope movement or restricted operating space are monitored by one of two ground-based synthetic aperture radar units. These units provide real time measurements and send out alert messages based on preset threshold values.

Exposed benches are routinely mapped for geological and geotechnical features using manual and photogrammetric techniques. The collected data, together with the existing database, feed the mine's geotechnical model and permit both predictive analyses and back analyses of slope stability.

Blasting against pit walls in particular has significant impact on slope stability and achievement of the design configuration, as well as implications for safety, productivity and mining costs. Various blasting designs have been applied to both footwall and hanging wall slopes. In general, hanging wall slopes are protected from excessive damage by pre-shearing prior to trim shots or modified production blasts, while trim shots and modified production blasts with two stepped stab holes are used when blasting against footwall slopes. These modifications to the blast design support a safe and economic mining operation.

7. ACKNOWLEDGEMENT

The authors would like to thank Rahadian Widiadi and Moulay Ahmed Hamoudy for their support, and Kinross Gold Corporation for permission to share these lessons by publishing this paper.

8. REFERENCES

Beale, G. and Read, J. (2013) Guidelines for Evaluating Water in Pit Slope Stability. 49 p.

Cai, M., Kaiser, P. K., Uno, H., Tasaka, Y., & Minami, M. (2004). Estimation of rock mass deformation modulus and strength of jointed hard rock masses using the GSI system. International Journal of Rock Mechanics and Mining Sciences, 41: 3-19.

Golder Associates. (2014). Tasiast West Branch Open Pit Slope Design Recommendations – Revision 1, Technical Memorandum. Buckinghamshire: Golder Associates UK Ltd.

Kanchibotla, S. S., Valery, W. and Morrell, S. (1999). Modelling fines in blast fragmentation and its impact on crushing and grinding. In Explo’99: A Conference on Rock Breaking, Kalgoorlie, WA, November 7-11, AusIMM, Vol. 99, pp. 137-144.

Read, J. and Stacey, P. (2008) Guidelines for Open Pit Slope Design. 275 p.

Schlumberger Water Services. (2014). Hydrogeological characterization of the West Branch Pit, Tasiast, Mauritania. Shrewsbury: Schlumberger Water Services.