



# Stability Risk and Economic Analysis of Steepened East Wall of Huni Pit- A case study

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**Abstract.** The high cost of mining is driving mine owners and designers to reduce cost by optimizing (steepening) open pit slope design parameters. Meanwhile, the catastrophic consequences of slope failures have the tendencies to negate the gains made from the steepening process if due processes are not followed. To access more ore at the base of the current Huni Pit, the bench face angle for the current east wall, was steepened from 65° to 75°. Steepening was the only geotechnical option available to optimise the design because of constraints posed by the location of east tailings storage facilities and the booster stations on the eastern corridor of the Huni Pit.

A geotechnical risk assessment was conducted using a quantitative risk assessment to identify risks on the overall slope of the east wall after the slope was modelled. Kinematic analysis was conducted using the dips software from Rocscience™ on the east wall to determine if the potential for structurally controlled bench scale failures existed. The availability of 3D limit equilibrium tools from Rocscience™, made it easy to appropriately perform further stability analysis by undertaking a probabilistic analysis.

Afterwards, an economic evaluation was conducted to select the design options that brought economic benefits to the mine.

**Keywords:** Steepening, Stability, Huni Pit.

## 1 Introduction

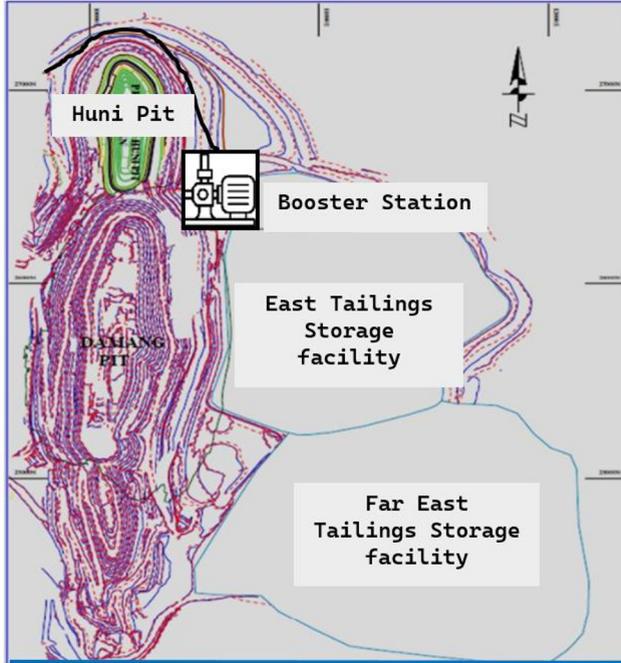
The orebody in the Huni pit is a low-grade gold mineralization that is steeply dipping to the east. The total ore of the current design is 4 million tonnes at an average grade of 1.2 g/t. Moreover, the history of failures has shown that the eastern portion of the Abosso Goldfields pits, has recorded the highest number of failures when compared to other sections of the pit.

Also, portion of the proposed pit is bounded by the booster pump with its associated tailings lines which assist in lifting tailings materials to the Far East Tailings Storage Facility (FETSF) as shown in Figure 1. The location of the Tamang water body makes it challenging for these tailings facilities to be situated along the western wall for obvi-

ous environment reasons, should the tailings lines rapture. Therefore, the current preferred location of these facilities make it unviable to enlarge the Huni pit by mining a large push back to the east.

On this note, steepening of the east wall of the Huni pit became an obvious choice to increase the mining width at the pit bottom and to expose more ore at depth for mining. Wall steepening, as a mining practice, is usually done by modifying the initial design parameters for a pit, allowing for more ore to be exposed for mining whilst reducing waste movement, thereby reducing overall cost. This mining practice of steepening slope angles in an open pit mining operation has been shown to have a material impact on improving the economics of mining [1], [2]. It has been demonstrated that a  $1^\circ$  increase in slope angle of a  $50^\circ$  slope, over a height of 500 m resulted in a 9000-t reduction in stripping per meter of face length [3], [4]. However, according to Stacey, [4] increasing the slope angle will generally reduce the stability of slopes, if all other factors remain consistent. The over steepening of slopes can induce failures which may cancel the economic benefits [2]. Slope failures can be catastrophic, resulting in fatalities and mining equipment damages. As a result, slope steepening must be treated with care and sound engineering judgement to avoid the pitfalls that come with it.

Unfortunately, the traditional method of slope design requires the use of estimated stability indicators like the factor of safety (FoS) and probability of failure (PoF) with generic acceptability criteria that are not directly tied to failure repercussions. A drawback of this type of approach is related to the difficulty of defining meaningful acceptability criteria [5]. To help solve this problem, geotechnical risk analysis has been introduced to the open pit design process to address the effect of an incident on the operation and compare the outcome to the risk levels of risks associated with other professional activities.



**Fig. 1.** Schematic diagram of the project area

## 2 Stability Analysis

Geotechnical mapping (window and scanline) were carried out on exposed pit faces to augment the historical data available. The parameters measured from the mapping were, dip, dip direction, strength/hardness, joint spacing/continuity and joint or groundwater condition, estimated RQD and infill types. Dips™ software package, a program designed for the interactive analysis of orientation-based geological data was used in the analysis of the data. This software allows the user to undertake kinematic analysis to determine if toppling, planar and wedge failure modes are kinematically feasible on the pit slope. Figure 2. Shows the stereo plot of the east wall of the Huni Pit.

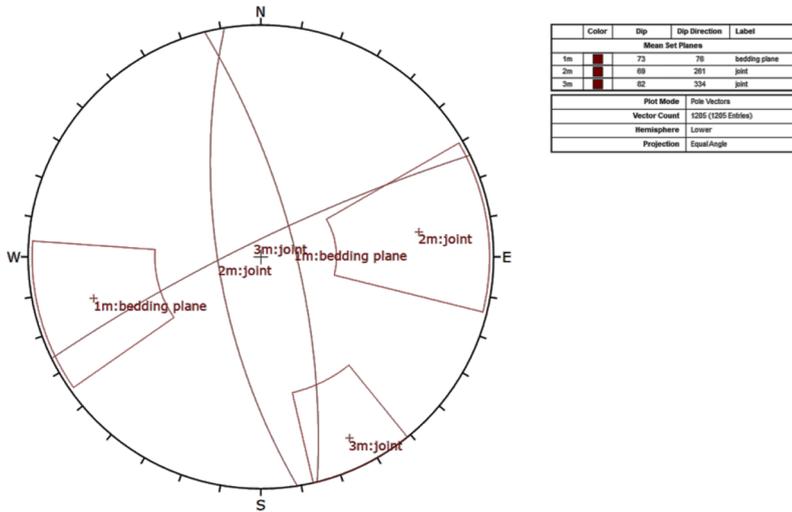


Fig. 2. A stereo plot showing the major discontinuity Sets on the east wall

The kinematic analysis conducted on the slope revealed that, the risk of flexural toppling is the highest mode of failure followed by direct toppling, planar and wedge. The risk posed by wedge failure was determined to be 22.94%. The oblique intersection between structural set 2 (69/261) and 3 (82/334) were responsible for this risk.

In addition to kinematic analyses, three Dimensional (3D) limit equilibrium analysis was also performed on the overall slope of the wall by using Slide3D™, from Rocscience. The various settings for the analysis were configured in the Project Settings dialog including the selection of probabilistic analysis for the modelling. Latin-hypercube was selected as the sampling method to produce a clear depiction of each input distribution, devoid of sampling artifacts. The open pit geometry obtained from the pit design was cleaned and loaded into the software to serve as the external boundary for the limit equilibrium analysis. The geology, structures and rock mass data available were also loaded into the model. The rock mass parameters adopted for the analyses is shown in figure 3.

Domain	$\rho$ (t/m <sup>3</sup> )	$E_i$ (GPa)	$\sigma_{ci}$ (MPa)	GSI	$m_i$	$D$	max $\sigma_3$ (MPa)	Segment 1		Segment 2		$\sigma_{tm}$ (kPa)	$\psi$ (°)	$E_{rm}$ (GPa)	$\nu_{rm}$
								$c$ (kPa)	$\phi$ (°)	$c$ (kPa)	$\phi$ (°)				
Fill	2.20	-	-	-	-	-	-	35	17	-	-	35	5	0.10	0.30
Huni Sandstone	2.72	71	182	61	24	0.0	2.0	2343	65	3540	60	401	10	38.45	0.23
Banket Sandstone	2.72	60	139	62	17	0.0	2.0	2211	61	3198	55	466	10	33.92	0.23
Banket Conglomerate	2.72	60	130	59	21	0.0	2.0	1633	63	2722	56	281	10	29.84	0.23
Tarkva Phyllite	2.86	82	124	69	17	0.0	2.0	3002	60	3945	55	705	10	58.75	0.22
Mafic (dolerite)	2.89	96	162	59	16	0.0	2.0	2180	61	3162	55	460	10	47.54	0.23

$\rho$ = Density	$c$ = Rock Mass Cohesion
$E_i$ = Intact Young's modulus	$\phi$ = Rock Mass Friction Angle
$\sigma_{ci}$ = Uniaxial Compressive Strength of Intact Rock	$\sigma_{tm}$ = Rock Mass Tensile Strength
GSI = Geological Strength Index	$\psi$ = Rock Mass Dilatation Angle
$m_i$ = Hoek-Brown material constant for Intact Rock	$E_{rm}$ = Young's modulus for the Rock Mass
$D$ = Hoek-Brown disturbance factor	$\nu_{rm}$ = Poisson's ratio for the Rock Mass
$\sigma_3$ = minor principal stress	

Fig. 3 Material properties for the Huni Pit

Results from the three-dimensional Limit equilibrium analysis indicated that, the critical failure surface of the pit is located on the south eastern sector of the slope (Figure 4). In this sector a factor of safety of 4.9 was determined with a corresponding probability of failure of 1.77%. Both values satisfy the design acceptance criteria for Goldfields. Although the design satisfied the acceptance criteria for the mine, the commitment of Goldfields to the safety of its employees, mining machinery and the nearby infrastructure informed the conduction of a quantitative risk assessment to determine any potential risks that might be associated with the steepening of the slope.

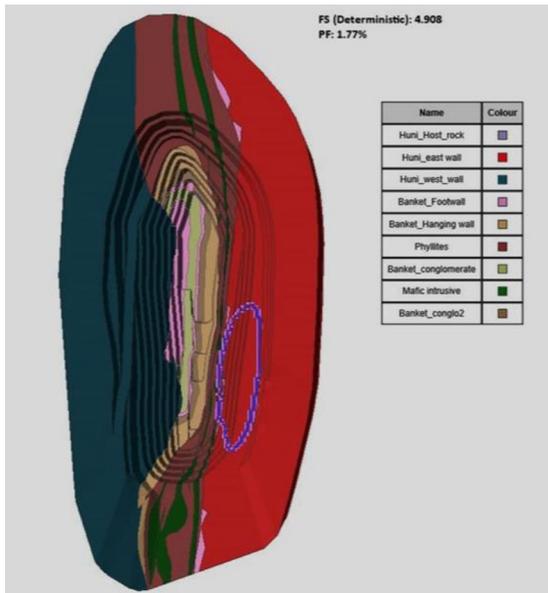


Fig. 4 Results of the 3D limit equilibrium analysis

### 3 Geotechnical Risk assessment

The geotechnical risk assessment is a Quantitative Risk Assessment (QRA) that was carried out on the east wall of the Huni Pit of the Abosso Goldfields Limited. In undertaking the QRA model the term geotechnical failure was focused only on overall pit slope scale instability. This is because this scale of failure is the largest unknown in terms of the emerging slope design, and it is readily accessible using slope stability analysis methods.

The following methodology was used to develop the QRA model and included:

1. Development of a fault tree to identify events that could initiate a full-scale slope failure on the east wall
2. Establish the possible sequence of events that could result from the slope failure. In this case it is the development of consequence trees for both safeties of personnel and equipment damage; and
3. Quantify in terms of probability and frequency, the likelihood of (1) and (2) above
4. Determine the overall risk by aggregating all the known quantified hazards.

To fully assess the potential inputs likely to drive a major failure on the walls, site personnel and external reviewers determined the numbers that were assigned to the fault tree based on industry occurrences of events, past experiences and engineering judgement. The results of the process were used in a fault tree diagram (Figure 5). Within this fault tree model, a variety of inputs were considered with more significant components being:

1. Structural geological uncertainty;
2. Hydrogeological uncertainty; adverse ground and surface water;
3. Blast damage (vibration); and
4. Geotechnical uncertainty.

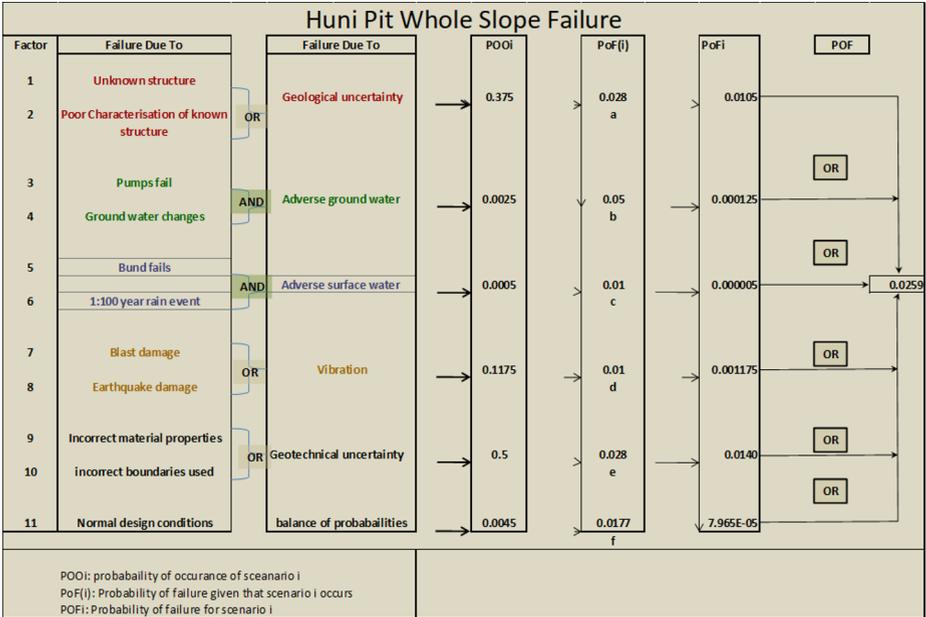


Fig. 5 Fault Tree of Defined Events Influencing a Whole Slope Failure on the East Wall of the Huni Pit.

The resulting probability of failure (overall slope) was found to be 2.60% and this value was subsequently carried forward into the risk/consequence (event tree modelling).

In order to assess the consequences of slope failure and the quantitative risk of slope failure to the operation, two consequence trees were defined based largely on previous work by [6]. However, this project work focused only on safety of personnel and damage to mining equipment. This event tree assessed the likelihood of either damage to or destruction of equipment, (or by default to fatality or injury to personnel). At a global slope scale, this primarily assesses whether the failure is detected or not, and then subsequently lead through several potential pathways to a specific outcome.

For the Risk/Consequence tree, the probability of each individual decision point has been defined. Many of these values are subjective and based on best estimates from personnel involved with the mining operation or subject matter experts. Once these probabilities were determined, each decision point multiplies with the next to produce a resultant outcome. These outcomes were multiplied against the slope failure event to produce the overall result of outcome occurring.

The risks derived from the modelling as summarised in table 1, were then plotted on acceptability criterion charts showing the level of fatality risk-potential associated with various activities and professions as shown in Figure 6.

Table 1. Summary of Risk Model Outcome (Whole Slope Failure)

Risk model outcome (Whole Slope Failure)	
Probability of Event	2.60%
Safety- Injury	0.108% (1.08E-03)
Fatality/ Equipment damaged	0.002% (2.19E-05)

It is evident from figure 6 that, the risk associated with steepening the east wall of the Huni Pit falls within tolerable limits when compared with the risk associated with activities of professional situations.

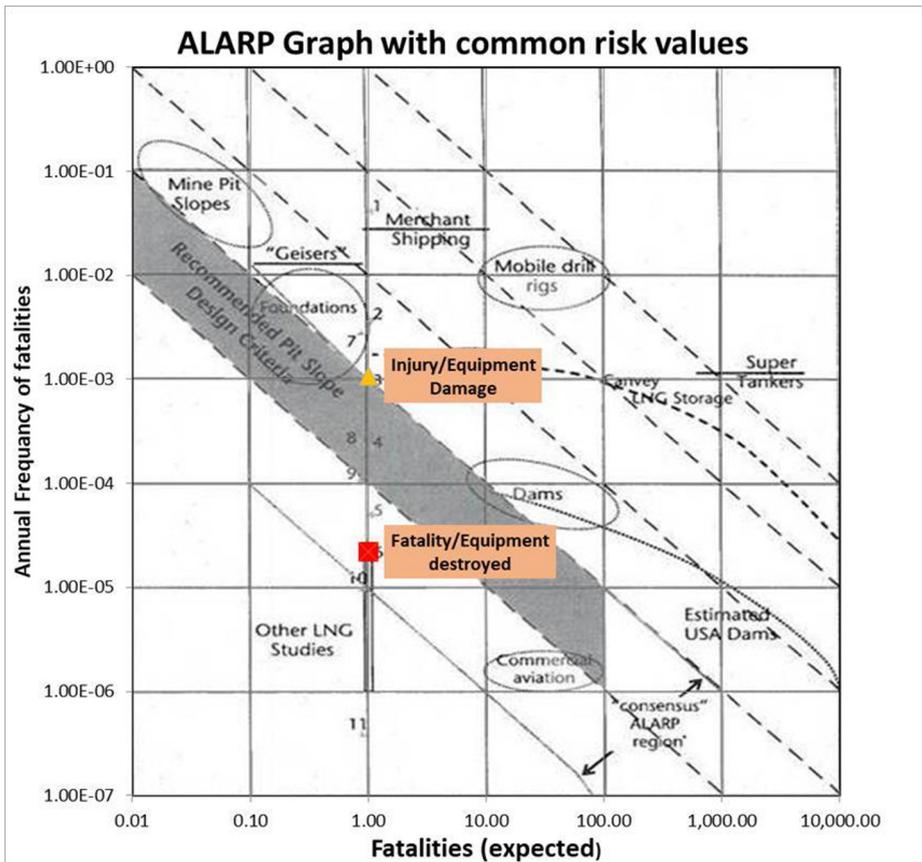


Fig. 6 Huni East Wall Risk Values Plotted Against Statistics of Common Activities or Professional Situations. [6]

## 4 Economic evaluation

To enable the Abosso Goldfields Limited make an economic decision on the Huni project, an economic evaluation was undertaken using a combination of Datamine Studio Op and Alastri Reserver Softwares. The two designs with the BFA 65° and 75° were analyzed.

Digital terrain models of the pit designs were generated and exported to Alastri Reserver Software for evaluations. In the Solid Lab of the Alastri Reserver Software, solids were formed between the pit designs and the topography. The block model of the deposit was prepared in Datamine Studio Op, converted to CSV and imported into the Alastri Reserver Software. The model preparation process included the application of modifying factors such as dilution and ore losses. The solids of the 65° and 75° pit designs were evaluated on the same block model in the Alastri Reserver Software to generate the pit inventories including ore tonnes, grade, waste tonnes, metal content, total tonnes and strip ratios. Mine call factor (MCF) and metallurgical recovery factor were applied to the metal within the solids for revenue calculations. Mining costs were determined based on established load and haul rates for each flicht, drill and blast cost per material type, grade control cost, dewatering and other ancillary costs. The processing cost applied is based on actual cost with allowance for potential escalation and efficiency improvements. The cost of selling the product was also applied in the evaluation.

Net revenue was determined for both the 65° and 75° pit designs and the results show that the 75° pit design has a higher economic value than the 65° pit design. The economic evaluation provided an outlook into the best option between the two bench face angles (650 and 750) that returned a good cash flow on the project. BFA of 650 and 750 returned a cash flow of US\$48 million and US\$57 million respectively.

## 5 Conclusion

Kinematically, there exists a potential for structurally controlled bench-scale failures. The dominant failure modes from the analysis were flexural, direct and planar failures. Also, the lower Probability of failure (1.77 %) obtained from the detailed 3D Limit Equilibrium analysis of the slopes, satisfied the design acceptance criteria limit for the mine (3%). The critical failure surface from the analysis was located on the south eastern portion of the east wall;

It was also evident from the studies that, the risks associated with the steepening of the east wall of Huni are within acceptable limits when compared with the risks associated with common activities and professional situations.

Finally, the economic benefit of the steepened slope (75°) is better than the existing (65°) bench face angle.

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