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Steepened open pit slopes can be stable: case studies of Gold Fields, Ghana

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Abstract

Gold Fields Ltd is a globally diversify gold producer with operations in Australia, Peru, Chile, South Africa and Ghana. The Tarkwa and Damang open pit mines are both in Ghana, and they produce a combined total of about 0.75 million ounces of gold annually.

The global hunger for minerals, coupled with increasing mine depths and lower grade deposits, is driving mine designers and mine owners to reduce overall mining costs by optimising or steepening open pit slopes (Golestanifar & Akbari Dehkharghani 2018). This practice involves varying design parameters on portions of, or whole, slopes for obvious economic reasons. It has been shown that an increase in overall slope angle of 1° in a 500 m-high 50° wall results in a reduction of approximately 9,000 t of stripping per metre of face length (Stacey 2009). The mining practice of steepening open pit slopes has both economic and safety impacts on every mining project (Stacey 2009).

The selection and implementation of the steepened slopes within the region (Gold Fields Ghana) was based on a solid understanding of the geology, critical structures (bedding/major structures), rock mass conditions, hydrogeological setting, operational capabilities and the historic performances of the slopes.

In Tarkwa, steepening was done across all operational pits. The bench face angles were increased from 75 to 90°. This resulted in the increase of inter-ramp angle from 55 to 65°. At the Damang mine, the bench face angle of the slope on the west wall of the Damang pit cutback (DPCB) was steepened from 75 to 80°, resulting in a steepened inter-ramp angle from 59 to 63°. The successful implementation of steepening improved safety, increased the mining width at lower elevations and created opportunities of accessing more ore at depth. Gold Fields Ghana's success with wall steepening was because onsite mining teams adhered to high drill and blast standards and mining controls. These, in combination with excellent wall cleaning practices, were fundamental for the safe and economically successful outcome.

The purpose of this paper is to highlight the processes of steepening, share results and, ultimately, outline the best industry practices that led to successfully mining steeper slopes within Gold Fields Ghana.

Keywords: *steepening, open pit slope, bench face angle*

1 Introduction

Wall steepening, or optimisation, is the prevalent mining practice of varying open pit design parameters on portions of, or whole, slopes. This practice is mainly undertaken to achieve the maximum slope configuration that is safe and stable, and has provided economic benefits such as increased mining inventory and reduced strip ratios. However, there are instances where steepened slopes failed, leading to fatalities, equipment damage and the temporary or permanent closure of mines. In other instances, slope steepening programs were adopted but later found to be unworkable. To avoid the potential pitfalls associated with wall steepening, Gold Fields Ghana undertook two slope optimisation (steepening) studies to identify and unlock the potential in steepening open pit slopes. The studies paid particular attention to the effect of geology, critical structures (bedding/major structures), rock mass conditions, the hydrogeological setting, operational capabilities and the historic performances of designs on the stability of the steepened slopes.

Both the Tarkwa and Damang mines are situated in the southwestern portion of Ghana. Tarkwa is located on latitude 5°15′ N and longitude 2°00′ W, and the Damang mine is on latitude 5°11′ N and longitude 1°57′ W (Figure 1). The Damang orebody is hosted in both the paleoplacer and hydrothermal-style deposits, with the main Damang pit located near the closure of the antiform. All other known palaeoplacer mineralisation is located on the east and west limbs of the Damang anticline. However, in Tarkwa, mainly tabular auriferous conglomerates are exploited, like those mined in the Witwatersrand Basin of South Africa.

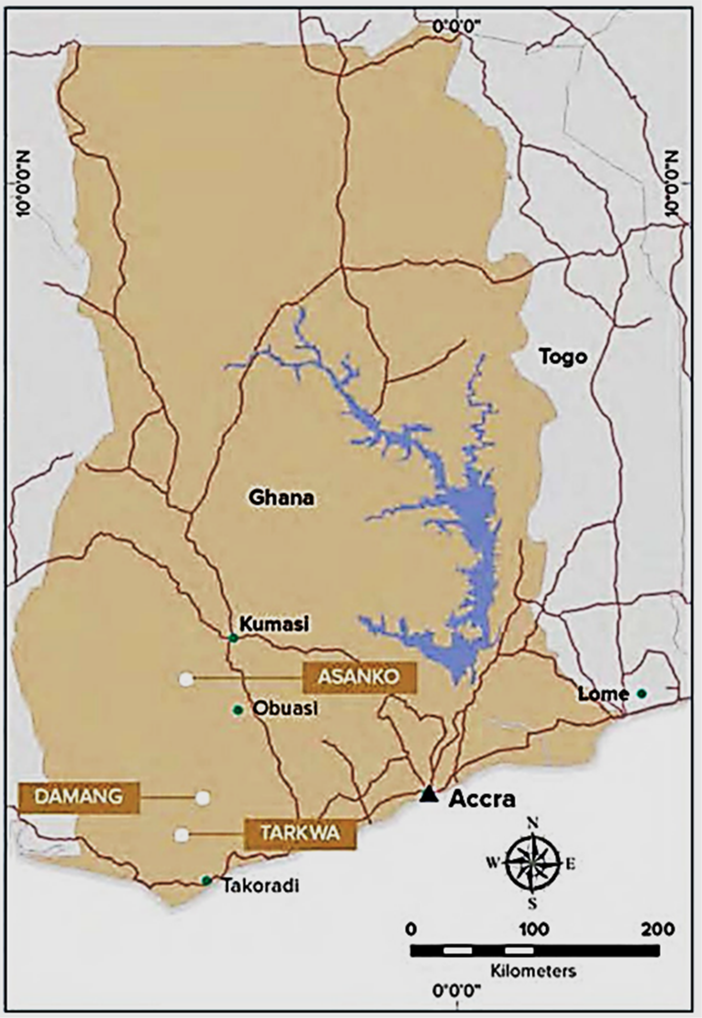


Figure 1 Map of Ghana showing the locations of the Tarkwa and Damang mines

2 Case study 1: Damang mine

2.1 Overview

In 2013, the corporate technical team (geotechnical) reviewed historical documents relating to mining history at Damang, including drill and blast performances on the open pit slopes. This allowed anecdotal and historical precedence to be included in the potential slope optimisation. It was evident from that review that the overall slope design angles were reduced significantly over the previous two years (Table 1). The changes were due in part because of the Ghanaian regulation that no bench height can be greater than 20 m vertical height. Damang previously had 24 m-high benches so to conform with new regulations, future bench designs were lowered to 18 m high. This allows for 3 m flitches over a 9 m bench. By changing to this regulation and not changing any other wall design parameters, the overall slope angle in fresh rock was reduced by 3°.

Table 1 Comparison of initial (2011 design) with design changes due to regulatory requirements

Initial east wall design parameters		**East wall design after regulatory changes**	
Bench height	24 m	Bench height	18 m
Inter-ramp angle	58.7°	Inter-ramp angle	55.1°
Bench face angle	70°	Bench face angle	70°
Spill berm width	6 m	Spill berm width	6 m
Overall slope angle	59.5°	Overall slope angle	56.4°
Initial west wall design parameters		**West wall design after regulatory changes**	
Bench height	24 m	Bench height	18 m
Inter-ramp angle	62.6°	Inter-ramp angle	59.0°
Bench face angle	75.0°	Bench face angle	75.0°
Spill berm width	6 m	Spill berm width	6 m
Overall slope angle	63.8°	Overall slope angle	60.4°

At the end of 2015, the original Damang mine was left with narrow pits and mining width constraints. A strategic review conducted by the mine resulted in the Damang Reinvestment Plan, intended to extend the life of mine by eight years. To optimise the slope parameters for the study, Abosso Gold Fields Ltd undertook a geotechnical assessment as part of wall steepening study for the east and west walls of the Damang pit cutback (DPCB). The purpose was to steepen the slopes with safety and stability in mind. This case study is only focused on the steepening of the west wall of the Damang pit cutback.

2.2 Geology of the west wall

The west wall is predominantly composed of the Huni sandstone over its entire strike length (Figure 2). This rock type is a fine- to medium-grained quartz sandstone. The unit is thickly bedded in the pit exposure and contains discontinuous sandstone lenses and beds. The unit contains well-defined primary bedding planes and weak cross beds. Sub-vertical jointing is well developed. The Huni sandstone has an average uniaxial compressive strength of 224 MPa and is therefore classified as a very strong rock. The rock quality designation values are typically in the range of 80–100%.

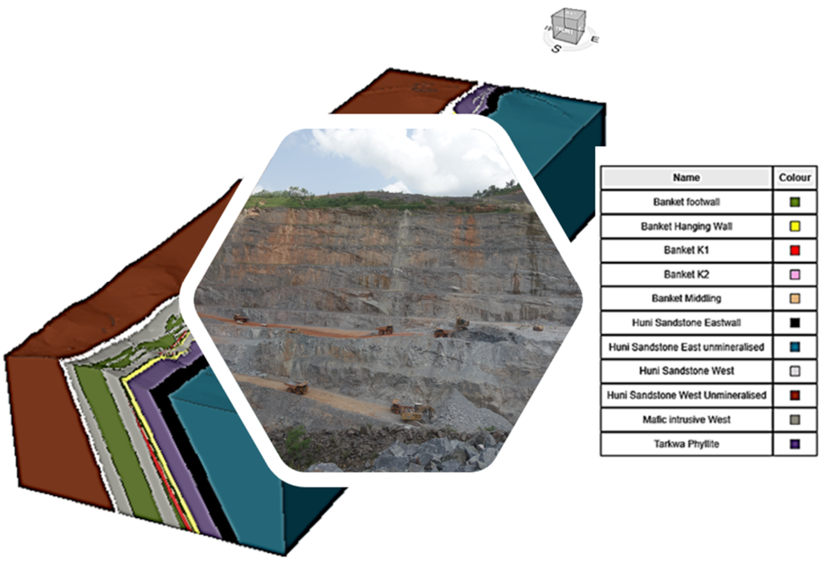


Figure 2 Exposure of the Huni sandstone on the west wall and an isometric view of the geology of the Damang pit cutback

2.3 Major structures

The major structural interpretations on the mine as illustrated in Figure 3 can broadly be classified as bedding parallel and crosscutting faults. These faults were considered significant, with the potential to impact slope stability. The Damang thrust fault is a steep easterly dipping fault which strikes parallel to the pit and intersects the west wall. The fault is weak and undulating, and occurs on the western contact of the dolerite and the sandstone. On a large scale, the fault dips steeper than the inter-ramp angle on the west wall. At the bench scale, the fault has controlled batter scale stability where it was exposed on the west wall.

The Rogan fault is an important northerly dipping crosscut fault that intersects both the west and the east walls. Deterioration of the ground around the Rogan fault has been the source of rockfalls in the DPCB.

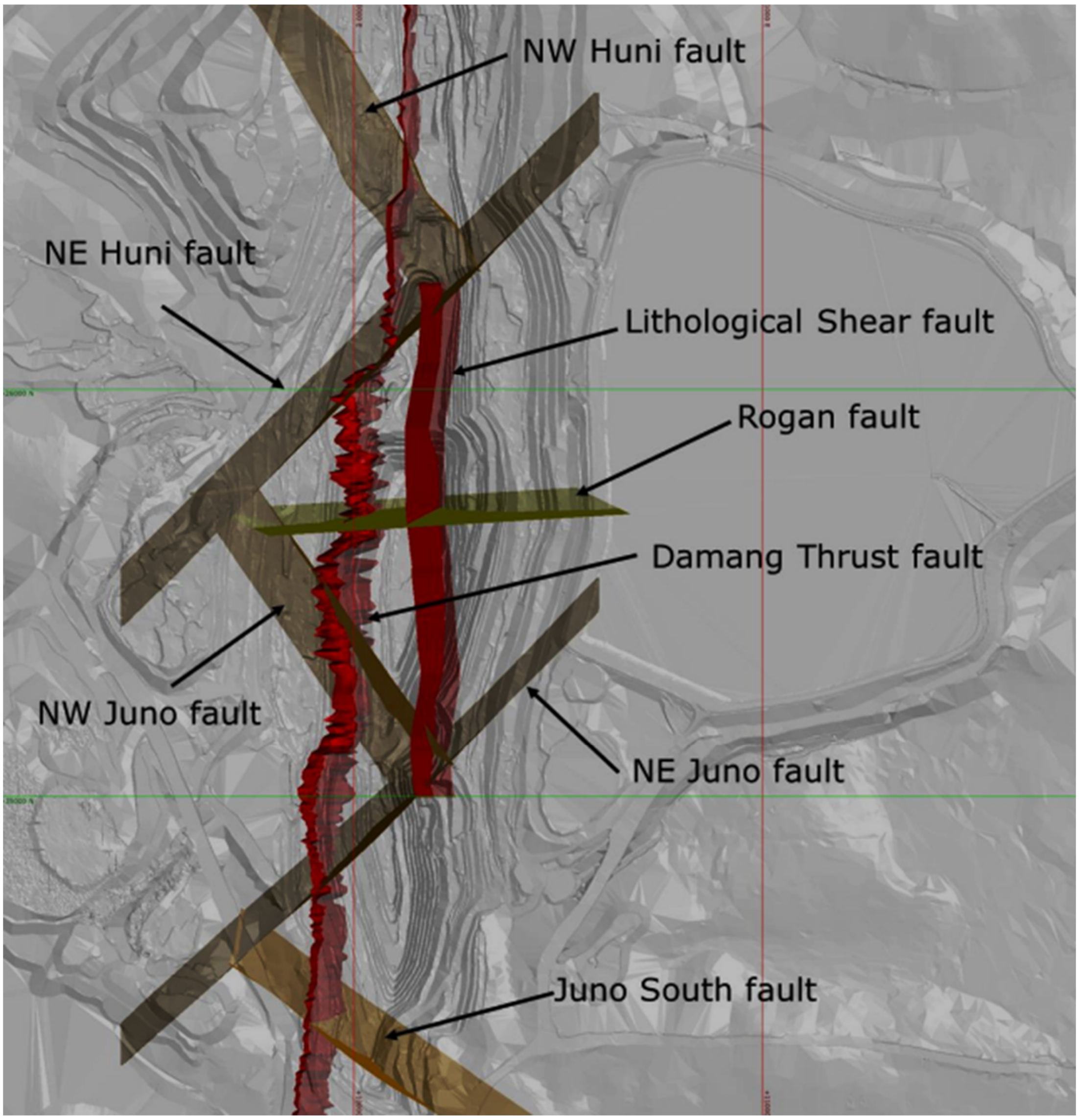


Figure 3 Plan view of fault interpretations of the Damang pit cutback

2.4 Groundwater

The groundwater flow regime around the pit comprises both high and moderate permeability zones along the centre and west of the deposit. The site is described conceptually as a fractured rock aquifer. The groundwater flow is considered variable and primarily controlled by rock structures.

Along the west wall, based on piezometers, the phreatic surface was assumed to be located 30 m behind the final pit face, and to follow the base of the oxides/fill at upper levels behind the pit crest. Hydrostatic conditions are assumed below the phreatic surfaces. The surfaces and pore pressures for each model are shown in Figure 4.

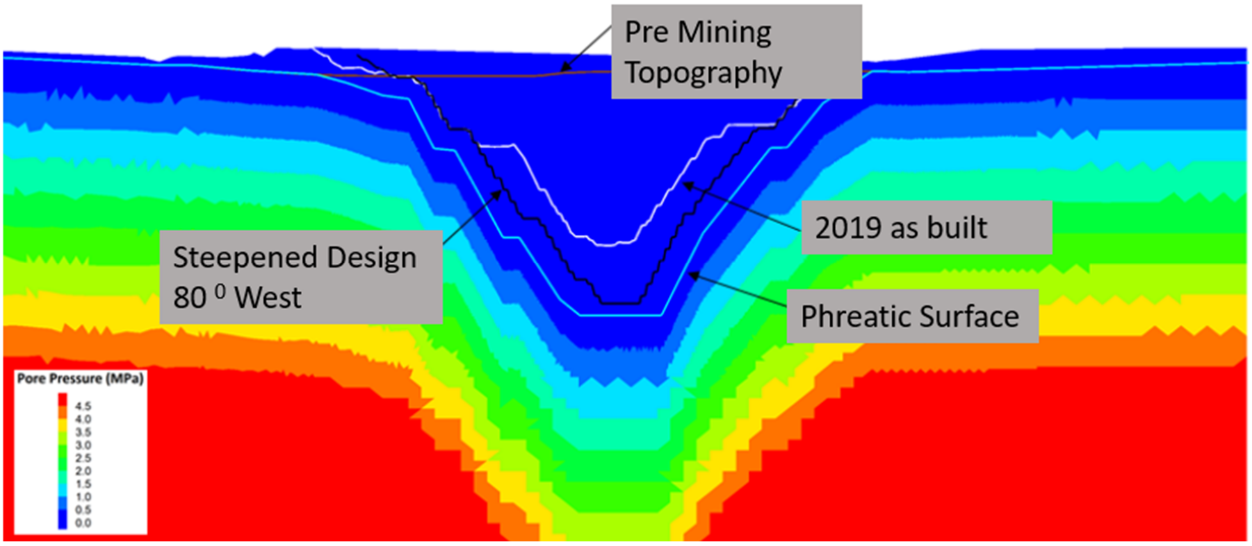


Figure 4 Phreatic surface and pore pressure adopted for the 25,700 N model

2.5 Rock mass

The rock mass properties used for the study were derived from laboratory testing on core and core logging. The methodology used to determine rock mass strength and tensile strength for the fresh rock mass domains were estimated using the Hoek-Brown failure criterion as described by Hoek et al. (2002). In the numerical modelling of the slopes, the 25th percentile values have been adopted for the uniaxial compressive strength, geological strength index and Hoek–Brown material constant. These lower-than-average values were adopted to account for the influence of rock mass variability. Table 2 summarises the material properties obtained from laboratory testing.

Table 2 Material properties obtained from a laboratory test

Domain	ρ (t\m^{3})	*E_i* (GPa)	σc_i (MPa)	GSI	m_i	maxσ_3 (MPa)	c (kPa)	ø (°)	c (kPa)	ø (°)	*σtm* (kPa)	ψ (°)	*Erm* (GPa)	*V*rm
Fill	2.2	–	–	–	–	–	35	17	–	–	35	5	0.1	0.3
Huni sandstone	2.72	71	182	61	24	2	2,343	65	3,540	60	401	10	38.45	0.23
Banket sandstone	2.72	60	139	62	17	2	2,211	61	3,198	55	466	10	33.92	0.23
Banket conglomerate	2.72	60	130	59	21	2	1,633	63	2,722	56	281	10	29.84	0.23
Tarkwa phyllite	2.86	82	124	69	17	2	3,002	60	3,945	55	705	10	58.84	0.22
Mafic (dolerite)	2.89	96	162	59	16	2	2,180	61	3,162	55	460	10	47.54	0.23

ρ = density, *E_i* = intact Young's modulus, σc_i = uniaxial compressive strength of intact rock, GSI = geological strength index, m_i = Hoek–Brown material constant for intact rock, maxσ_3 = minor principal stress, c = rock mass cohesion, ø = rock mass frictional angle, σtm = rock mass tensile strength, ψ = rock mass dilation angle, Erm = Young's modulus for rock mass, *V*rm = Poisson's ratio for rock mass

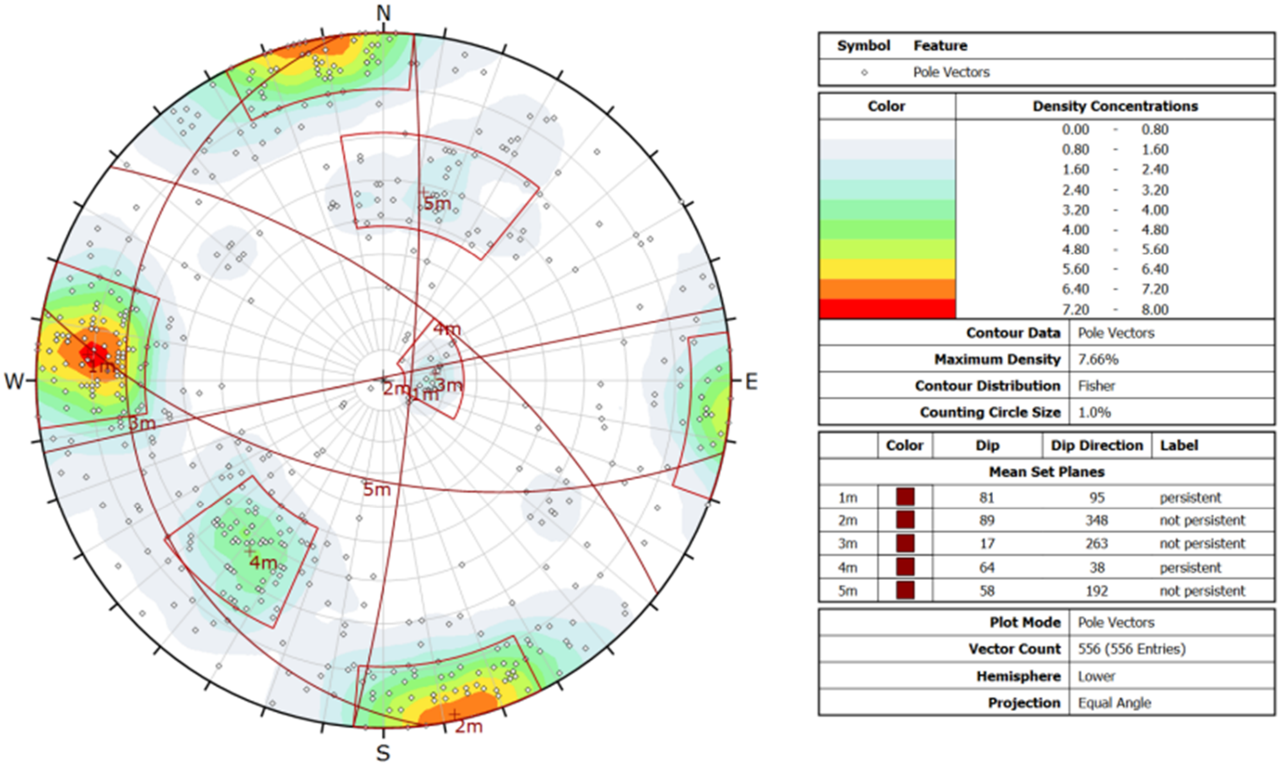
2.6 Historic performance of the west wall

Historically, the western wall of the DPCB was the most stable wall comparatively to the east wall, which experienced failure on the upper sections of the slope. Minor rockfalls on the west wall were associated with the Damang fault, which strikes subparallel to the slope face and dips steeper than the bench face angle (75°). Another source of minor rockfalls on the west wall was the portion of the slope intersected by the Rogan fault, caused by the deterioration of infill material along the fault zone.

2.7 Stability analysis

As part of the study, extensive window mapping was conducted on exposed faces of the DPCB pit. A window for this project was 30 m width over an 18 m bench height. Additional structural data was obtained from the independent structural analysis conducted using high-resolution laser mapping by a third-party consultant on the DPCB. Structural data gathered from the geotechnical drilling program were also added to the available structural data.

A stereo plot of discontinuities was generated using Rocscience Dips™ software as shown in Figure 5. A kinematic analysis was conducted on the structural data obtained from window mapping and structural core logging. Analyses were done for 75°, 80° and 85° BFA to determine if there were any adverse interactions between discontinuities and the slope, which could pose stability challenges. The results from the analyses indicated that planar and wedge failures were expected to be the dominant failure modes on the west wall of the DPCB (Table 3) . It should be noted that the results of the kinematic analysis are not truly equivalent to the probability of failure but instead provided a relative indication of the dominant kinematic failure modes on the west wall.



Symbol	Feature
◇	Pole Vectors

Color	Density Concentrations
⬜	0.00 - 0.80
⬜	0.80 - 1.60
⬜	1.60 - 2.40
🟩	2.40 - 3.20
🟩	3.20 - 4.00
🟩	4.00 - 4.80
🟨	4.80 - 5.60
🟨	5.60 - 6.40
🟧	6.40 - 7.20
🟥	7.20 - 8.00

Contour Data	Pole Vectors
Maximum Density	7.66%
Contour Distribution	Fisher
Counting Circle Size	1.0%

	Color	Dip	Dip Direction	Label
Mean Set Planes				
1m	🟥	81	95	persistent
2m	🟥	89	348	not persistent
3m	🟥	17	263	not persistent
4m	🟥	64	38	persistent
5m	🟥	58	192	not persistent

Plot Mode	Pole Vectors
Vector Count	556 (556 Entries)
Hemisphere	Lower
Projection	Equal Angle

Figure 5 Stereo plot of the structures on the west wall

Table 3 Summary of kinematic analyses results

Summary of critical structure sets for direct toppling					
Wall	BFA (°)	Friction angle (°)	Joint dip (°)	Joint dip direction (°)	All pole (%)
West wall	75	29–38	81	095	9
	80	29–38	81	095	10
	85	29–38	81	095	10.8
Summary of critical structure sets for flexural toppling					
West wall	75	29	81	095	6.8
		38	81	095	6.5
	80	29	81	095	6.8
		38	81	095	6.7
	85	29–38	81	095	6.8
Summary of critical structure sets for planar failure					
West wall	75	29–38	81	095	6.7
	80	29–38	81	095	11.7
	85	29–38	81	095	15.7
Summary of critical structure sets combination for wedge sliding					
West wall	Set 1		Set 2		
	Joint dip (°)	Dip direction (°)	Joint dip (°)	Dip direction (°)	
	89	348	64	038	
	58	192	64	038	
	BFA (°)	Friction angle (°)			All pole (%)
	75	29			30.9
		38			28
	80	29			40
		38			37.1
	85	29			48.2
		38			45.5

SBlock™, a stability analysis tool, was also used to further determine the stability of the slopes. The software uses the key block principle (Goodman & Shi 1985). The spacing of discontinuities used for the analysis ranged from a minimum of 1.2 m to a maximum of 2.5 m. The length of the discontinuities also ranged from 4 m to greater than 7 m. These input parameters were obtained from window mapping of exposed faces. SBlock analyses were also performed on 75°, 80° and 85° BFA and the results indicated that the probability of failure for 80° BFA was within design acceptance criteria (DAC). Table 4 summarises the results of stability analysis using SBlock™.

Table 4 West wall stability analysis results

BFA (°)	Max. Probability of Failure	Average effective berm width (m)	Failure-free bench length (%)	Average failure volume (m^3/m)	Average required berm width (m)
75	4.5	5.9	95.6	1.1	2.2
80	6.9	5.8	93.1	1.4	2.6
85	28.9	5.5	71.2	3.9	4.4

The overall stability of the west wall was analysed by external consultants using the UDEC™ program as shown in Figure 6. A vertical section taken along the northern 25,700 mN was analysed. This section of the slope represents the steepest portion of the west wall. The rock mass properties used are shown in Table 2. The geology and structural information used in the model are as described in Sections 2.2 and 2.3, respectively. In addition to the use of the groundwater information as captured in Section 2.4, the phreatic surfaces used were assumed to be 30 m behind the slope face and hydrostatic conditions were also below the phreatic surfaces. It was assumed that drains will be installed on the slopes to keep the phreatic surfaces at a minimum distance of 30 m away from the slope faces to effectively control the build-up of pore pressure. The Factor of Safety from this analysis satisfied DAC for the mine.

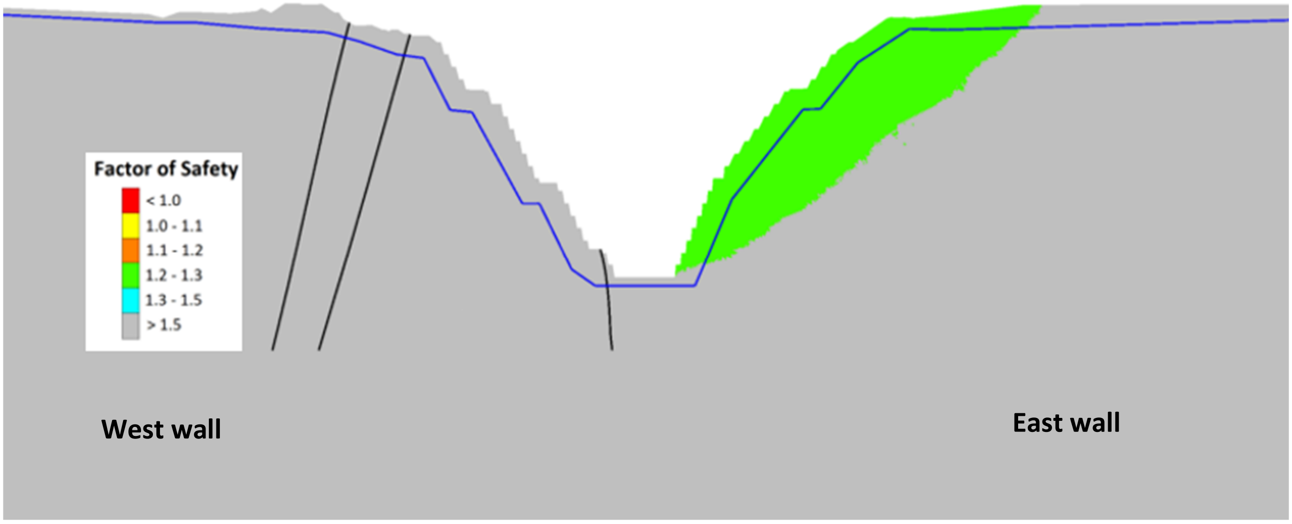


Figure 6 UDEC modelling result of an east–west section taken along the 25,700 mN (Itasca 2018)

2.8 Wall management practices

As part of the implementation strategy of the steepened slope, the following controls were implemented to ensure compliance to design:

1. Pre-split and buffer/trim blasting was introduced to minimise the effect of blasting on the wall.
2. Weep holes drilling targeting structures was adopted to reduce the build-up of pore pressure behind the steepened slope.
3. The effect of blasting on the walls was monitored and the data obtained was used to optimise subsequent blasting parameters.
4. Radar monitoring was undertaken on the performance of the design.
5. Where the Damang fault interacts with the wall creating slabs, the bench face was cleaned to the Damang fault plane.

2.9 Steepening results

Results from the stability analysis conducted for the study indicated that the risk associated with increasing the BFA from 75° to 80° was tolerable. This was evident in the results obtained from kinematic analysis (Table 3), S-Block and overall stability analysis. Thus, changes were made to the design, as shown in Table 5 (and Figure 7). The overall height of the west all is 384 m.

Table 5 Comparison of the initial and steepened design parameters

	Initial	After steepening
Bench face angle	75°	80°
Spill berm width	6 m	6 m
Bench height	18 m	18 m
Inter-ramp angle	59°	63°

Additionally, economic analysis conducted on the steepened designed revealed that 2 Mt of waste stripping was reduced over the life of the pit because of the steepening and an additional 39 koz of gold was gained, increasing the mineral reserve. The increased mining width obtained from this exercise resulted in an improvement in operational efficiencies as well as the safety of personnel.

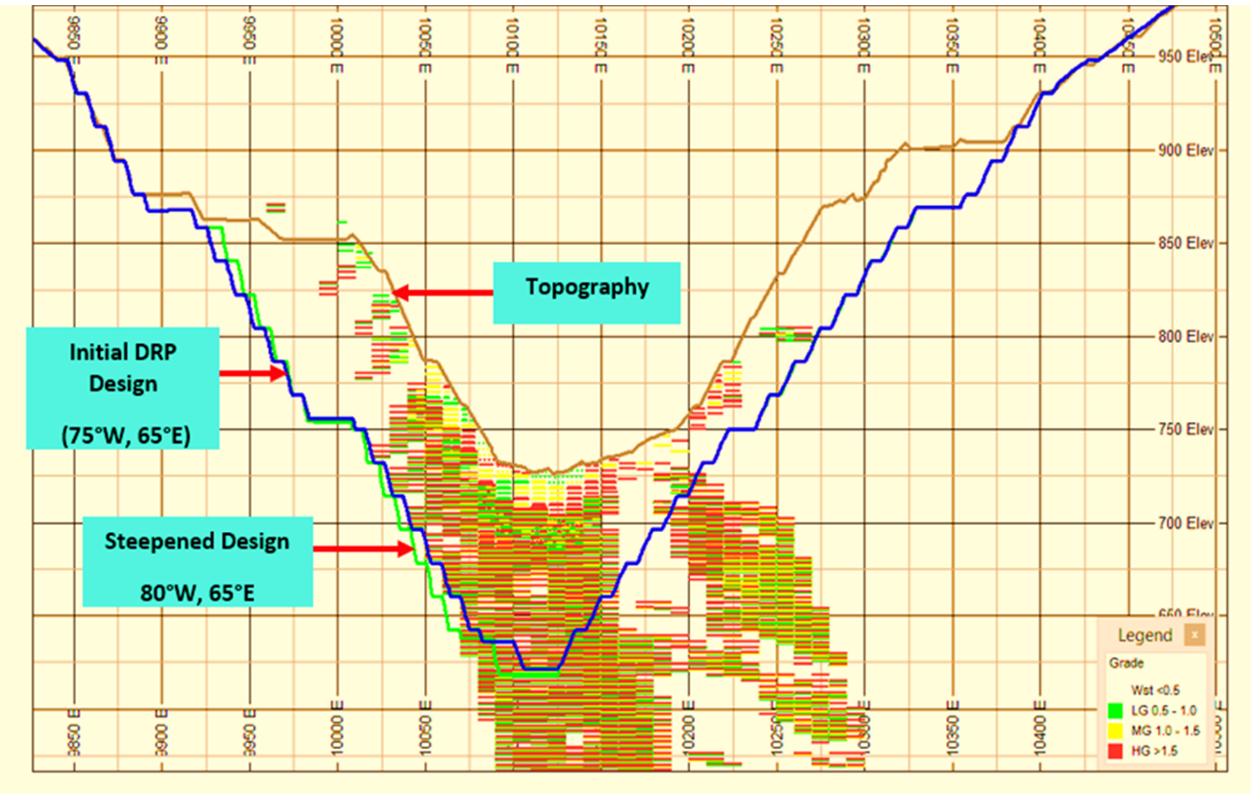


Figure 7 East–west section showing the pit designs, topography and block model

The performance of the steepened design exceeded the expectations of Goldfields Damang. Apart from periodic and effectively managed rockfalls along the Rogan fault after rainy events, the mine did not record any failure on the west wall, as shown in Figure 8. The implementation/execution strategies of the design were also successful. Overall, the percentage compliance for batter and berm reconciliations for the design were all within acceptable limits throughout the project life.

Figure 8 A view of the west wall of the DPCB (camera facing south)

3 Case study 2: Tarkwa mine

3.1 Overview

Tarkwa mine is a low-grade open pit mine that produces between 500 and 600 koz of gold annually. The mine operates under mining leases covering a total area of approximately 20,800 ha. The scale of the operation, has resulted in the division of the mine into mining districts described in this paper as zone 1 and zone 2. The pits under zone 1 are Pepe, Mantraim 1, Mantraim 2 and Teberebie. Zone 2 pits are Underlap, Akontansi Central and Akontansi Ridge.

Prior to the implementation of the steepening exercise, the geometry of the hanging wall slopes on the Tarkwa mine was 75° BFA with an 8 m-wide spill berm and 12 m bench height. The footwall slopes were usually developed to mimic the dip of shallow bedding planes. However, after undertaking a benchmarking exercise on a neighbouring mine operating within the same Tarkwaian environment, the bench height was increased to 18 m, leaving the other design parameters the same. In 2019, the potential of steepening the pit walls was evaluated to tap the gains hidden in mining steeper walls. This resulted in modification of the BFA from 75° to 90°, leaving other design parameters unchanged.

3.2 Geology of the Tarkwa mine

The Tarkwa mine is located on the southern end of the western limb within the Tarkwa Basin: a broad synclinal structure that contains fluvial sediments of continental origin and Pre-Cambrian age known as the Tarkwaian System. These sediments rest unconformably on the basement of metamorphosed sedimentary, volcanic and intrusive rocks referred to as the Birimian Series. The Tarkwaian System is an approximately 2,000 m-thick sequence of conglomerates, sandstones and siltstones.

The gold mineralisation within the Tarkwaian System is contained within the Banket series: a sedimentary unit 120 to 160 m-thick with horizons of quartz pebbly conglomerates. The number of ore zones range from five in the east to seven in the west. The conglomerates comprise matrix-supported, well-rounded to ellipsoid pebbles of quartz, with varying proportions of the sub-rounded to angular clast of schistose metasediments and volcanic derived from the Birimian basement rocks. Thin quartzite partings (sandstone interbeds) occur within the Banket conglomerates, where the breccia conglomerate grades into pebbly sandstone locally termed ‘grits’. Alteration is not significant in the Banket Reef Zone rocks. This occurs as a regional lower green schist facies metamorphism, causing the development within the sequence of chlorite and muscovite micas including sericite.

3.3 Major structures

The major structures on the mine (Figures 9 and 10) are generally sub-vertically dipping and intersect the slope faces at different locations. These very persistent structures have thicknesses varying between 0.1 to 20 m, depending on the intensity of the disturbance zones. The persistence of the faults can influence stability on the bench, inter-ramp and overall scales. These structures have always served as transportation conduits of groundwater. The deterioration and weathering of the infill/gouge material within the fault zones has been identified as the source of rockfall on the mine.

In certain portions of the pit, intrusives (dykes and sills) have intruded the sedimentary sequences and occur adjacent to zones of structural complexity. Most dykes are highly to completely weathered and are composed of ferruginous and sericitic clays. Thin lentoid quartz veins are typically associated spatially with the dyke intrusions and structurally disturbed zone. Most dykes appear concordant to semi-concordant with the main sequence and have only rarely intruded the Banket Reef Zone sequences.

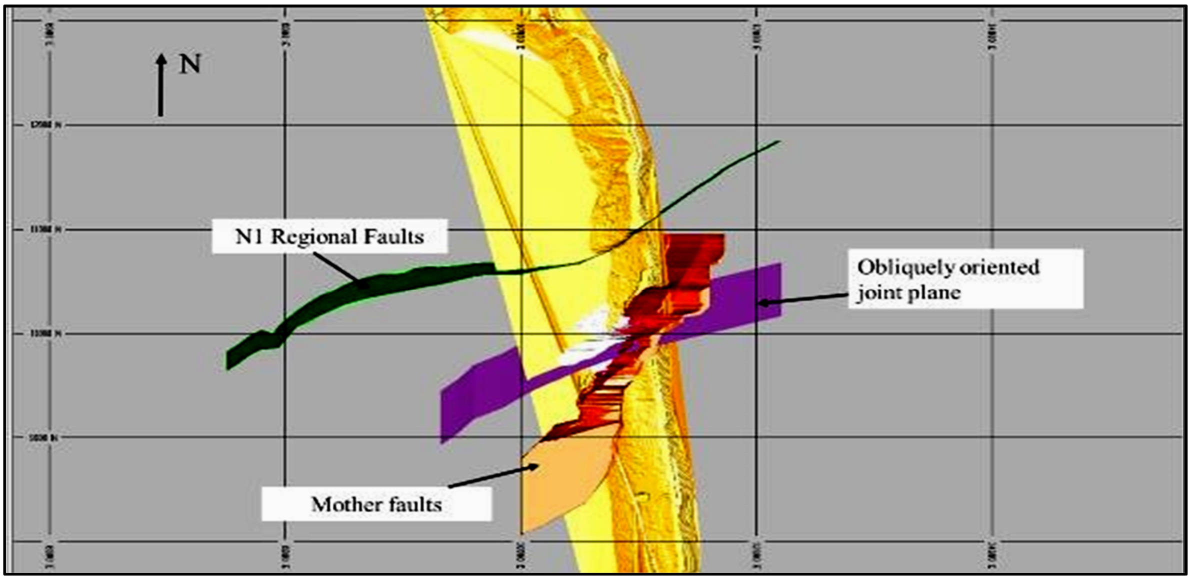


Figure 9 Major structures in zone 1

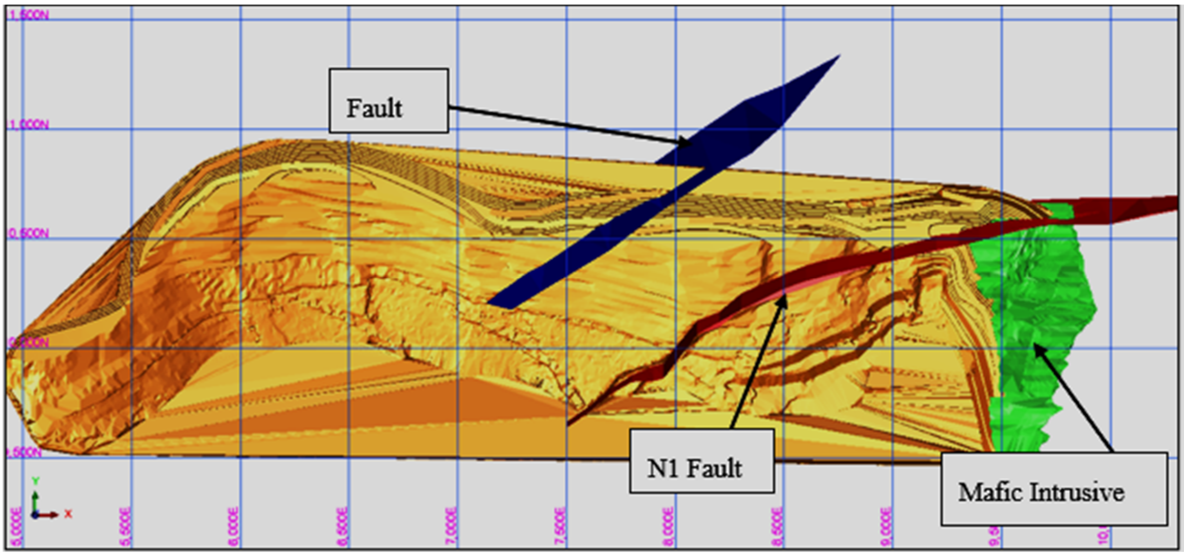


Figure 10 Major structures in zone 2

3.4 Groundwater

As part of the project, hydrogeological assessments were carried out and the data was used to evaluate possible groundwater profiles. The packer tests conducted on the mine revealed a range of permeability test values of 1.8×10^{-8} to 1.4×10^{-6} m/s, with an average value of 2.4×10^{-6} m/s. Permeability test values within fault zones are relatively high: 3.0×10^{-6} to 5.4×10^{-6} m/s from both packer and well tests.

Inflow into the pit is estimated at between 315 to 355 l/s, with high inflow from fault zones. Thus, contribution to total accumulated pit water from groundwater is minimal as compared to runoffs from storm events.

3.5 Rock mass

The main stratigraphic unit on the mine is the Banket series, which contains two rock types. These are quartzites (waste) and pebbly conglomerates (ore). The quartzites are a strong to very strong rock unit. Weathering ranges from slightly weathered to fresh. The primary discontinuity type observed within the quartzite is bedding which has an average dip of about 15° and is very persistent with spacing of between 1 to 3 m. The are other 2–4 discontinuity sets with spacings between 0.5 and 10 m, with chloritic infill that is <1 mm thick. The conglomerates are strong to very strong rock units. Weathering ranges from slightly weathered to fresh. The bedding planes within the conglomerates have similar dip, spacing and persistence as those observed within the quartzites. Table 6 shows the rock mass classification of the rocks on the mine. The values in brackets are averages.

Table 6 Rock mass classification values for rocks in zones 1 and 2

Zone 1					
Pit	Lithology	RMR	MRMR	GSI	IOSA
All pits	Quartzite	44–67 (56)	42–66 (53)	39–62 (51)	51–63 (56)
	Conglomerate	55–63 (59)	46–58 (51)	53–58 (54)	53–59 (56)
Zone 2					
Pit	Lithology	RMR	MRMR	GSI	IOSA
All pits	Quartzite	54–64 (61)	45–57 (50)	53–59 (56)	53–58 (55)
	Conglomerate	54–66 (58)	52–60 (55)	53–58 (54)	56–60 (57)

RMR = rock mass rating; MRMR = mining rock mass rating; GSI = geological strength index; IOSA = indicative overall slope angle

3.6 Historic performance of designs

A review of the historical instabilities indicated that planar and wedge failures were the most frequent. The consequences of these historical failures were very minor. The only major instabilities were encountered in areas where the Mother Fault intersected the Mantraim pit. Due to this historical precedent, fault zones have been isolated from the wall steepening studies.

Generally, the major structures (especially fault zones) have planar to slight undulating surfaces with the presence of fine clay gouge infill materials. This condition is especially prevalent in the Teberebie-Mantraim fault-bound zone on the east wall of zone 1, and the N1 fault stretch on Underlap pit’s south wall. These areas have produced instabilities associated with large blocks (see Figure 11).

Historically, the east walls of the Underlap and Kottraverchy pits experienced sliding along steep-dipping structures caused by extremely weathered felsic intrusives sandwiched between bedding planes. These failures were effectively managed through robust deformation/failure management protocols available at the mine. These areas of concern were also not included in the optimisation study.

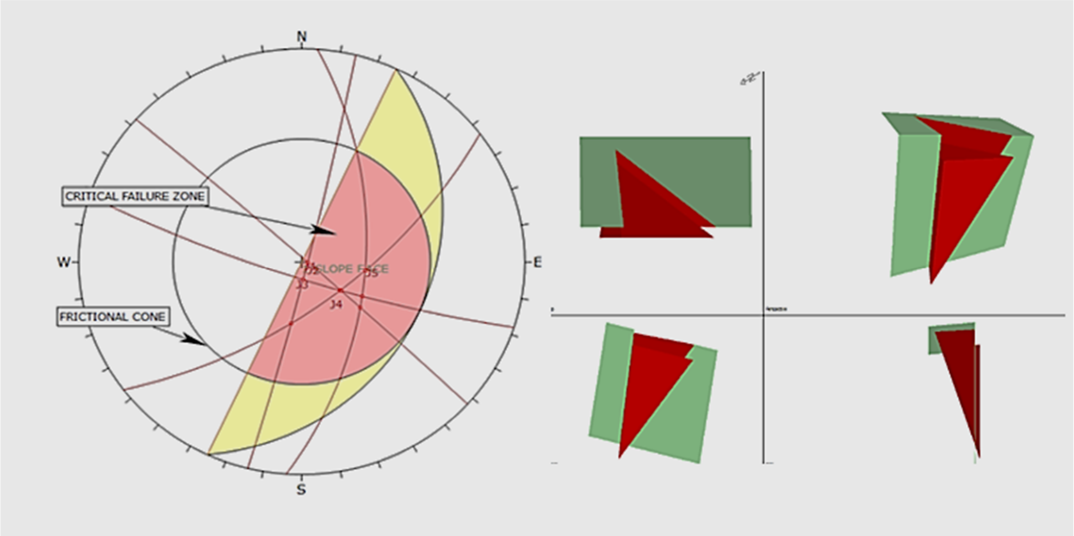
(a) (b)

Figure 11 Pictures of instabilities influenced by major structures in (a) Zone 1 and (b) Zone 2

3.7 Optimisation stability analysis

The methodology applied for stability analysis is as follows:

1. Kinematic analysis was conducted on available structural data to determine the possibilities of toppling, wedge and planar failures. Dips was used for the analysis.
2. Wedge analysis was undertaken using Dips and S-Wedge™ since wedge failures are the dominant failure modes on the mine, as shown in Figure 12.
3. Further kinematic analysis using S-Block™ was done to model and determine portions of the slope which were at risk. The effect of primary and large-scale structures such as faults and persistent joint planes on the stability of the slope are easily determined by the software. The software allows users to evaluate the bench-berm design and areas of the pit slope at risk of failure. The input parameters for the analysis are average dip and dip direction of discontinuities and their ranges, joint spacing, joint persistence, cohesion, frictional angle, and the density of the rocks and design configuration. The results of this analysis satisfy DAC, as shown in Table 7.
4. Overall slope stability analysis was undertaken using RS2™ software. Geology, structures and rock mass information, as discussed in Sections 3.3, 3.4 and 3.5, was used. The watertable used in the modelling is 10 m away from the pit. The material properties used are shown in Table 8 and the summary of the results of the RS2 modelling is shown in Table 9. See Figure 13 for the overall slope stability analysis results.



(a) (b)

Figure 12 Example of wedge analysis for zone 1 slopes using (a) Dips and (b) S-Wedge

S-Block™ was also used on the mine to analyse the effect of primary and large-scale structures such as faults and persistent joint planes on the stability of the slope. The software allows users to evaluate the bench-berm design.

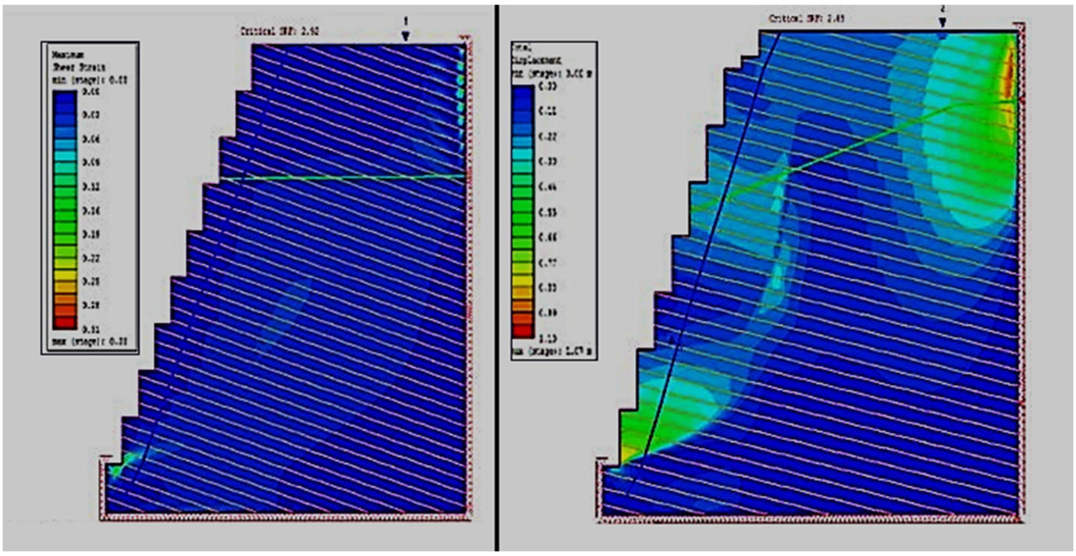
Table 7 Summary of S-Block™ analysis conducted

Location	Avg. failure volume (m^3/m)	Avg Factor of Safety of blocks\wedges	Avg effective berm width (m)	Failure-free bench length (%)	Avg non-zero failure volume (m$_i$/m)	Avg required bench width (m)	Probability of Failure crest\face failure (%)
Zone 1: Pepe	0.9	3.2	7.9	94.7	2.8	2.1	9.5
Zone 1: Teberebie	0.1	2.8	8	99.2	3.1	0.8	1.2
Zone 2: Underlap	0.4	1.7	7.9	94.5	3.5	1.5	5.5
Zone 2: Akontansi Ridge	0.1	0.43	8	98.4	1.7	0.6	1.6

Table 8 Material properties used for RS2

Parameters for zone 1		**Rock type**	
	Quartzite–fresh	Quartzite–transition	Dolerite
Hoek–Brown classification			
Sigci (MPa)	150	100	150
GSI	61	46	61
Mi	20	20	16
D	1	1	1
Hoek–Brown criterion			
mb	1.325	0.423	0.987
s	0.002	1.23	0.002
a	0.502	0.508	0.503
Failure envelope range application – slopes			
Sig3max	4.284	1.107	0.277
Unit weight (kN/m^3)	26	26	26
Slope height (m)	200	50	10
Parameters for zone 2		**Rock type**	
	Quartzite–fresh	Quartzite–transition	Dolerite
Hoek–Brown classification			
Sigci (MPa)	120/150	80–110	150
GSI	55/62	45–51	62

Parameters for zone 2		Rock type	
Mi	20	20	16
D	1	1	1
Hoek–Brown criterion			
mb	0.804–1.325	0.423	1.16
s	5.53e (004)	1.23	0.002
a	0.504–0.504	0.508	0.502
Failure envelope range application – slopes			
Sig3max	1.161–4.284	1.085–1.116	0.278
Unit weight (kN/m³)	26	26	26
Slope height (m)	200	50	10



(a) (b)

Figure 13 RS2 overall slope stability analysis along (a) 10,300 N, zone 2 and (b) 9,300 E, zone 1

Table 9 Summary results for RS2 analysis for both zones

Location	Water conditions	Maximum shear strain	SRF	Displacement (m)	Comments
Zone 1: 10300N	Dry	0.06	3.62	0.12	Whole slope
Zone 1: 10300N	10 m in	0.22	2.92	–	Whole slope
Zone 2: 9300E	Dry	0.12	2.89	–	Whole slope
Zone 2: 9300E	10 m in	0.14	2.68	0.88	Whole slope

3.8 Steepening results

Results from the stability analyses performed above support the steepening of the slopes as shown in Table 10. The implementation of the steepened slopes at Gold Fields Tarkwa mine has also been very successful.

Table 10 Comparison of the initial and steepened design parameters

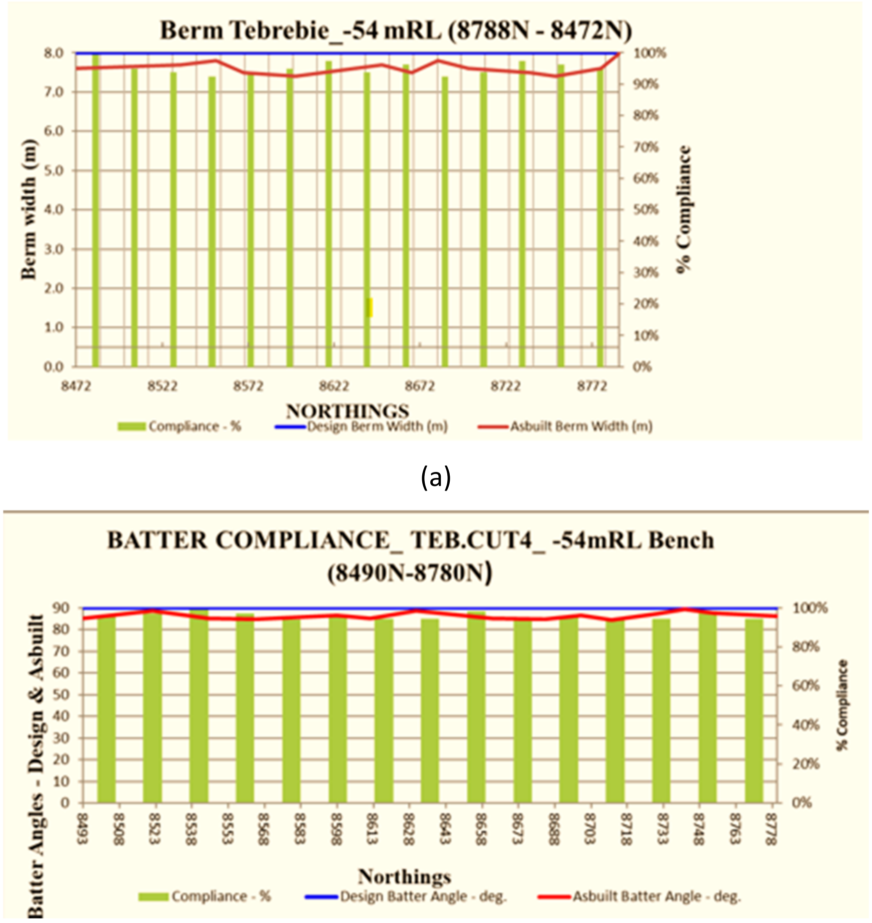
	Initial	After steepening
Bench face angle	75°	90°
Spill berm width	8 m	8 m
Bench height	18 m	18 m
Inter-ramp angle	55°	65°

The following are the benefits of the steepening exercise:

1. The optimised pit designs resulted in increased pit depth and a lower stripping ratio compared to the previous designs.
2. An increase in the mineral reserve of 157 koz.
3. Drilling efficiencies emanating from drilling vertical holes instead of angled holes.

3.9 Performance to date

A review of the performance of the steepened designs indicates that the steepened slope of the Tarkwa mine is performing very well. There are no recorded failures on the pit slopes. Rather, the mine reaped several safety and economic benefits from this steepening exercise. The key performance indicators for the batter and berm reconciliation were also in line with the mine's acceptable limits as shown in Figures 14a and 14b.



(a)

(b)

Figure 14 (a) Example of the good berm reconciliation of the steepened Teberebie pit; (b) Example of the good batter reconciliation of the steepened Teberebie pit

4 Conclusion

Based on the outcomes provided in the wall steepening cases studies above it can be concluded that a thorough and comprehensive understanding of rock mass conditions, geological structure, potential failure modes and hydrogeological conditions are required to undertake a successful wall steepening program.

This knowledge, combined with assurances based on multiple numerical modelling forecasts, are essential to the result.

However, a successful outcome to wall steepening cannot occur without the onsite mining teams ensuring excellent drill and blast standards and controls are in place. These, in combination with excellent wall cleaning practices, are considered fundamental for the mine's safe and economically successful outcome.

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