

Determination of Optimum Slope Design for Northern Boxcut in Zone 5 Khoemacau Copper Mine, Botswana

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Abstract

An optimum design of box cuts in soil formations is very crucial in order to obviate the major risk factors originating from the collapse of sidewalls and flooding of excavations during storm rainfall. The present paper aims to present a holistic classification of the Kalahari Formation stratigraphy in Zone 5 and define engineering properties of each lithological unit, in order to establish a safe working design. For the present objectives, collection of data was carried out through logging core from selected geotechnical boreholes drilled within vicinity of the proposed Northern mine box cut. Hydrogeological assessments and feasibility studies within the purview of study region were also considered. Geotechnical logging parameters gathered on site were derived from the Rock Mass Rating system (RMR) for design requirements [1]. Input parameters and material characteristics taken from laboratory test results provided by KCM were incorporated in the analysis. The box cut slopes were modelled in “Rocscience software” for evaluation of safety factor using “limit equilibrium method”. Slope optimization required the slope surface to be as steep as possible while maintaining an adequate factor of safety ranging from 1.5 - 1.8. For the box cut design with optimum safety, the recommended parameters are: stable slope angle—35° - 40°; ramp angle—8°, depth of pit—60 meters; bench width—4.9 meters and the bench length—13.25 meters.

Keywords

Boxcut Slope, Slope Stability, Finite Element Analysis, Limit Equilibrium Analysis, Rocscience Software

1. Introduction

Khoemacau Copper Mining Company (KCM) is located in the North Western part of Botswana along the Kalahari Copper Belt. It is subdivided into nine prospecting areas which cover a total area of 4041 km² (Figure 1). The Zone 5 area is one of nine mining prospects for KCM situated in the “Ghanzi-Chobe Copper Belt”. Zone 5 ore body dips at about 55° to the east and extends for at-least 4.5 km in strike length, the ore body has been confirmed to extend to almost 1.2 km deep.

This type of ore body geometry requires extraction of the ore in levels going down. Sub level open stoping has been proposed as the preferred mining method for economic, safe and sustainable extraction of the ore body. The Kalahari Formation provides a 30 m thick cover which hampers easy access to the ore body, therefore, box cuts have been proposed from which declines will be developed to access the underground workings. The box cuts will be constructed on Kalahari Formation with the decline entrance located in the zone of the Ngwako Pan Sandstone [2] [3].

The Kalahari Formation is highly weathered and easily collapsible under load or when watered. All this taken into consideration has a potential of causing a major failure to the mine design. Therefore, it is critical to understand the engineering behaviour of the Formation in order to establish slope configurations that ensure mine stability.

2. Stratigraphy

The “Ghanzi-Chobe Copper Belt”, which is part of “Kalahari Copper Belt” is defined by a succession of sedimentary and volcanic rocks deposited in Late Mesoproterozoic and Early Neoproterozoic eras [4]. Deformation and metamorphism on the belt occurred during the Pan African “Damaran Orogeny”. “Kgwebe Formation” forms basal unit of the belt and is overlain by Ghanzi Group (530 Ma - 1020 Ma) which consists of “Ngwako Pan”, “D’Kar” and “Mamuno Formations” [5] (Figure 2).

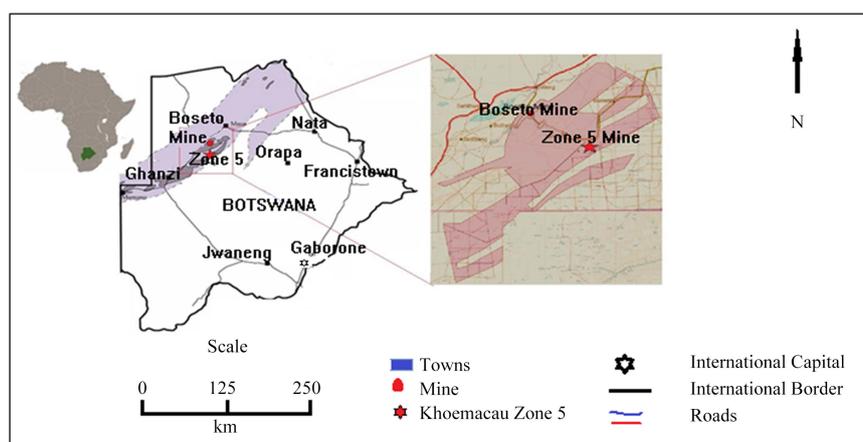


Figure 1. Location Map of Study Area. After Master (2010).

AGE	UNIT		LITHOLOGICAL SECTION	DESCRIPTION
NEOPROTEROZOIC	LATE	~~~Unconformity~~~		
		MAMUNO FORMATION (1500 m)		Oxidized, well sorted red arkosic sandstones, siltstones, shales and limestones. Cross bedding and wave ripples.
		D'KAR FORMATION (1500 - 2500)		Reduced greyish green siltstones, mudstones and sandstones. Parallel laminations and graded beds.
		NGWAKO PAN FORMATION (0 - 3500 m)		Oxidized red arkosic sandstones, siltstones and shales. Parallel and graded laminations and cross- bedding.
	KUKE FORMATION	Conglomerate and pebbly sandstones		
EARLY	~~~~~Unconformity~~~~~			
LATE MESOPROTERZOIC U-Pb Zircon 1108 ± 6 Ma	KGWEBE FORMATION (0 - 2500 m)	Upper Member		Volcanic complex
		Lowe Member		Basalt and Rhyolite flows & tuffs intercalated fluvial to lacustrine arkosic sedimentary rock

Figure 2. Stratigraphy of “Kgwebe Formation” and “Ghanzi Group” After Modie (2000).

2.1. Kgwebe Formation

Basin evolution in the Ghanzi-Chobe Belt occurred in stages that broadly correspond to the major depositional environments of the Kgwebe Formation the “Kgwebe Formation” represents the earliest stage of basin development that was initiated by extensional tectonics, which led to intracontinental rifting and subsequent bimodal volcanism, about 1106 Ma ago. Sedimentation contemporaneous with volcanism resulted in the accumulation of sandstone and tuffitic siltstones of the Kgwebe Formation. “Kgwebe Formation” is 2500 m in thickness forming the unit consisting of Rhyolites, Dacites, Basalts and minor intercalated sedimentary rocks [5].

2.2. Ngwako Pan Formation

“Ngwako Pan Formation” locally known as NPF is approximately 2000 m thick and is underlain by a thin Sandstone with Conglomerate containing clasts from the underlying Kgwebe volcanics. The formation was deposited due to exten-

sional faulting of the intercontinental basin which led to deposition of alluvial to lacustrine sediments.

2.3. D'kar Formation

“D'kar Formation” that conformably overlies “Ngwako Pan Formation” is approximately 1500 m. This Formation consists of reduced fine grained Sandstones, oolitic Limestones and Marlstones. These rocks show parallel laminations and normally graded rhythmites. These are believed to have been deposited due to enlargement of the basin and a major marine transgression [5].

2.4. Mamuno Formation

“Mamuno Formation” lies at the top of the “Ghanzi Group” “Mamuno Formation”, composed of reddish Sandstone, Mudstones, Siltstones and minor Limestone intraclasts. This Formation has not been intersected in Khoemacau Mining license area. According to [3] the Formation is characterized by cross bedding, planar parallel laminations and wave ripple structures suggesting nearshore to shoreline depositional environment.

3. Structural Geology

[6] suggests that there are fold units observed at the bottom of “D'Kar Formation”. These fold units are asymmetrical and have a southeast inclination. Their asymmetry is evidenced by variations in thickness of the northwest and southeast limbs of these folds. These limbs have dips ranging from 45° to 90° and their axial planes strike 220° and 235° and dip between 80° to the northwest and vertical. There is also a weakly developed foliation or cleavage observed in the region most especially in the fine-grained lithology like Marls and Siltstones, but no foliation is discovered in the Sandstones of “Ngwako Pan Formation” [3].

4. Hydrogeology

The Zone 5 site has a mean annual precipitation of 471 mm based on the rainfall information acquired for Maun (2009-2017) which is approximately 40 km north-east of the Project area. Between the years of 2014 and 2015, KCM conducted several hydrogeological assessments and feasibility studies. These studies allowed KCM to design a cost-effective and efficient dewatering system for the mine based on advanced planning of predicted mine inflows. From the studies it was found that the groundwater levels to the west of Zone 5 near the Kgwebe Hills were shallow and ranged between 26 m and 40 m below ground level, indicating a possible recharge zone. Borehole drilling data indicated that NPF Sandstones are poor aquifers and that the main aquifer in the Zone 5 mine area is the “D'Kar Formation”.

5. Methodology

The Northern mine box cut was picked as the focus of this study (Figure 3). The

Geological logging data revealed the lithological units comprise of soil, sand, calcareous sand, sandy Calcrete and Sandstone (Figure 4) Laboratory tests of consolidated undrained triaxial test, direct shear and Uniaxial Compressive Strength with Young's Modulus and Poisson's Ratio were done for all lithological units.

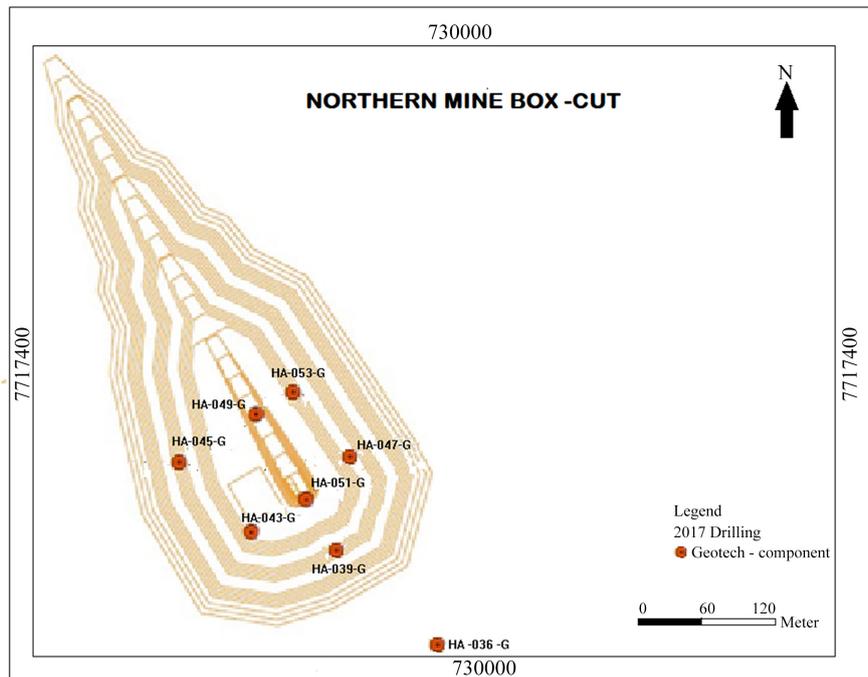


Figure 3. Proposed northern box cut in Zone 5 mine.

LITHOLOGICAL UNIT	LITHOLOGICAL CODE	DESCRIPTION	DEPTH (m)	CORES
SOIL	SOIL	Loose brown unconsolidated sand	0 - 4	
SAND	KAS	Pure sand with little or no fine particles.	4 - 20	
CALCAREOUS SAND	KAS-CLC	Large proportion of sand few calcrete nodules.	20 - 33	
SANDY CALCRETE	CLS-KAS	Large proportion of calcrete to a small amount of sand	33 - 37	
SANDSTONE	SST	Sand sized particles. It forms the local hanging valley	The bore holes logged up to 45 m only	

Figure 4. Stratigraphic units logged.

Modelling Slopes with Rs2 & Slide 2018 Softwares

With consideration to the height and width of the mining equipment and the size excavation the box cut slopes with dimensions provided in **Table 1** were modelled in Slide 2018 software for evaluation of safety factor of slope failure surfaces using limit equilibrium method. The models were imported into RS2 and analysed by Shear Strength Reduction (SSR) method.

Input parameters and material characteristics (**Table 2**) were taken from the laboratory test results provided by KCM. To optimize the slope design, the slope surface was made as steep as possible while maintaining an adequate factor of safety ranging from 1.5 - 1.8 following the acceptance criteria for open pit slopes based on [7] (**Table 3**).

Table 1. Dimensions used to model the slopes in rocscience software.

Parameter	Value
Bench Width	3 m
Bench Height	13.25 m
Ramp angle	8°

Table 2. Input parameters for soil properties and finite element model.

Lithological unit	Unit Weight KN/m ³	Initial Element Loading	Failure Criterion	Material Type	Cohesion (Residual) (kPa)	Friction Angle (residual)	Dilation Angle
SOIL 	20.907	Field stress and body force	Mohr-coulomb	plastic	0.233	37.13°	0°
KAS 	20.165	Field stress and body force	Mohr-coulomb	plastic	11.05	34.35°	0°
KAS/CLC 	19.177	Field stress and body force	Mohr-coulomb	plastic	6.686	32.17°	0°
CLC/KAS	20.410	Field stress and body force	Mohr-coulomb	plastic	7.5	34.25°	0°
SST 	26.066	Field stress and body force	Mohr-coulomb	plastic	11.133	35.25°	0°
BACKFILL MATERIAL 	26	field stress & body force	Mohr-coulomb	Plastic	13	35°	0°

Table 3. Design acceptance criteria for open pit slopes. After wesseloo & read (2009).

Slope scale	Consequences of failure		
	Low	Medium	High
Bench		FoS ≥ 1.1 PoF ≤ 25% - 50%	
Inter-ramp	FoS ≥ 1.15 - 1.2 PoF ≤ 25%	FoS ≥ 1.2 PoF ≤ 20%	FoS ≥ 1.2 - 1.3 PoF ≤ 10%
Overall	FoS ≥ 1.2 - 1.3 PoF ≤ 15% - 20%	FoS ≥ 1.3 PoF ≤ 5% - 10%	FoS ≥ 1.3 - 1.5 PoF ≤ 5%

FoS—Factor of safety; PoF—Probability of failure.

6. Results and Discussion

Two methods were used during slide analysis, Bishop simplified method and Janbu simplified method while SSR method was used during RS2 analysis based on the Mohr Coulomb shear strength criterion. Different values of factor of safety attained for different slopes of the box cut are due to varying lithology.

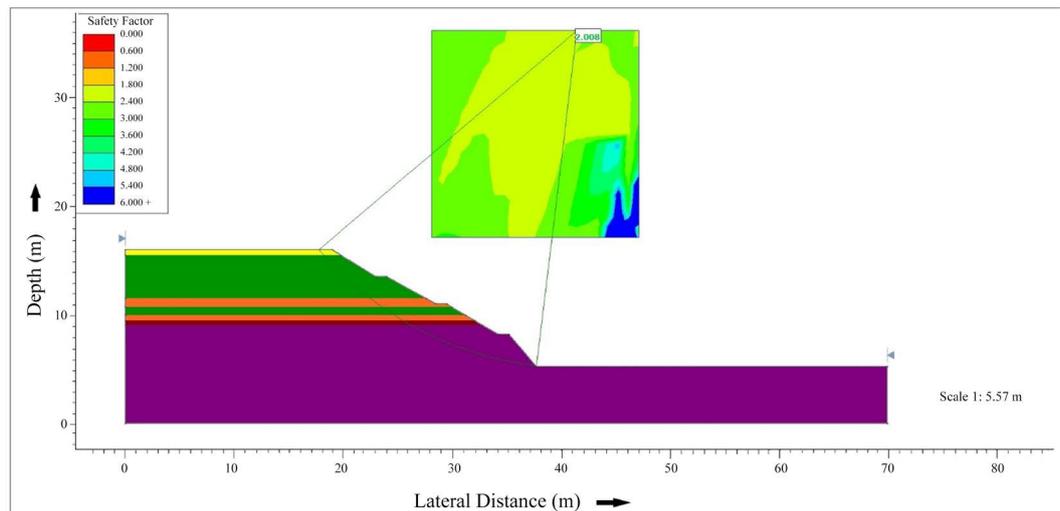
[8] investigated the effects of spatially variable anisotropic soil fabric in a slope on its safety factor and failure mechanisms. [9] investigated the random nature of the geometric interfaces between soil and rock as a two-phase random medium. [10] examined the necessity of three-dimensional analysis when dealing with slope with full randomness in soil properties.

Table 4 shows that factor of safety increased with decreasing slope angles. Slope angles less than 35° gave high factors of safety, greater than 1.8 which implies the slope will be overdesigned and costly. Optimum slope angle was at 35° as the safety factors ranged from 1.5 - 1.8 which are aligned with the acceptance criteria. Although an overall slope angle of 40° gives an acceptable factor of safety, it is not considered optimum since the north east slope produced low factor of safety of about 1.3, which will not be adequate for the life of mine. Typical results from slide and RS2 showing critical SRF and FOS respectively for south West slope are shown in **Figure 5(a)** & **Figure 5(b)**.

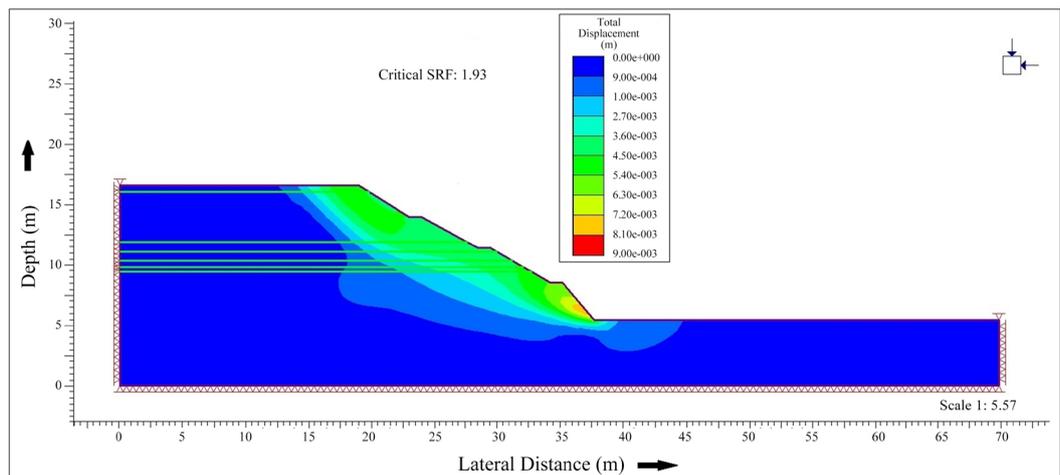
Strength reduction factor also showed sensitivity to change in overall slope angle, the low slope angles of 30° to 35° gave higher SRF of 1.560 to 2.008. The finite element analysis (FE) result was relatively higher than the limit equilibrium (LE) analysis but the deviations between both methods are negligible which validate the locations of failure surfaces.

Table 4. Results from Slide and Rs2.

OVERALL SLOPE ANGLE	ANALYSIS PROGRAM	SOUTH EAST SLOPE	NORTH EAST SLOPE	SOUTH WEST SLOPE
SLIDE: FoS				
30°	Bishop Simplified	2.052	1.964	2.008
	Janbu Simplified	1.952	1.912	1.928
	RS2: SRF	1.910	1.890	1.930
SLIDE: FoS				
35°	Bishop Simplified	1.838	1.647	1.642
	Janbu Simplified	1.723	1.636	1.630
	RS2: SRF	1.650	1.620	1.56
SLIDE: FoS				
40°	Bishop Simplified	1.696	1.363	1.433
	Janbu Simplified	1.574	1.362	1.427
	RS2: SRF	1.430	1.370	1.420



(a)

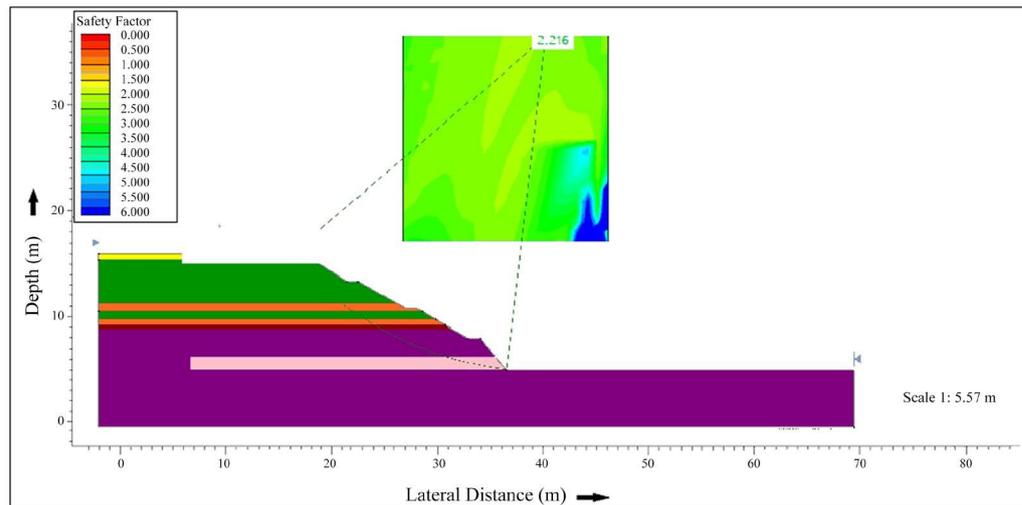


(b)

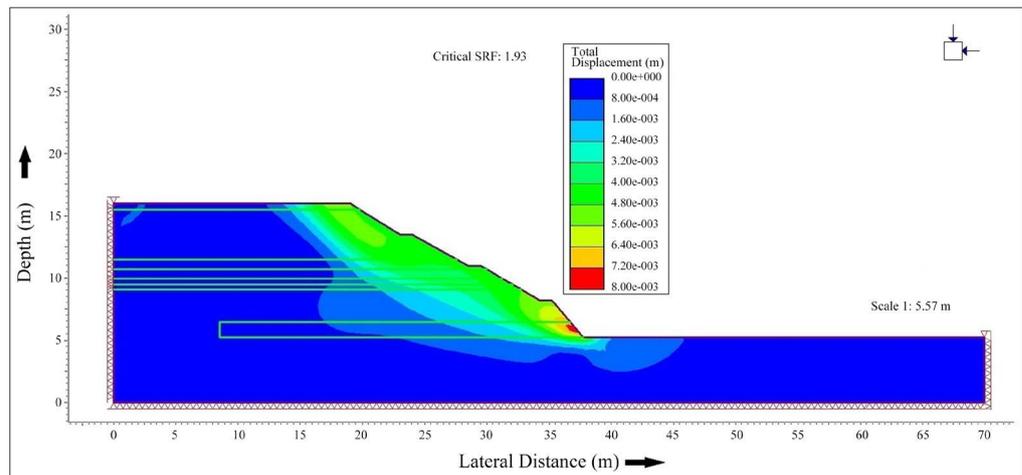
Figure 5. (a) Typical results from slide showing FOS for south west slope. (b) Typical results from Rs2 showing critical SRP for south west slope.

Excavation of the portal affects stability of the overall slope hence it is important to consider this in the design of the slope. A factor of safety of the portals has to be great enough to provide safe access for workers, material and equipment to the underground over a definable mine life. Following excavation of the portal, the overall slope failed hence a backfill material was used to reinforce and stabilize the slope. This backfill material will be in place of a lining to be used to support the portal. Typical results from slide and RS2 showing critical SRP and FOS respectively for south East slope with an excavated portal are illustrated in **Figure 6(a)** & **Figure 6(b)**.

The results in the **Table 5** show that the FoS and SRP of the south east slope were higher due to the addition of a portal that was reinforced with backfill. Without support, the presence of the portal reduces the convergence of the material around the tunnel which reduces the overlying slope's stability.



(a)



(b)

Figure 6. (a) Typical results from slide showing FOS for south east slope with excavated portal. (b) Typical results from Rs2 showing critical SRF for south east slope with excavated portal.

Table 5. Results from slide and Rs2 for the south east slope with a portal.

SLOPE ANGLE	ANALYSIS PROGRAM	
30°	SLIDE: FoS	
	Bishop Simplified	2.235
	Janbu Simplified	2.091
	RS2: SRF	
		2.080
35°	SLIDE: FoS	
	Bishop Simplified	1.976
	Janbu Simplified	1.853
	RS2: SRF	
		1.820
40°	SLIDE: FoS	
	Bishop Simplified	1.761
	Janbu Simplified	1.629
	RS2: SRF	
		1.630

7. Conclusion

Based on the present study, the following conclusions have been drawn:

- Slope angles ranging from 35° - 40° will be optimum slope angles with safety factors ranging from 1.5 - 1.8.
- With the suggested optimum angles, an economic box cut design can be achieved without compromising safety.
- Support and reinforcement of the portal are mandatory to ensure stability.

8. Recommendations

Based on geotechnical analysis of the study area we recommend the box cut design parameters to be as follows;

- Overall slope angle: 35° - 40°.
- Ramp angle: 8°.
- Depth of pit: 60 meters.
- Bench width: 4.9 meters.
- Bench length: 13.25 meters.

To prevent the collapse of side walls we recommend spraying 300 mm thick Shotcrete into wire mesh. The backfill material used for analysis suggests that, a 50 MP concrete lining with a minimum thickness of 250 mm with additional steel reinforcement is recommended for overburden depths of up to 80m to support the portal.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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