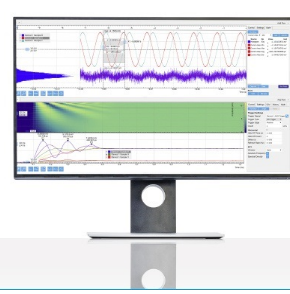
Transforming underground to surface mining operation – A geotechnical perspective from case study

Cite as: AIP Conference Proceedings **2363**, 060006 (2021); https://doi.org/10.1063/5.0061589
Published Online: 23 November 2021

Barlian Dwinagara, Oktarian W. Lusantono, Prasodo D. Prabandaru, et al.



Transforming Underground to Surface Mining Operation – A Geotechnical Perspective from Case Study

Barlian Dwinagara[1, a)], Oktarian W. Lusantono[1, 2, b)], Prasodo D. Prabandaru[2, c)], and Rizky Ardiansyah[3, d)]

[1]*Department of Mining Engineering, UPN "Veteran"Yogyakarta – Jl. Pajajaran (SWK 104), Condongcatur, Sleman, Yogyakarta, 55283, Indonesia*

[2]*PT Studio Mineral Batubara, Mining Consultant – Jl. Gang Mulia VI No 67, Sariharjo, Ngaglik, Sleman, Yogyakarta, 55281, Indonesia*

[3]*PT Cibaliung Sumberdaya – Pandeglang, Banten, Indonesia*

a)Corresponding author: barliandn@upnyk.ac.id
b)oktarian.lusantono@upnyk.ac.id
c)prasodo@mcsindonesia.co.id
d)rizky.ardiansyah@csd.co.id

Abstract. Mining methods selection traditionally determined at the beginning of the feasibility study and non-changeable, along with the life of mine (LOM). The change in mining methods sometimes unavoidable when the criteria are met. One of the criteria is geotechnical aspects. This study was conducted through a case study in PT Cibaliung Sumberdaya. This study investigates geotechnical criteria that should be followed to transform an underground operation to surface operations. Geotechnical analysis conducted through numerical modeling using limit equilibrium and finite element methods. Parameter investigated in this study are Factor of Safety (FoS), Probability of Failure (PoF), stresses, and total displacement. The model and simulation were focusing on the area where there will be an intersection between underground openings and slope for surface mining. The allowed FoS and PoF for safety criteria are 1.05 and <10%, respectively, assuming moderate severity. The total displacement criteria for the safe working condition in the surface mining area is 1.80 m. In conclusion, the transformation of mining methods is feasible from a geotechnical perspective and should be followed with continuous monitoring.

Keywords: *Geotechnical analysis, numerical modeling, open-pit mining*

INTRODUCTION

PT Cibaliung Sumberdaya (PT CSD) is a subsidiary of PT Antam, Tbk that operates in a gold mining sector. PT CSD has conducted operations with an underground mining system using cut and fill methods since 2009. Since the gold price is rocketing throughout the year, PT CSD is eager to optimize its mining methods for better gold recovery. The remaining gold deposits lie within the crown pillar on the Cikoneng Block area. Thus, a transformation from underground (UG) to Open-pit mining is necessary.

The transformation needed to be planned carefully. Geotechnical is one of the top considerations aspects that need to be considered for safety reasons. Several potential failures may occur during the transition, such as slope failure and subsidence [1]. The slope failure may be considered a complex mechanism affecting materials, structural geology, and water presence [2]. Subsidence that may occur in this situation may happen in the mining front due to the equipment load. Hence, a comprehensive geotechnical study is mandatory to address the uncertainty and minimizing potential failure risk. This study will look from a geotechnical perspective through numerical modeling on a certain area in Cikoneng Block.

3rd International Conference on Earth Science, Mineral, and Energy
AIP Conf. Proc. 2363, 060006-1–060006-10; https://doi.org/10.1063/5.0061589
Published by AIP Publishing. 978-0-7354-4154-5/$30.00

Limit equilibrium method (LEM) is a traditional way to obtain Factor of Safety (FoS) for slope stability analysis. However, it has limitations such as (1) historically used in soft-rock materials, (2) critical failure surface usually formed in a circular shape, (3) available for only one failure mechanism such as sliding or circular failure [3]. Numerical modeling has been divided into several approaches based on the assumption of material conditions (continuum and discontinuum). Based on field measurement, rock conditions in PT CSD are considered as slightly weathered – fresh, joint strength similar to intact rock, and joint persistence is short and discontinuous. Therefore, the continuum model is preferred in the analysis. The finite element method (FEM) is one of the approaches for the continuum materials model [4]. The analysis looking for slope stability in terms of FoS and probability of failure (PoF) and stress implication at certain points on underground opening (stope and cross-cut). The simulation of underground opening conditions was conducted based on the availability of filling materials.

FACTOR OF SAFETY AND PROBABILITY OF FAILURE

The shear strength reduction (SSR) method is a calculation method that is commonly used for FoS calculation in FEM model. SSR is defined as the ratio of actual shear strength to the minimum shear strength required to avoid failure [5, 6, 7]. The SSR approach looks for the strength reduction factor (SRF), which makes the slope fail. Shear strength was reduced by factor of safety (FoS) through an iteration trial calculation adjusting cohesion (C') and friction angle (φ'). Using Mohr-Coulomb approaches, the process of adjustment is shown in equation (1) and (2).

$$C' = \frac{C}{SRF} \quad (1)$$

$$\varphi' = tan^{-1}\frac{\tan\varphi}{SRF} \quad (2)$$

Where SRF is Strength Reduction Factor, φ is the original friction angle (in degree), C is the original cohesion. To find the exact Factor of Safety (FoS), it is necessary to initiate a systematic search for the SRF value that will just cause the slope failure. FoS is determined as the corresponding SRF value; therefore FoS is equal with SRF.

Since the FEM model can express major and minor stress ($\sigma1$ and $\sigma3$), respectively, the calculation FoS for underground opening could be expressed using the Mohr-Coulomb equation. The equation for Mohr-Coulomb safety factor is defined in the equation 3.

$$\frac{\sigma1-\sigma3}{2} = \frac{(\sigma1+\sigma3)}{2}\sin\varphi + C\cos\varphi \quad (3)$$

Probability of Failure (PoF) is calculated from a deterministic model. The deterministic model has input parameters such as cohesion and friction angle that are considered a random variable with probabilistic distribution type [8]. Novel explanation about PoF is expressed in the graph (**FIGURE 1**). Based on the graph, PoF is illustrated as the ratio between the area with FoS < 1 divided with the total area in the probabilistic curve [9]. A random variable has a limited range to ensure the FEM model has enough random variable Monte-Carlo simulation. Monte-Carlo Simulation is a simulation process to make random numbers under certain distribution types multiplied with each random variable [10].

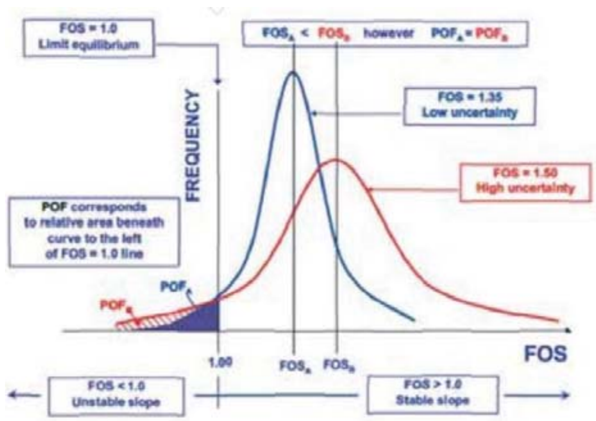


FIGURE 1. PoF curve

NUMERICAL MODELING

Numerical modelling in this study conducted using FEM approach through Rocscience^{TM} RS2 program. The input parameter of this study consists of rock mass classification, material properties, ground water condition and discontinuity. The rock mass classification used in PT CSD is adopting Rock Mass Rating (RMR) system [11]. Generally, rock type in Cikoneng Block is divided into four types of lithology: andesite, breccia, porphyry, and vein. Each rock type has been classified through RMR system. Rock mass class II is a material group with a range of RMR values from 60 - 80 with the Good category, rock mass class III with a value range of RMR 40 - 60 with the Fair category, and the Poor category, which is the rock mass class IV with a value of RMR 20 - 40.

The material properties are obtained through laboratory testing and calculation. A combination of Hoek-Brown Failure criterion [12] and Mohr-Coulomb was used in this study. The Mohr-Coulomb criterion was used to comply with Monte-Carlo simulation for probabilistic analysis in RS2. The material used as input parameters in the model is shown in **Table 1.**

TABLE 1. Material Properties

Material Types	Parameter	Units	Statistical Parameters			
			Mean Values	Standard Deviation	Relative Minimum	Relative Maximum
Soil	Unit Weight	(MN/m^3)	0.02	0.00	0.00	0.00
	Young's Modulus	(MPa)	118.29	58.32	67.39	110.99
	Cohesion	(MPa)	0.03	0.01	0.01	0.01
	Friction Angle	(˚)	30.76	8.74	14.02	17.05
Andesite Class II	Unit Weight	(MN/m^3)	0.03	-	-	-
	Young's Modulus	(MPa)	2777.98	2589.28	2657.98	5052.02
	Cohesion	(MPa)	0.81	0.35	0.39	0.65
	Friction Angle	(˚)	53.84	4.16	6.97	5.74
Andesite Class III	Unit Weight	(MN/m^3)	0.03	-	-	-
	Young's Modulus	(MPa)	916.48	850.64	873.71	1688.48
	Cohesion	(MPa)	0.36	0.11	0.14	0.18
	Friction Angle	(˚)	43.13	5.44	8.54	7.79
Andesite Class IV	Unit Weight	(MN/m^3)	0.03	-	-	-
	Young's Modulus	(MPa)	421.20	335.24	393.39	531.04
	Cohesion	(MPa)	0.17	0.07	0.09	0.11
	Friction Angle	(˚)	29.04	7.04	10.02	9.77
Breccia Class II	Unit Weight	(MN/m^3)	0.03	0.00	0.00	0.00
	Young's Modulus	(MPa)	5278.40	5552.42	5184.31	12897.20
	Cohesion	(MPa)	0.74	0.36	0.44	0.88
	Friction Angle	(˚)	50.21	4.80	10.81	7.28
Breccia Class III	Unit Weight	(MN/m^3)	0.03	0.00	0.00	0.00

Material Types	Parameter	Units	Statistical Parameters			
			Mean Values	Standard Deviation	Relative Minimum	Relative Maximum
	Young's Modulus	(MPa)	1740.32	1825.97	1706.79	4306.50
	Cohesion	(MPa)	0.31	0.10	0.16	0.22
	Friction Angle	(˚)	39.23	6.00	12.59	9.76
Breccia Class IV	Unit Weight	(MN/m^3)	0.03	0.00	0.00	0.00
	Young's Modulus	(MPa)	800.32	738.28	778.51	1410.09
	Cohesion	(MPa)	0.14	0.06	0.09	0.11
	Friction Angle	(˚)	25.52	6.84	11.62	11.27
Porphyritic Class II	Unit Weight	(MN/m^3)	0.03	-	-	-
	Young's Modulus	(MPa)	9535.47	6899.49	7177.04	14687.93
	Cohesion	(MPa)	0.34	0.10	0.13	0.19
	Friction Angle	(˚)	42.20	4.89	8.43	7.34
Porphyritic Class III	Unit Weight	(MN/m^3)	0.03	-	-	-
	Young's Modulus	(MPa)	3120.16	2484.29	2448.18	5590.92
	Cohesion	(MPa)	0.20	0.05	0.08	0.09
	Friction Angle	(˚)	33.27	5.11	8.32	7.96
Porphyritic Class IV	Unit Weight	(MN/m^3)	0.03	-	-	-
	Young's Modulus	(MPa)	1135.08	736.33	772.70	1508.06
	Cohesion	(MPa)	0.11	0.04	0.06	0.07
	Friction Angle	(˚)	23.65	5.17	7.99	8.18
Vein Class II	Unit Weight	(MN/m^3)	0.02	0.00	0.00	0.00
	Young's Modulus	(MPa)	5341.79	4773.27	4319.99	12488.51
	Cohesion	(MPa)	0.53	0.32	0.37	0.77
	Friction Angle	(˚)	45.17	8.31	17.20	11.50
Vein Class III	Unit Weight	(MN/m^3)	0.02	0.00	0.00	0.00
	Young's Modulus	(MPa)	1762.29	1568.04	1398.14	4169.65
	Cohesion	(MPa)	0.24	0.11	0.16	0.23
	Friction Angle	(˚)	34.05	8.69	16.43	13.54
Vein Class IV	Unit Weight	(MN/m^3)	0.02	0.00	0.00	0.00
	Young's Modulus	(MPa)	809.93	616.44	573.08	1358.48
	Cohesion	(MPa)	0.11	0.06	0.08	0.12
	Friction Angle	(˚)	21.49	7.87	12.98	13.77

Open pit mining will commence in nearly October 2020 through multiple stages. Stage 1and 2 were excavated from elevation 1180 – 1160 mRL. Stage 3 was excavated from elevation of 1160 to 1150 mRL. The final stage (stage 4 and 5) excavated until elevation of 1145 mRL. Single bench of excavation is 6 m with single slope of 65°. The material domain used in this study displayed in **FIGURE 2**.

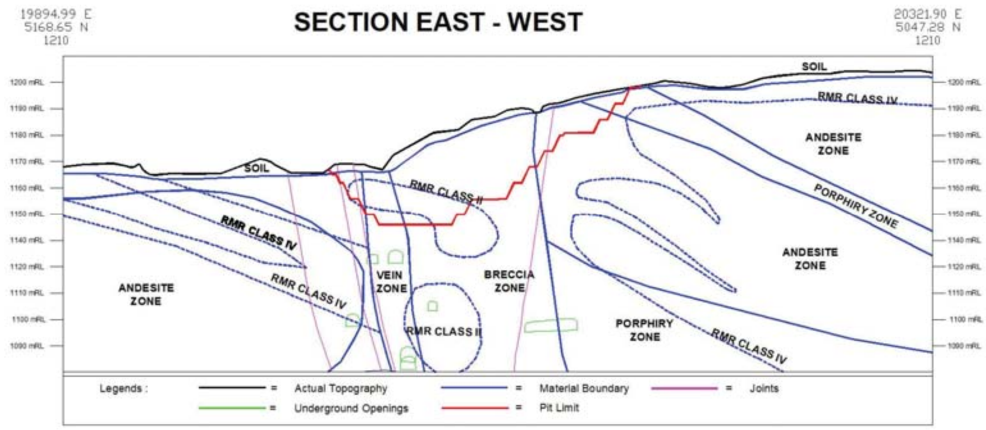


FIGURE 2. Material domain

External factors such as seismic load and equipment load are also considered in this analysis. The seismic load will act as vibration factors in the slope stability analysis. Hence, the analysis is considered a pseudo-static analysis. The seismic load was adapted from Peak Ground Acceleration (PGA) or Sn in the bedrock for specific time-periods with a value of 0.3g. (**FIGURE 3**). The equipment load is equivalent to static load. This load was calculated from mining equipment with a ground pressure of 5.07 MPa in the mining front. The ramp's static load was calculated from mining trucks ground pressure with a value of 0.8 MPa.

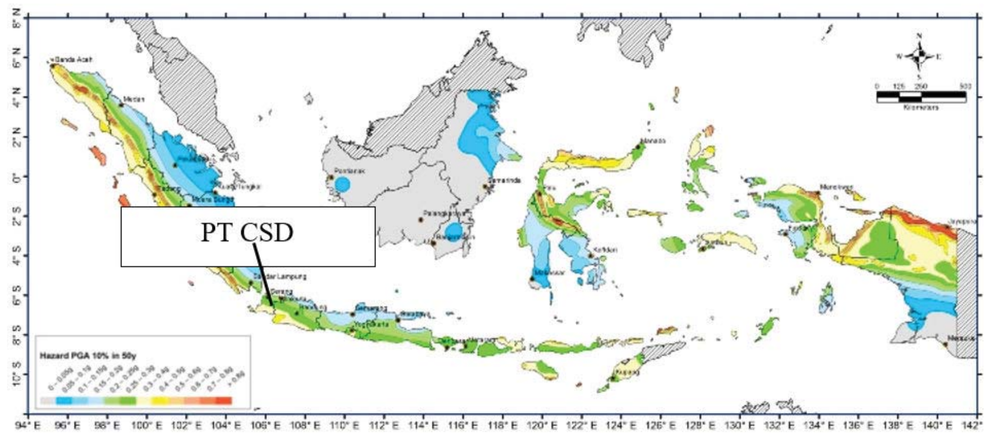


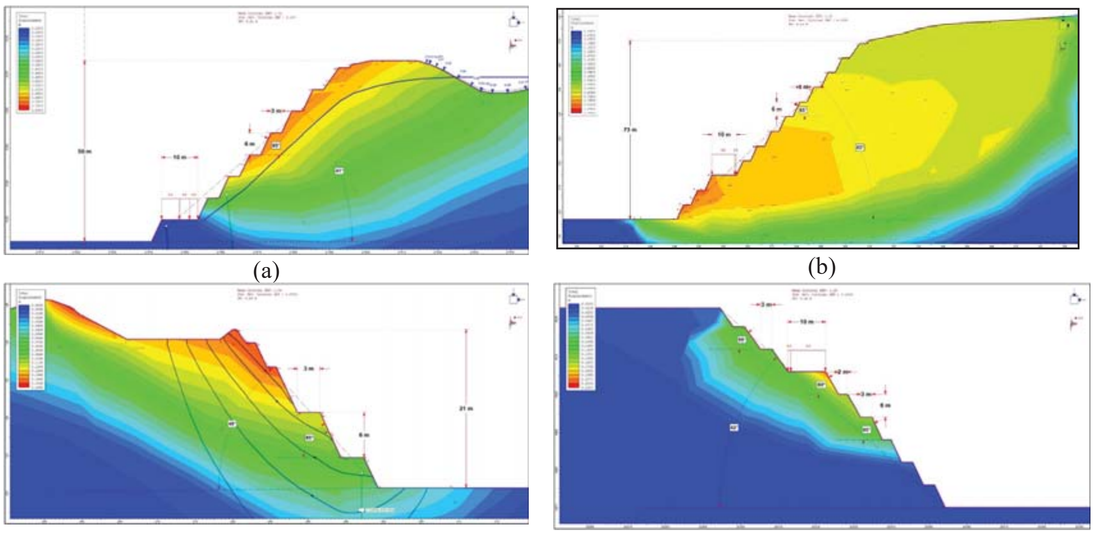
FIGURE 3. Map of Peak Acceleration in Base Rocks 10% Probability in 50 Years

Groundwater condition in the overall slope is assumed to be a half-saturated slope. Slope stability analysis has been done in four locations, namely North Slope, East Slope, West Slope, and South Slope. The safety criteria used in this analysis is FoS ≥ 1.05 and PoF ≤ 10% with moderate severity. Meanwhile, underground opening safety criteria are FoS ≥ 1.5 for cross-cut (XCut) and FoS ≥ 2.0 for decline access (ACC). Observation point in underground opening is taken in the roof, walls, and floor with eight observation points. The underground opening has standard support of rock bolt, 10cm liner, and hard-beam (in the decline access).

RESULT AND DISCUSSION

The results of the analysis are divided into two parts; slopes stability analysis and underground stability analysis. The slope stability analysis has been done through its safety criterion (FoS and PoF). Meanwhile, underground stability analysis is looking at FoS through the Mohr-Coulomb equation (Equation 3).

The results of slope stability shown in **FIGURE 4** and **TABLE 2**. Based on the result, overall slope height between 21 – 73 meters and overall slope angle between 41° - 49° were met with the safety criterion. This result also has shown a potential indication of weak zone materials through total displacement contours. Cikoneng slope stability is within the safety criterion threshold, and no indication of underground openings near the surface (slope face). An underground opening has the potential to reduce the level of stability.



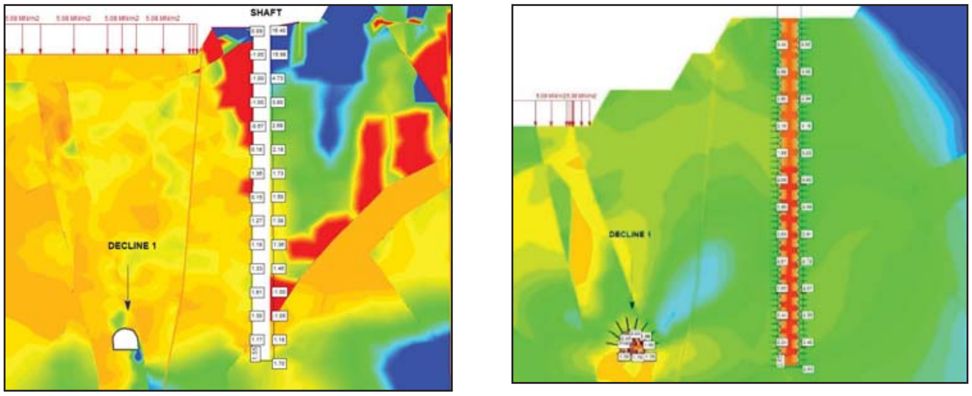
(a) (b) (c) (d)

FIGURE 4. Interpretation Result of North Slope (a) East Slope (b) West Slope (c) And South Slope (d)

TABLE 2. FoS and PoF on Cikoneng Slope

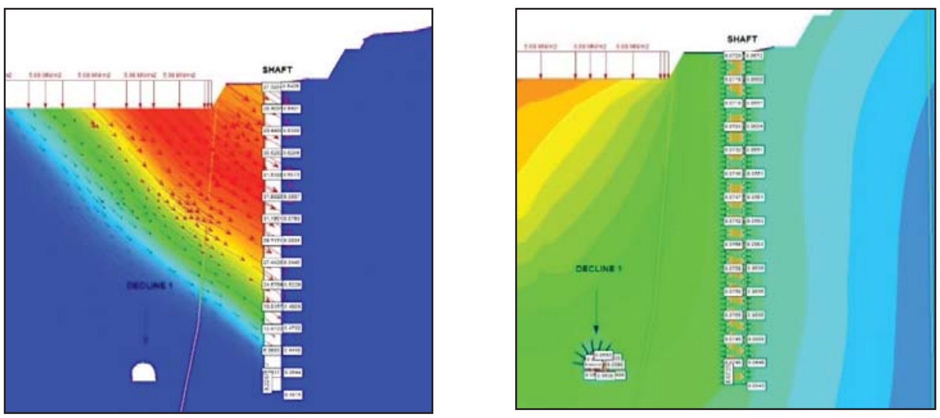
Location of Slopes	Overall Slope Height (m)	Berm Width (m)	Overall Slopes Angle (◦)	Factor of Safety	Probability of Failure (%)	Safety Criteria
North	50	3	41	1,31	5,51	Safe
East	73	3	43	1,21	6,18	Safe
West	21	3	49	1,84	0,09	Safe
South	53	3	42	1,25	9,96	Safe

In the South slope, there is a ventilation shaft that exists in the area. Thus, the analysis near the shaft is necessary to identify the correct treatment for the slope and shaft. The shaft was connected to the ramp in the surface area. The strength factor and total displacement contours are used for analysis (**FIGURE 5** and **FIGURE 6**). The simulation is carried out by providing filling material along with the shaft's opening for each mining sequence. Based on the strength factor value interpretation, a significant contour change between the conditions before and after the filling. The strength factor contour, which was originally dominated by values in the range of 0.98 to 1.70 (orange to yellow), changed to 2.50 to 3.00 (green color).



(a) (b)

FIGURE 5. Interpretation of Strength Factor on Shaft in South Slope (a) Before Filling (b) Filled Condition



(a) (b)

FIGURE 6. Interpretation of Total Displacement on Shaft in South Slope (a) Before Filling (b) Filled Condition

Based on the simulation before filling and filling the condition, the strength factor (SF) value has increased significantly in the filled condition. The shaft condition on before filling dominated with SF < 2. The SF numbers along the shaft were observed through query data (**FIGURE 7**). An indication of the excess load from equipment in the mining front might affect the result. SF parameters validated using total displacement (TD) contours. The contours are improved significantly after filling in the shaft.

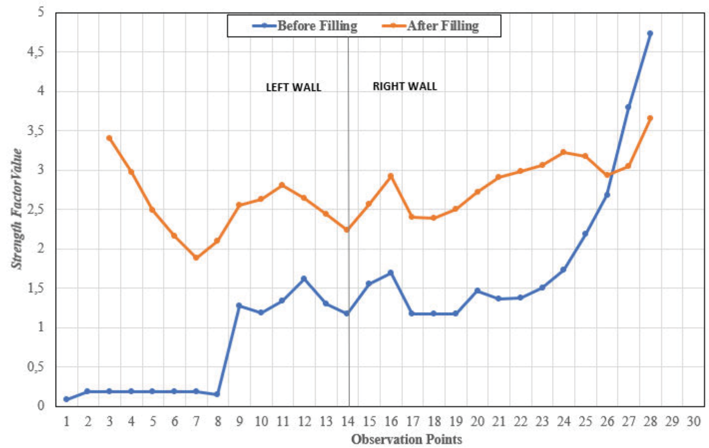


FIGURE 7. Graph of Strength Factor Value in The Shaft Wall

Mining front is the most critical location where underground opening and surface mining working areas met. The mining front analysis has been done by looking through monthly stages of surface excavation against underground opening stability criterion. The simulation modeled through filling sequences in the decline access (CKN_XC2_ACC) and stope (CKN_XC2). Location of the decline access and stope shown in **FIGURE 8**.

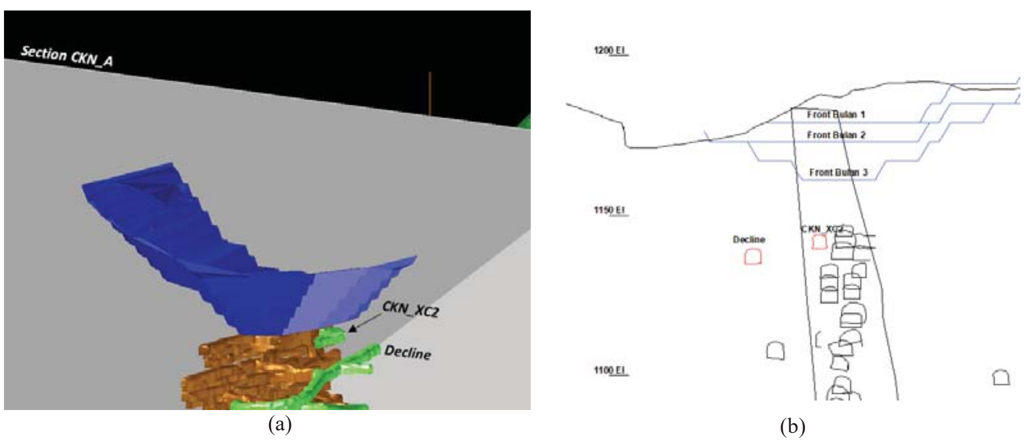


FIGURE 8. The Underground Condition as (A) 3d View (B) Section View

The analysis results presented in the interpretation of the major and minor stresses (σ1 and σ3, respectively). The opening's stability was analyzed for mining sequences 1, 2, and 3 months for the simulation conditions without filling and filling in the underground opening. The safety factor values for the CKN_XC2 and decline locations can be seen at **Table 3** and **Table 4.**

TABLE 3. Factor of Safety Value in Each Condition for Decline Access

Location	FoS Before Filling			FoS After Filling		
	Month 1	Month 2	Month 3	Month 1	Month 2	Month 3
Lower Left Wall	1.01	1.01	1.01	1.02	1.01	1.03
Middle Left Wall	1.06	1.07	1.06	1.13	1.05	1.07
Upper Left Wall	1.74	1.49	1.74	1.57	1.56	1.71
Roof	3.17	2.78	3.17	3.73	3.73	3.97
Upper Right Wall	1.34	1.40	1.34	1.48	1.45	1.37
Middle Right Wall	0.99	1.01	0.99	1.06	1.06	1.09

Location	FoS Before Filling			FoS After Filling		
	Month 1	Month 2	Month 3	Month 1	Month 2	Month 3
Lower Right Wall	1.00	1.00	1.00	1.01	1.02	1.02
Floor	1.11	1.09	1.11	1.03	1.01	1.05

TABLE 4. FoS Value in Each Condition for Stope

Location	FoS Before Filling			FoS After Filling		
	Month 1	Month 2	Month 3	Month 1	Month 2	Month 3
Lower Left Wall	1.01	1.01	1.01	1.02	1.01	1.03
Middle Left Wall	1.06	1.07	1.06	1.13	1.05	1.07
Upper Left Wall	1.74	1.49	1.74	1.57	1.56	1.71
Roof	3.17	2.78	3.17	3.73	3.73	3.97
Upper Right Wall	1.34	1.40	1.34	1.48	1.45	1.37
Middle Right Wall	0.99	1.01	0.99	1.06	1.06	1.09
Lower Right Wall	1.00	1.00	1.00	1.01	1.02	1.02
Floor	1.11	1.09	1.11	1.03	1.01	1.05

Filling condition has shown to improved FoS in the decline access and stope. The filling has been shown as stabilization methods to minimize subsidence from underground openings. Subsidence is likely to happen from the roof then wall and followed by floor collapse. Based on the analysis, the closer mining front to the underground openings is linear with potential instability in the underground.

CONCLUSIONS

Based on the analysis, several things are highlighted for the transformation of underground mining to open-pit mining as follows:

a. Underground openings should be identified in the first place. Underground openings may increase the instability of slope.
b. The current slope for open-pit mining is within the safety criterion of FoS and PoF. Mine drainage is mandatory action to maintain its stability in Cikoneng Block.
c. Potential subsidence might occur in the surface near the underground opening, such as decline access, shaft, and stope. The filling is mandatory to improve stability in the underground and reduce potential subsidence risk on the surface.
d. Mining methods transformation is feasible from a geotechnical perspective and must be followed with a strict stabilization protocol and continuous monitoring.

ACKNOWLEDGEMENTS

This study was directed by PT Studio Mineral Batubara and Mining Engineering Department UPN “Veteran” Yogyakarta. We would thank PT Cibaliung Sumberdaya, especially the board of directors and the team in the quality control department for research supports.

REFERENCES

[1] J. Read and P. Stacey, "Guidelines for Open Pit Slope Design", CSIRO Publishing, 2009.

[2] D. C. Wyllie and C. W. Mah, "Rock Slope Engineering: Civil and Mining", 4th ed., New York: Taylor & Francis, 2007.

[3] K. Khabbaz, B. Fatahi and C. Nucifora, "Finite Element Methods againts Limit Equilibrium Approaches for Slope Stability Analysis," in *11th Australia - New Zealand Conference on Geomechanics - Ground Engineering in a Changing World*, 2012.

[4] D. V. Griffiths and P. A. Lane, "Slope stability analysis by finite elements," *Geotechnique,* vol. 49, pp. 387-403, 1999.

[5] C. Matthews, Z. Farook and P. Helm, "Slope stability analysis - limit equilibrium or the finite element method?," 2014.

[6] G. You, M. A. Mandalawi, A. Soliman, K. Dowling and P. Dahlhaus, "Finite Element Analysis of Rock Slop Stability Using Shear Strength Reduction Method," *Soil testing, Soil Stability and Ground Improvement,* 2017.

[7] E. M. Dawson, W. H. Roth and A. Drescher, "Slope Stability Analysis by Strength Reduction," *Geotechnique,* vol. 49, pp. 835-840, 1999.

[8] I. Arif, "Geoteknik Tambang", Jakarta: PT Gramedia Pustaka Utama, 2017.

[9] O. K. Steffen, L. F. Contreras, P. J. Terbrugge and J. Venter, "A risk evluation approach for pit slope design," in *The 42nd US Rock Mechanics Symposium and 2nd US-Canada Rock Mechanics Symposium*, San Fransisco, 2008.

[10] Missouri University of Science and Technology, "Monte-Carlo Simulation," in *Probabilistic Engineering Design*, Missouri University Press, 2011, pp. 1-16.

[11] Z. T. Bienawski, "Engineering Rock Mass Classifications: A Complete Manual for Engineers and Geologists in Mining, Civil, and Petroleum Engineering", New York: John Wiley & Sons, 1989.

[12] E. Hoek and E. T. Brown, "The Hoek-Brown failure criterion and GSI - 2018 edition," *Journal of Rock Mechanics and Geotechnical Engineering,* pp. 1-19, 2018.