Development of a Strategy Around the Placement and Design of Temporary Bridges Spanning Mining Scars on an Opencast Strip Mine in South Africa Using Sound Rock/Soil Mechanics Practices

Yogendran Arunachellan(✉)

Seriti Resources, Cnr. Chaplin & Oxford Road, 15, Johannesburg 2196, South Africa
yogendran.arunachellan@seritiza.com

Abstract. The pursuit of operational targets such as tonnage and grade can often outpace the rehabilitation rate. This tends to leave large areas of mined-out strips (also known as scars) that must be traversed to ensure the hauling distance is shortened. Therefore, the resource must be efficiently extracted without disregarding sound safety principles. A geotechnical strategy was developed and implemented to mitigate this risk at an opencast strip mine in South Africa. The protocol involved a visual observation checklist, safe declaration and inspection during operations, numerical modelling in the forms of limit equilibrium, finite element, settlement analysis and an inspection sheet for the rock engineering report for the construction of a temporary bridge.

The bridge constructed in the mentioned case study will need to support surface infrastructure such as temporary powerlines and will serve as a dual carriageway for haul trucks and a walkway for the dragline. Geotechnical challenges that had to be overcome included underground workings, spontaneous combustion, tension cracks along the high wall and pore water pressures at the base. The ramp parameters (dimensions) were established by mine planning, with various slope angles, safety berm distances, and water pressures simulated using limit equilibrium modelling (L.E.M), finite element modelling (F.E.M) and Settle3 programs. The finalized design was determined by looking at the factor of safety, probability of failure, the position of the safety berm, the amount of soft and hard waste material available and the establishment time. The proposed design was accepted at a 37° slope angle with safety berms placed 18 m from the crests of the bridge, and this would require a minimum of ~531 000 m^3 of material.

The bridge was monitored throughout the construction process by regular inspections and using a monitoring and surveying radar. In conclusion, the temporary bridge enabled the mine to continue fast and safe production. The models were successfully used to construct a bridge that was used for medium-term transportation in an opencast mine.

Keywords: Mining · Opencast · Limit Equilibrium · Finite Element · Trigger action response plan

R. E. Hammah et al. (Eds.): RIC 2023, AHE 19, pp. 467–477, 2023.
https://doi.org/10.2991/978-94-6463-258-3_46

1 Setting and Geology

Mine A was established in 1983 to supply ~15 Mtpa of low-grade bituminous coal for power generation [1]. The colliery is in Viljoensdrif in the province of the Free State, and it exploits the N.E. section of the Vereeniging-Sasolburg Coalfield. The general stratigraphy and lithology of the mine can be seen in Fig. 1. The major geological discontinuities (faults and dykes) strike from E-W across the operation with dip angles ranging from 45–80° [2]. Historically the Top, Middle and Bottom seams have been mined using bord and pillar techniques. The opencast extraction is done via the strip-mining method, which involves the advancement of open pits or strips.

This paper will primarily focus on the development of an industry-wide, fit-for-purpose strategy to span across mining scars; the following objectives will need to be achieved:

- To develop a risk assessment and procedure for the operational personnel
- To develop a modelling methodology for the stability of a bridge design
- Implementation of inspection criteria for the operational personnel

The restrictions which have governed the project will be mainly operational factors such as the following:

- The volume of material that is available
- The availability of operational equipment, such as dozers and trucks
- Time and distance studies from the loading to the tipping site

1.1 Slope Stability at Mine A

Statistically, circular failures have been identified as the most common failure mode at Mine A (Fig. 2); they tend to range in size from 1900 to 150 000 m3.

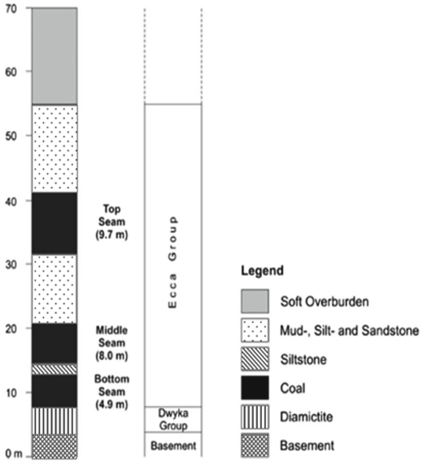


Fig. 1. Stratigraphic column of Mine A

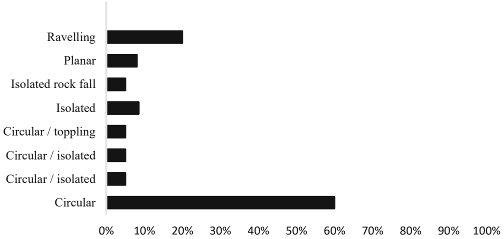


Fig. 2. Slope failure database, showing the modes of failure for Mine A from the past five years

Table 1. Rock mechanic design acceptance criterion used at Seriti Resources

Slopes	Acceptable FoS	Acceptable PoS (%)
Low walls	1.2	90
Advancing end walls	1.2	90
Dumps	1.2	90
High walls	1.2	90
Box cuts	1.2	90
Note: Shallow pits (≤50 m overall depth) with a short to medium strip lifespan (≤6 months).		

1.2 Acceptance Criteria Implemented at Seriti Resources

The processes and criteria that guide numerical modeling at Mine A will be covered below, emphasizing the factor of safety (FoS) and the probability of failure (PoF).

The guidelines that govern geotechnical designs, along with their acceptable FoS and tolerable PoF in Seriti Resources, are the in-house Global Technical Guideline 17 (GTG 17) and Operational Management System (O.M.S.) documents. The criteria are summarized in Table 1 and are derived and modified from research on probabilistic stability analysis of variable rock slopes [3].

2 Methodology

The methodology implemented below tracks closely with the rock mechanics design process [4, 5].

2.1 Material Properties

Mine A has a geotechnical properties database consisting of more than 12 years of data conducted on the various rock and soil types. The pore water pressure of the soft overburden is represented as the Ru ratio and ranges from 0.05 (drained disturbed material) to 0.25 (saturated material) [6] (Table 2).

Table 2. Geotechnical properties of the building materials to be used in the numerical modelling

Material type	Properties	Mean	Standard deviation	Ru
Base/ Tillite	Unit weight (kg/m^3)	2.45	Not available	0,00–0,25
	Cohesion (kPa)	78.00	19.50	
	Friction angle (°)	34.00	3.40	
	Poisson ratio	0.2	Not available	
	Young modulus (GPa)	12		
Primary material/ Fluvial sand	Unit weight (kg/m^3)	1.67	Not available	0,00–0,25
	Cohesion (kPa)	25.00	12.50	
	Friction angle (°)	31.50	3.20	
	mv (m^2/kN)	0.00075	Not available	
	Es (kPa)	62500		
	Esur (kPa)	10000		
	Poisson ratio	0.25		
	Young modulus (GPa)	0.8		
Note: Normal statistical distribution applied to the relevant material properties				

2.2 Numerical Modelling

The primary approach used was L.E.M utilizing SLIDE3, which predicts the FoS and the PoF for circular failures of the various design configurations. Mohr-Coulomb principles to determine the shear strength along a sliding surface. The Spencer method was used for a circular shear surface, and the method has the following characteristics according to [7] and [8]:

The secondary approach was to determine the displacements, if any, were to occur at the slope crest. F.E.M would be considered in the form of RS2 [9] for the design simulations. Further assessment was carried out to determine the bridge's stability when operational equipment utilizes it with the use of SETTLE3[10]. The input of rock mass properties into the modeling program allows a statistical distribution to be applied. This distribution will account for the heterogeneity in the rock mass.

2.3 Operational Risk Assessment (O.R.A) and Operational System Audits [11]

One of the most important aspects to consider was the buy-in needed from the operational personnel for a successful project. The first stage of involvement was the operational risk assessment. Apart from the mandatory information required, the critical risk assessment included the following:

- The experiences of the operational personnel account for potential oversight from the technical team

- Historical slope failure database was consulted to identify the most common slope failures, their contributing factors and root causes to ensure that there is no repeated failure
- Tied with the failure database mentioned above are the learning from an incident (L.F.I) investigations conducted by the safety departments on the operation,
- The current paperwork, such as the standard operating procedures (S.O.P), had to be evaluated to ascertain how the risks are mitigated
- The annual rainfall trends for the operation

3 Results

3.1 Key Outputs from the O.R.A

The following loopholes were identified and will be addressed with the revision of the S.O.P:

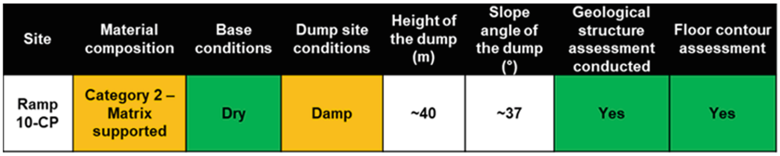
- The regular assessment of the dump behavior is upheld but is operator dependent and is not documented. This should be documented in a formalized risk assessment and filed for future reference
- There was no logbook to document the cracks developing on the pad with a sketch indicating where the cracks developed
- There was no evidence that during shift changeover, there was positive communication between the outgoing and oncoming teams

3.2 Development of Dumping and Dozing T.A.R.P

A trigger action response plan (T.A.R.P) for mining hazards is a set of procedures and protocols that are put in place to identify potential hazards and to respond quickly and effectively in the event of an emergency [12]. The T.A.R.P. should include specific triggers that will initiate the response plan, such as the detection of a gas leak or a seismic event. Once a trigger is activated, the plan should outline the specific actions that should be taken by mine personnel, including evacuation procedures, communication protocols, and emergency response procedures.

The TARP should also include procedures for monitoring the situation and assessing the effectiveness of the response, and returning to normal operations once the emergency has been resolved [13]. Three trigger levels were identified: a green trigger indicating a conventional operational environment, a yellow trigger indicating moderate risk, and a red trigger indicating a high risk.

The revised inspection reports combined aspects such as the material matrix type [14] and the direction of water flow based on the floor gradient amongst different sites' saturation levels. The triggers would inform the on-site geotechnical personnel to either modify the simulation parameters for the proposed design or to ensure the medium to high-risk triggers are sufficiently mitigated as seen in Fig. 3.



Site	Material composition	Base conditions	Dump site conditions	Height of the dump (m)	Slope angle of the dump (°)	Geological structure assessment conducted	Floor contour assessment
Ramp 10-CP	Category 2 – Matrix supported	Dry	Damp	~40	~37	Yes	Yes

Fig. 3. Caption taken from the geotechnical field inspection sheet as a T.A.R.P

3.3 Improvements Made to the Standard Operating Procedures.

The following changes and additions to the procedure were initiated after the audit; the following improvements allowed for a safer operation:

- The dozer operators, inclusive of the foremen, are to inspect the tipping pad prior to the shift commencement and complete a checklist which should be signed off by the mine overseer and safety officer
- The dozing operations should be conducted such that the load ahead of the blade does not exceed the height of the mentioned blade, thus affording the operator the opportunity to clearly see any changes or drop in the height of the pad floor or crack initiation
- Dozing operations should not be allowed to go beyond the identified opened crack
- Regular inspections should be conducted during dozing operations to facilitate the timely identification of any abnormalities or further movement during dump development
- Demarcation cones should be placed along the dump area 10 m away from the crest; these should act as markers to indicate the truck dumping limit
- If there are any abnormalities such as toe bulging, fines hanging up the crest, excessive fines in the dumped material, or water build up on the dump pad, it should be reported as per the mine reporting procedure inclusive of all stakeholders concerned
- The lighting plant should be used to enhance visibility when visibility is deemed insufficient, especially where dump development operations are to be conducted during dark hours, as seen in Fig. 4
- Work activities should be stopped during misty and rainy conditions
- Cracks developing on the dump crest should be plotted in the logbook, and such position should guide the limit of dozer & truck encroachment to the dump crest

As important as the above procedural information is, communication of them is more vital, and the geotechnical and operational departments need to ensure all dozer and truck operators are briefed on the agreed-upon safe dumping controls.

3.4 Behaviour of the *In-Situ* Sand (Primary Building Material)

The number of measurements amounted to 88, which provided the opportunity to do statistical analysis for obtaining many parameters. The only two of interest for this study is the slope angles of a stable slope (Fig. 5) and resting angles of a failed slope (Fig. 6) , an average slope angle of 36.5° was determined. This value will ultimately influence the slope angle of the bridge.

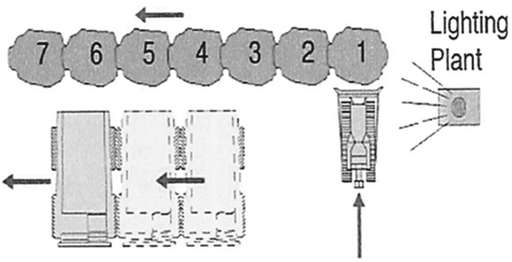


Fig. 4. Dumping and dozing methodology along the slope crest to ensure a constant moving tip head and adequate lighting is in place in areas of poor illumination [15]

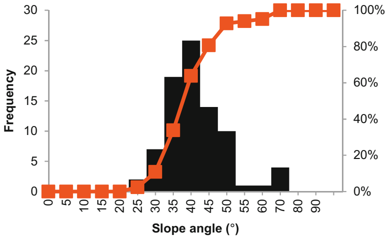


Fig. 5. Field measurements of slope angles on a stable sand slope with cumulative frequency plotted in orange

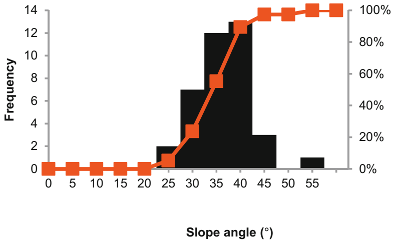


Fig. 6. Field measurements of resting slope angles of a failed slope with cumulative frequency plotted in orange

3.5 3D l.E.M (Slide3)

The slope failure database dictated a high potential for circular failures. The first step in designing a safe bridge was to determine how the material reacts when subjected to changes in the slope angle and pore water pressures. As the slope angle was varied from 25° to 37° (Fig. 7), the highest FoS and lowest PoF were observed for angles 25–31°, with an exponential increase in the FoS. The slope angles from 34–37° have a linear relationship between the FoS and PoF. The effects of pore water pressure in the form of Ru (Fig. 8) had a more significant effect with steeper slope gradients on both FoS and PoF.

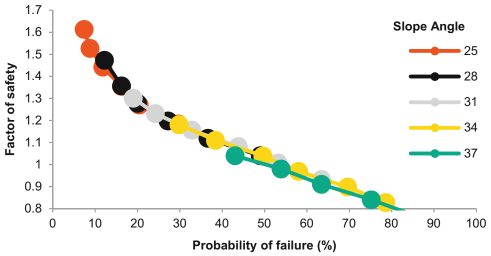


Fig. 7. Plot showing the changes in the L.E.M. results (FoS and PoF) as the slope angle varies on the bridge design

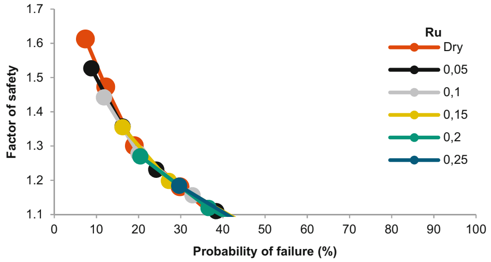


Fig. 8. Plot showing the changes in the L.E.M. results (FoS and PoF) as the pore water pressure (Ru) varies for a 37° bridge design

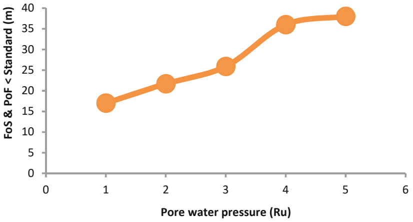


Fig. 9. Plot showing the influence of pore water pressures on the degrees of slope displacements for the accepted bridge designs

3.6 2D F.E.M (Rs2)

Changes in the Ru factor of the slope resulted in various levels of crest displacements (Fig. 9); this was evaluated to give insights into the effects of seasonal changes for medium-term stability. The displacements along the crest also provided guidance in terms of placing a physical berm that will separate the areas of potential movement from the temporary infrastructure; this was to be 18 m away from either side.

3.7 3D Settlement Analysis (SETTLE3)

When considering the various forms of settlement, the immediate settlement and total time-independent consolidation have been simulated. The immediate settlement of the

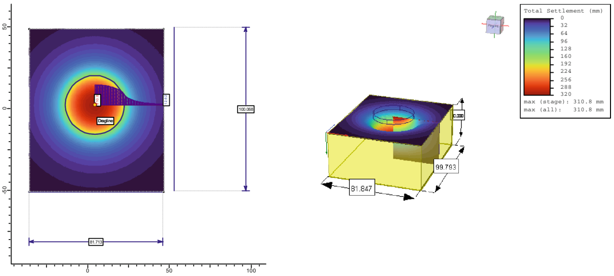


Fig. 10. Settlement analysis along the bridge showing the primary consolidation expected when the dragline uses the bridge to cross pits

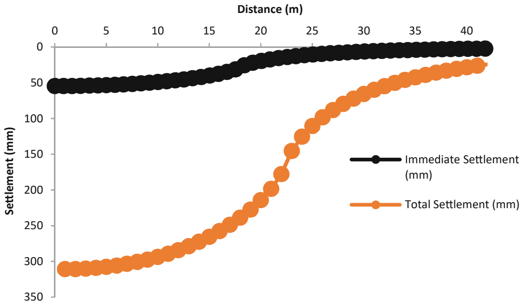


Fig. 11. 55 mm of immediate settlement is predicted to occur with 310 mm of total settlement when the dragline walks across the bridge

bridge occurs with little to no volume changes, unlike the consolidation, whereby water-air pores start to collapse[16]. The 139 kPa [17] stresses exerted on the bridge by the dragline were assessed. Figures 10 and 11 indicate that the total settlement expected would be 310 mm.

4 Discussion & Conclusion

The successful completion of the project hinged around a robust risk assessing and audit process to improvise the standard operating procedures. Along with the whittling down of fit-for-purpose designs and the study requirements, a final decision was made. The protection of the highest value mechanized asset was considered with floor condition settlement not exceeding the dragline's walking parameters, which is 4.3°. The width was chosen due to the project parameters and the expected crest displacements that will not affect the infrastructure. The determined slope angle was from a combination of the limit equilibrium modelling results along the average field measurement resting angles of the *in-situ* slopes; these two variable parameters were the most significant influence in determining the volume requirements, hauling and truck efficiencies.

Using all the acquired knowledge, from experience to simulations, the project began on the 18th of February with completion on the 15th of July, and the project spanned the drier autumn and winter months, timeline visual shown in Fig. 12.

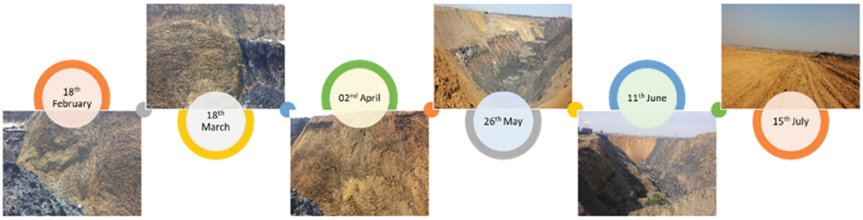


Fig. 12. Timeline of the bridge progression at Mine A

The number one gauge of a successful mining operation is Zero Harm, which was achieved. The case study allowed for the revision of standard operations procedures around tipping and dozing and geotechnical inspections of these areas. The T.A.R.P and slope stability standard were developed because of the project with the study objectives being met such as:

- A decrease of 15% in the total material volume needed, which equated to 1238 fewer loading and tipping trips in comparison to using a shallower slope angle based on only using the Seriti accepted criteria mentioned in Table 1
- Unlock potential from the North Pit, allowing for a shorter haulage distance to the tip across the mining scar and electrification of the pit
- The two-fold effect of using the sand to construct the bridge was the decrease in spontaneous combustion along the high wall, thus protecting the resource

The learnings from the case study will be shared throughout Seriti Resources and eventually across the coalfields in South Africa. Further improvements will be implemented when the radar data is back analyzed and compared to the modelling conducted.

References

1. Hancox, P.J., Götz, A.E: South Africa's coalfields – A 2014 perspective. International Journal of Coal Geology. 132, 170–254. (2014).
2. Dhege, E: Better understanding of structures at Mine A. (2015).
3. Priest, S.D., Brown, E.T: Probabilistic stability analysis of variable rock slopes. Transactions of Institution of Mining and Metallurgy. A1–A12. (1983).
4. Bieniaswski, Z.T: Principles of engineering design for rock mechanics, Rock Mechanics, Proceedings 33rd U.S. Symposium on Rock Mechanics. In: Editor, Tillerson, Wawersik, Balkema. pp. 1027–1036. (1992).
5. Stacey, T.R: Presidential address: Rock engineering – good design or good judgement? The Journal of The South African Institute of Mining and Metallurgy. 103. 411–422. (2003).
6. Gundogdu, B: Relations between pore water pressure, stability, and movements in reactivated landslides. Middle East Technical University. MSc Dissertation. (2011)
7. Aryal, K.P: Slope Stability Evaluations by Limit Equilibrium and Finite Element Methods. Doctoral Thesis. Norwegian University of Science and Technology. ISBN 82-471-7881-8. (2006).
8. Ching, R.K.H., Fredlund, D.G: Quantitative Comparison of Limit Equilibrium method of Slices. Proceedings of the Fourth International Symposium on Landslides. Toronto. 373–379. (1984).

9. Rocscience website: https://www.rocscience.com/help/rs2/tutorials/tutorials-overview. Accessed on 2023-02-09.
10. Rocscience website: https://www.rocscience.com/help/settle3//tutorials. Accessed on 2023-02-09.
11. Joel, F.J: Bridge Development Risk assessment between Ramps 10 & 11. Anglo American Thermal Coal. (2015).
12. Bakken, K.M, Chapin, G.K & Abrahams, M, G: 'Trigger action response plan development and optimization at the Bingham Canyon Mine'. In: Dight, P.M, Slope Stability 2020: Proceedings of the 2020 International Symposium on Slope Stability in Open Pit Mining and Civil Engineering, Australian Centre for Geomechanics, Perth, pp. 177–190. (2020).
13. Mining Industry Occupational Health and Safety: https://www.mosh.co.za/falls-of-ground/leading-practices/tarp-summary. Accessed on 2023-02-16.
14. Simmons, J.V & McManus, D.A: Shear strength framework for design of dumped spoil slopes for open pit coal mines. Proceedings, Advances in Geotechnical Engineering. The Skempton Conference. 2. 981–991. (2004).
15. Mine A Sand Load Haul and Dump Procedure: DOC AATC018006. (2015).
16. Fenn, D, du Kanda, A and Dukhan, D: Determining settlement rates and surface stability using in-situ density of backfill as a proxy for displacement. The Journal of the Southern African Institute of Mining and Metallurgy. 115. 1035–1043. (2015).
17. Mine A, Engineering Technical Specifications Pit Machinery, Revision 0. (2009).