Slope support analysis at Jwaneng Mine

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ABSTRACT: Jwaneng Mine is an open pit located in Botswana. The eastern wall is characterized by quartzitic shale bedding planes that dip moderately into the pit slope, hence, posing a risk of planar sliding once undercut. The Bench 17 area, located on the eastern wall, hosts one of the two major life of open pit mine switch-backs access to kimberlite. Previous failures in the interim design have reduced the switch-back width, adversely impacting effective haul truck movement. Mine operations developed a plan that optimized switch-back width by installing a 32 m high geogrid reinforced rockfill retaining wall. A study of additional foundation supports was recommended to meet the design acceptability criterion for this area. This paper describes a numerical assessment of the support design.

Keywords: Slope stability, structural support, support design, numerical modeling.

1 INTRODUCTION

Jwaneng Mine is located in south-central Botswana about 120 km west of the capital, Gaborone. Jwaneng, meaning “a place of small stones,” is owned by Debswana, a partnership between De Beers and the government of Botswana. Jwaneng Mine is the richest diamond mine in the world by value. The eastern wall is characterized by quartzitic shale bedding planes that dip moderately into the pit slope, hence, posing a risk of planar sliding once undercut. The Bench 17 area, located on the eastern wall, hosts one of the two major life of open pit mine switch-backs access to kimberlite (see Figure 1). Previous failures in the interim design (Cut 8) have reduced the switch-back width, adversely impacting effective haul truck movement. Mine operations developed a plan that optimized switch-back width by installing a 32 m high geogrid reinforced rockfill retaining wall. A study of additional foundation support was recommended to meet the design acceptability criteria for this area. Different support options were assessed explicitly in order to meet the Design Acceptance Criteria (DAC). This paper describes the detailed numerical assessment of the support design using *FLAC3D* (Itasca, 2019). *FLAC3D* is a numerical modeling software for geotechnical analyses of soil, rock, groundwater, and ground support. Such analyses include engineering design, factor of safety prediction, research and testing, and back-analysis of failure.

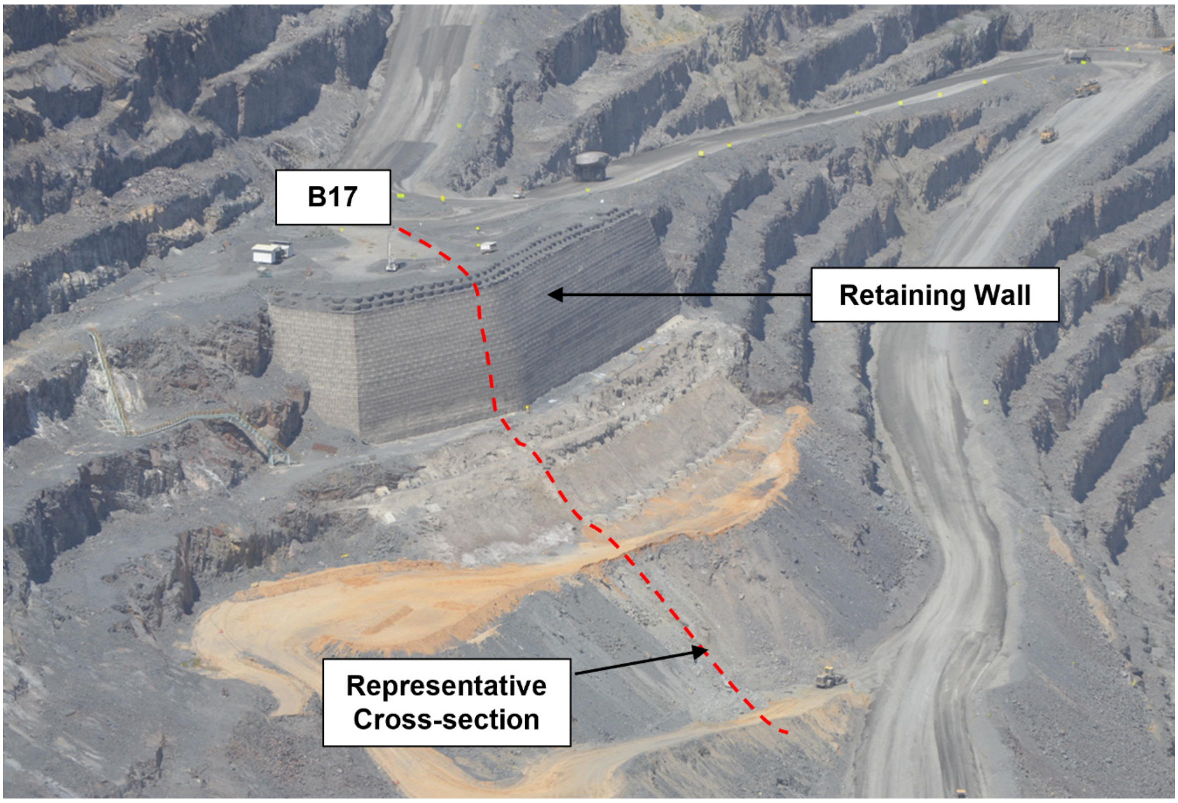

Figure 1. Photo of the Bench 17 area after installation of the reinforced rock fill retaining wall.

2 DISCONTINUITIES AND ROCK MASS PROPERTIES

As mentioned, the eastern wall is characterized by shale bedding planes that dip into the pit slope, hence, posing a risk of planar sliding once undercut. A representative cross-section through the retaining wall (see red dotted line in Figure 1) is shown in Figure 2. Therefore, one of the key aspects in this study is the strength of the bedding planes, whose characterization is the result of previous back-analyses. The bedding planes follow a brittle strain-softening behavior with peak and residual strengths as listed in Table 1.

Table 1. Discontinuity Properties.

Discontinuity	Peak Strength			Residual Strength	
	Cohesion (kPa)	Friction (°)	Dilation (°)	Cohesion (kPa)	Friction (°)
Bedding (QS)	5	37	5	0	35
Faults	5	30	5	0	30

The rock mass has been characterized as a Mohr-Coulomb material with conservative shear strength properties (friction angle of 36° and cohesion of 1 MPa). The rock mass is assumed to have zero tensile strength to account for cross-joints. Even though the shear strength properties are conservative, no rock mass shear failure is observed in the models.

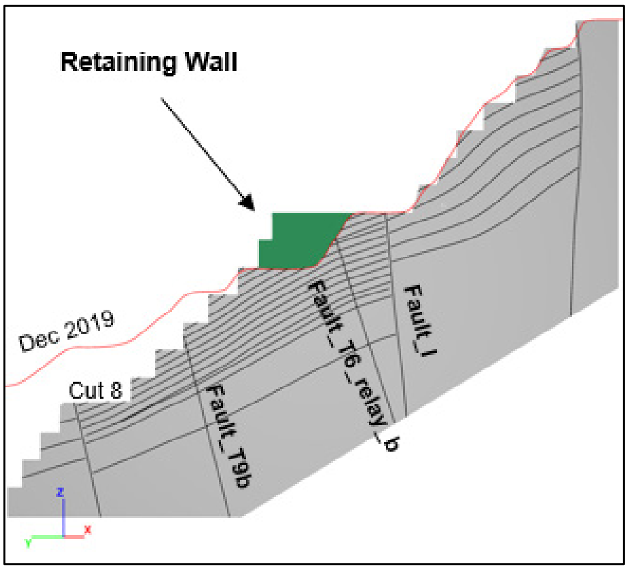

Figure 2. Representative cross-section through the area of interest showing explicit bedding planes and faults. The December 2019 geometry and planned Cut 8 design are also shown.

3 STABILITY CONDITION WITHOUT SUPPORT

Early models showed safety factors of 1.0 to 1.1 without support for a variety of slope design alternatives considering the installed retaining wall. The factor of safety (FoS) contours of one of the early designs is shown in Figure 3. The failure mode involved sliding on bedding surfaces and along the rockfill interface at the rear of the retaining wall.

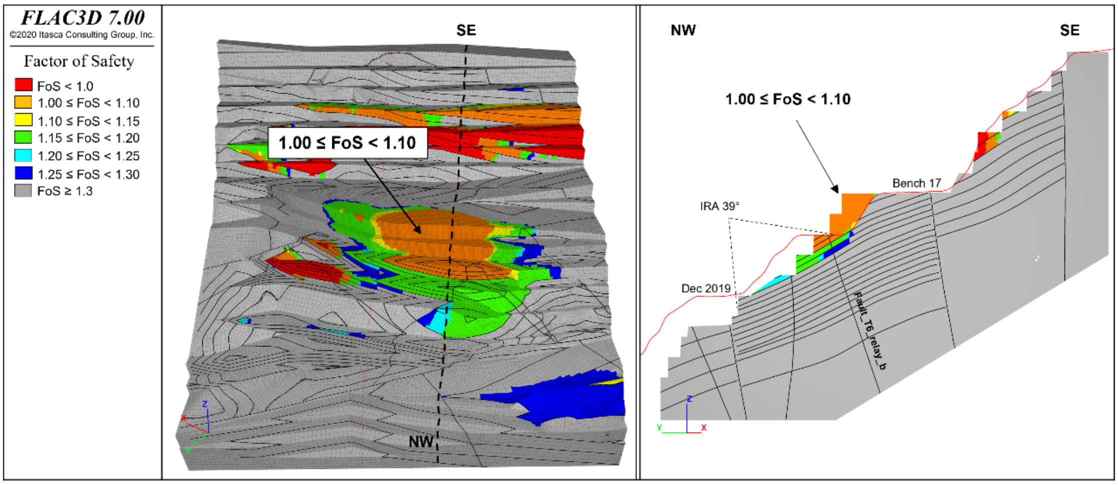

Figure 3. Safety factor contours for condition at the end of Cut 8 mining without support.

4 REPRESENTATION OF THE GEOGRID WALL

The wall is reinforced with geogrids (ParaLink 500) and metal steel cages for the facing as shown in Figure 4. The reinforcement provides confinement to the fill material, which can be converted into an equivalent cohesion. This is a simplification of the local interaction between the fill and the reinforcement normally adopted especially for large structures where the detailed analysis becomes very onerous and time consuming. Nonetheless, due to the importance of this project, Itasca developed a detailed model of the reinforcement (see Figure 5) and performed a full analysis to verify that the “continuum-equivalent” model of the fill-reinforcement matrix would provide satisfactory response.

The facing is modeled using pile elements because the steel can take bending and shear. The geogrid is modeled with cable elements reacting only in the axial direction (no bending and shear capacity for the geogrid). The interaction with the fill is purely frictional via links connected to the hosting zones. The friction between the fill and reinforcement is considered to be 32 degrees. The structural capacity of the geogrid is limited to the creep load (270 kN/m) and a limit strain of 8% is also considered.

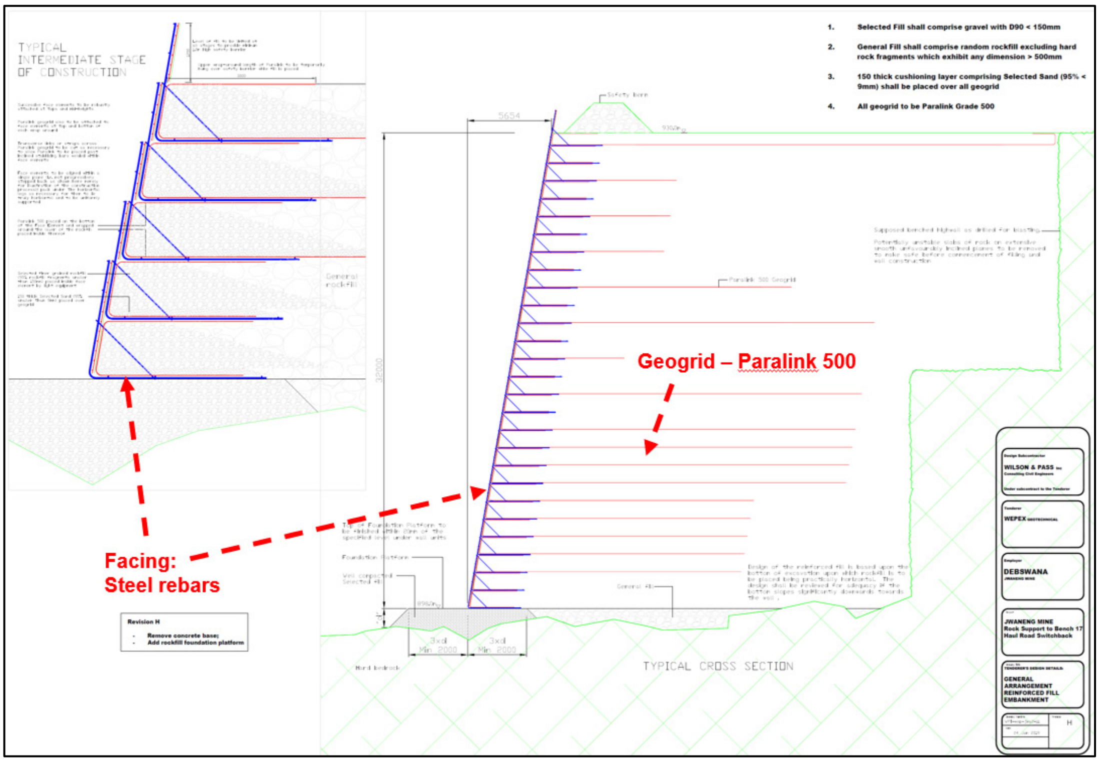

Figure 4. Details of the 32-m high geogrid wall.

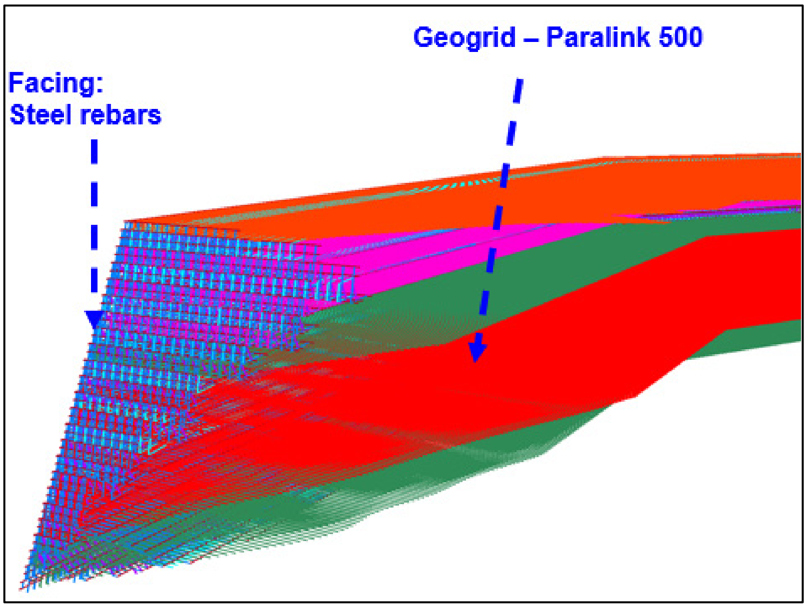

Figure 5. Numerical representation of the geogrid wall and facing.

The maximum simulated displacement of the wall was on the order of 70–80 mm, very similar to the displacement obtained with the continuum approach. The detailed analysis carried out considering the detailed reinforcement of the wall (facing plus geogrid) confirms the assumption made in terms of equivalent strength of the fill. The detailed analysis demonstrated that the geogrid wall could be represented as an equivalent material behaving as a Mohr-Coulomb material, emplaced after the excavation with a density of 2160 kg/m^3, cohesion of 20 kPa, and a friction angle of 40°. The explicit representation of the retaining wall neglects the tensile reinforcement provided by the geogrid but does provide the surcharge, which is key to correctly assessing the stability of this area. The main advantage of the equivalent strength is a significant gain in running time, which has been important considering the numerous analyses that were necessary.

5 INCLINED PRE-STRESSED ANCHORS

Anchors are tension structural elements that transmit compression force to the rock mass through a pre-stress. The pre-stress applies additional normal stress across discontinuities and thereby strengthens the rock mass. By definition, an anchor consists of three main components, as shown in Figure 6:

- Bond length: The anchor is fixed in the borehole using grout (cement mortar) and can transfer the forces to the load-bearing soil via bond and skin friction.
- Free length: Each strand is uncoupled from the borehole using individual ducts so that it can freely extend in the unbounded length. This way, tension can be applied to the anchor system.
- Anchor head: The anchor head transfers the anchor force to the substructure and, thus, to the structure that needs to be anchored.

In this study, multi-strand cable anchors (15 strand) are modeled considering Y1860 High Grade steel with a 14.5 m free length and a 4.8 m bond length as shown in Figure 6a. The installed anchors are shown in Figure 6b. As shown in Figure 6b, a concrete pad is required to get the right stress distribution along the anchors.

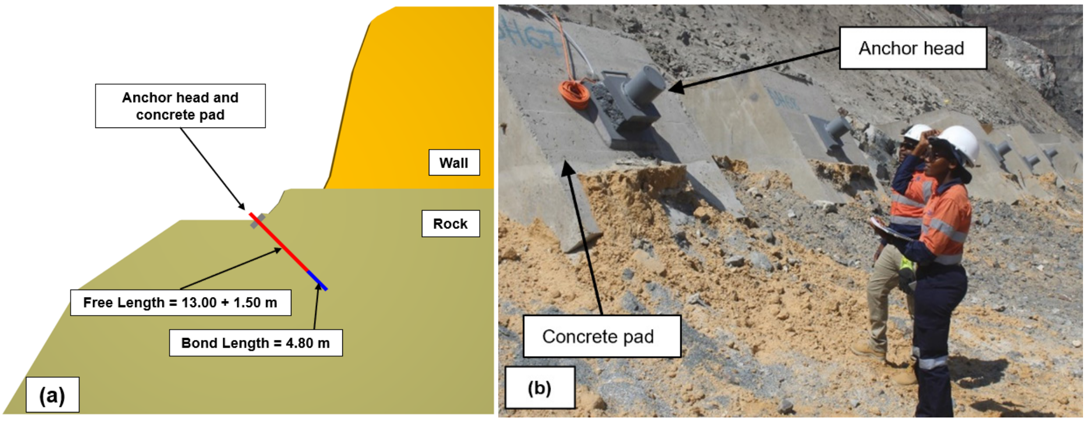

Figure 6. (a) Cross-section through the reinforcement area showing inclined pre-stressed cable anchor. (b) Photograph of installed high-capacity permanent strand anchors below reinforced rockfill retaining wall. The photograph shows the concrete pads used to distribute the applied force.

6 AS-BUILT ANALYSIS

Due to differences between the design assumptions and the constructed conditions, it was necessary to simulate the as-built conditions using actual retaining wall geometry, actual anchor locations, lengths, pre-stress (approximately 1900 kN) and orientations. The results were checked against expected loads and deformations. The results shown in Figure 7 illustrate agreement with the design expectations. The maximum axial force in the anchors was predicted to be about 2400 kN, which is lower than the yielding capacity (3450 kN). There was no need for additional anchors/support.

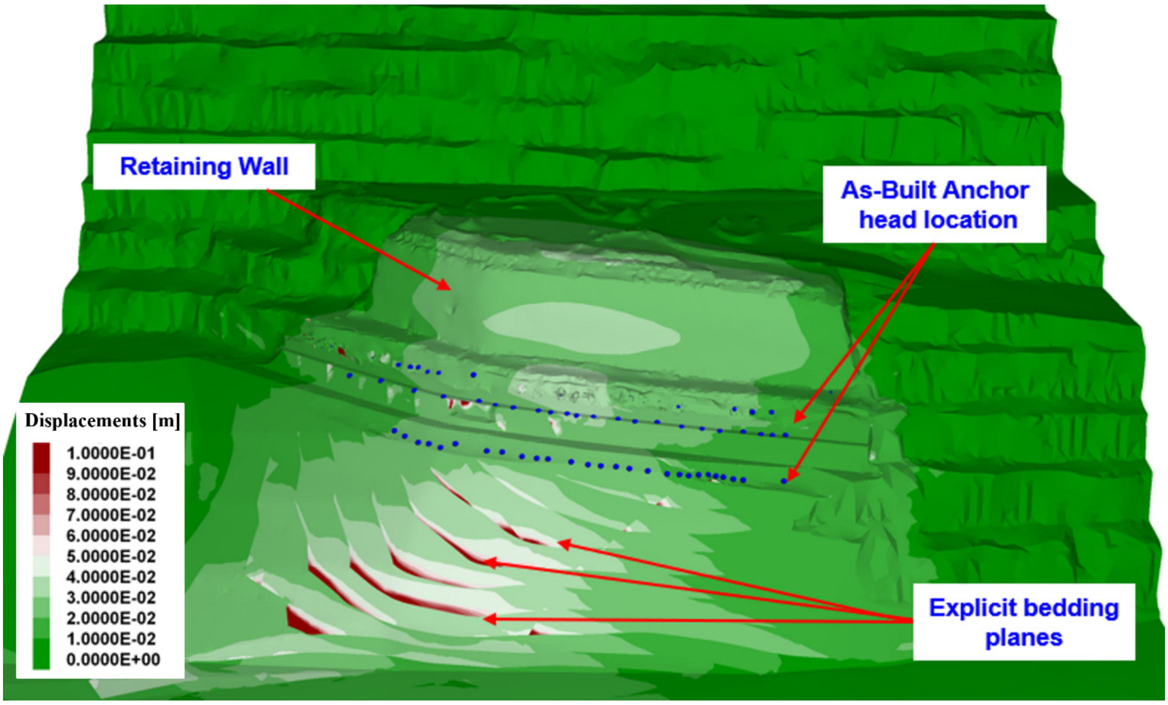

Figure 7. Final as-built configuration of reinforced rock retaining wall and anchor support. Maximum displacement (red) is about 10 cm.

7 FINAL REMARKS

This paper illustrates how a complex rock-structure interaction problem can be simulated in a three-dimensional numerical model. The rock is represented as a continuum but has explicit faults and bedding planes, which may slip along discrete surfaces. It was concluded that high-capacity pre-stressed cable anchors were required to meet design acceptability criteria. Reinforcement within the rock is represented by pre-stressed cable elements. The reinforced concrete blocks used to distribute the load were represented with structural elements. The geogrid wall was simulated with explicit representation of the geogrid and facing in the model to confirm an equivalent behavior without explicit elements.

The numerical model was used not only to demonstrate compliance with Design Acceptance Criteria, but to separately assess extreme conditions resulting from monsoon-like rain and earthquakes. A separate dynamic model was used to assess the impacts of nearby blasting. Alarm thresholds for instrumentation were established by reducing the bedding friction. Finally, the entire area was heavily instrumented with inclinometers, piezometers, Smart Cables and MPBXs. To date, all parameters are below any of the alarm thresholds.

REFERENCES

Itasca Consulting Group, Inc. (2019) “FLAC3D — Fast Lagrangian Analysis of Continua in Three Dimensions,” (Version 7.0). Minneapolis: Itasca.