Solving a slope stability problem at the Cleo open pit in Western Australia

AngloGold Australia Ltd (AngloGold) owns the Sunrise Dam gold mine, which includes the Cleo open pit, on the shore of Lake Carey, a large salt lake near Laverton in Western Australia. The Cleo pit on completion will be more than 450 metres deep – one of the deepest in Australia. The operation, which uses large-scale mining equipment, is one of the lowest cost producers in Australia.

The geological setting of the Cleo deposit is unusual for Western Australia. The gold, like most local deposits, is hosted mainly by weathered and fresh rock masses. However, unlike most other deposits, the rock masses are overlain by very thick intervals of very stiff lake clays and other transported sediments.

Snowden Mining Industry Consultants (Snowden)* has been involved with Cleo since March 1999 and has addressed a wide range of geotechnical issues, many of which are compounded by the local hydrogeological regime. Snowden has used a variety of Rocscience software, including DIPS, SLIDE and ROCFALL, to investigate and address these various issues and acquire a sound understanding of the geotechnical setting of the deposit.

In particular, Snowden used SLIDE to resolve uncertainties regarding a slope failure in the lake clay sediments, enabling reliable designs to be developed for ultimate slopes in the lake clays.

Geotechnical setting

Figure 1 shows the geology intersected by the northwest wall of the planned pit. Surficial sediments up to 25m thick overlie a 20m to 60m thick sequence of transported lacustrine clays and gravels. These transported sediments blanket the entire Cleo deposit, with the thickest sequence being in the southwest end of the pit (at left in Figure 1). The clayey materials of the transported overburden are generally stiff to very stiff, while the sandy, gravely materials are medium dense to dense and occasionally loose. Sediments are thickly bedded.

* Snowden Mining Industry Consultants is a multi-disciplinary, international mining consultancy with a head office in Perth, Western Australia, and with regional offices in Brisbane and Kalgoorlie (Australia), Johannesburg (South Africa) and Vancouver (Canada). Snowden provides open pit and underground mining consulting services ranging from resource evaluation through geotechnical engineering to mining engineering.

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Two major aquifer types are encountered at Cleo – sandy palaeochannelbeds at the base of the transported sediments and fractures within the moderately weathered and shallow fresh bedrock. Hydrogeological studies have focused on the regional hydrogeology and the characteristics of the major aquifers.

However, in a geotechnical context, there has been uncertainty regarding the local characteristics of the piezometric profiles within the low-permeability domains within which the pit slopes are excavated. These domains include the transported lake clays, the upper weathered bedrock interval and the fresh bedrock.

The consequences of this uncertainty were illustrated by a slope failure, which occurred in April 2000 in the thickest interval of transported lake clays at the southwest end of the pit (left side of Figure 1). Snowden was able to obtain a good understanding of the local groundwater regime indirectly through failure back analysis using SLIDE.
Initial back analysis of a major slope failure using SLIDE

The failure occurred in a slope excavated in transported lake clays (Figure 2) when the overall slope height was about 60m. Based on the surface expression of the failure, a circular failure surface was inferred through the lake clays with translation on the interface between these and the underlying, extremely weathered bedrock.

A considerable quantity of laboratory-derived shear strength data had been obtained for the clays, providing a sound understanding of the strength characteristics of these materials. Consequently the focus of the back analysis of the failure was on the principal unknown quantity; i.e. the hydrological regime in the slope, rather than material strength.

Snowden analysed a range of groundwater scenarios in an attempt to identify one that replicated the sliding surface geometry at a Factor of Safety (FOS) of 1.0. The results of the analysis indicated the surface could not be replicated accurately for what was thought to be the most likely groundwater scenario; i.e. high groundwater levels and pore pressures within the lake clays. Limiting equilibrium conditions could only be obtained for a fully saturated slope and, under these conditions, the predicted failure surface intersected the whole slope rather than just the lower section (as occurred) and was shallow seated. These characteristics were not consistent with the observed failure conditions.
Between April 2000 and October 2000, the slope continued to fail in a benign manner until finally stabilising at the limits shown in Figure 3. The displacement of the mass from the ultimate failure zone is shown in Figure 4.

The duration of instability and magnitude of movement is very unusual for Western Australian conditions, where benign failures (usually in weathered, weak rock masses) usually experience small vertical and horizontal displacements and stabilise rapidly. As well as its considerable displacement, the mass had the appearance of a highly viscous flow.

A possible explanation is that, following initial failure, the flow of the failure mass was sustained by groundwater seepage through the mass and elevated pore pressures immediately above the failure surface. However, the source of this groundwater was uncertain. It was unlikely to be the lake clay interval, as saturated conditions would be required to develop the pore pressures driving the mass, which would have resulted in a different failure geometry to that which occurred.

Figure 3: Extent of Failure in lake clays following stabilisation
Evidence of an unusual hydrogeological regime

Late in 2000, multilevel piezometers were installed behind the crest of the failure to better understand the prevailing hydrogeological regime. Levels within the extremely weathered bedrock were found to be significantly higher than their interface with the lake clays. This was an important finding, given that translation on this interface formed part of the failure mechanism.

Based on the results of the earlier back analyses, the failure surface should not have followed this interface unless it formed a weak “seam” and there was no evidence of such weakness in surface exposures of the interface in adjacent pit walls. It was now realised that, whilst the lake clays and the weathered bedrock are both regarded as low permeability materials, uplift pressures could have developed on the base of the less permeable lake clays in the translational section of the failure profile. These could have initiated the failure and facilitated the observed ultimate displacements.
Comprehensive back analysis of the failure using SLIDE

Using SLIDE, Snowden undertook further comprehensive back analysis to test this theory.

Figure 5 shows the SLIDE model used to test the theory that elevated pore pressures on the clay/bedrock interface played a part in the initial failure. The model uses SLIDE’s facility to investigate circular-translational failure surfaces. SLIDE’s multi-piezometric surface and water table facility was used to model these surfaces in the surficial sediments, clays and weathered bedrock. The latter was modelled by assigning an elevated piezometric surface to a thin layer of lake clay at the interface.

The bedrock piezometric surface and the water table in the lake clays were adjusted until the closest simulation of the actual failure mechanism was obtained for a factor of safety (FOS) of 1.0. SLIDE’s critical surface searching routine was used to identify this surface, and the analysed surfaces were filtered to show adjacent low FOS surfaces. Figure 5 shows the final model which best simulated the initial failure. This simulation was considered to be accurate.

Figure 5: Final failure model from back-analysis of initial lake clay failure
Significant conclusions were as follows:

- The failure was curvilinear, with translation on the clay/bedrock interface.

- The elevation of the weathered bedrock piezometric surface suggests the piezometric head is about twice the overburden thickness above the translational section of the failure surface and is considerably more than twice the overburden thickness at the toe of the failure. Therefore, the uplift pressures at the interface are similar to overburden pressure and probably exceed overburden pressure at the toe.

- The indicated water table elevation in the lake clays is the maximum permissible for the observed failure mechanism. This suggests significant pore pressures were not being maintained in this material.

The results of the analyses strongly support the theory that elevated pore pressures in the weathered bedrock promoted the initial instability.

Back-analyses were then performed on the ultimate failure mass (Figures 3 and 4) to further assess the likely hydrogeological environment once the failure mass had stabilised. The analysis was also used to validate the geotechnical properties used for the failed material, these being based on laboratory tests on remoulded samples of lake clay. Figure 6 shows the SLIDE model used.

![Figure 6: Back-analysis of ultimate main failure profile](image)

The model uses SLIDE’s facility to undertake critical surface searching for irregular failure surfaces. Again SLIDE’s multi-piezometric surface and water table facility was used to model these surfaces in the clays, the failure mass and the weathered bedrock. The latter was modelled by assigning an elevated piezometric surface to a thin layer of failed material at the sliding surface.
The model was back analysed by adjusting the profile of the bedrock piezometric surface until a critical surface with a FOS of around 1.0 was obtained. Figure 6 shows the results of the back-analysis.

Again, SLIDE’s critical surface searching routine was used to identify this surface, and the analysed surfaces were filtered to show adjacent low FOS surfaces.

Conclusions from the back-analysis were as follows:

- It appears likely that an elevated piezometric surface was associated with the weathered bedrock below the failure mass, although pore pressure dissipation into the failure mass would have reduced the piezometric level towards the toe of the mass.

- Following the breach of the clay/bedrock interface on initial failure, it is likely the flow of the failure mass was initiated and sustained by elevated pore pressures in the mass immediately above the failure surface and by groundwater seepage from the bedrock into the failure mass driven by the high piezometric level in the bedrock.

**Performance of the remedial slope**

Snowden provided AngloGold with design recommendations for a remedial slope based on the geotechnical and hydrogeological models developed from the back analyses. It was anticipated that the remedial slope would intersect the estimated position of the failure surface, but that slumping on the surface could be managed.

Excavation of the remedial slope has been completed within the last few months (Figure 7), and the performance of the slope has been largely as expected. The old failure surface was indeed intersected and failed material on the surface has slumped. Displacements were small and manageable and significant failure of the over- and underlying lake clays has not occurred.

Figure 7: Remedial slope showing isolated slumping on old failure surface