Geotechnical Characteristics of the African Copperbelt Saprolites and their Influence on Pit Slopes

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Abstract

The Central African Copperbelt is in a sub-tropical area characterised by high seasonal rainfall and elevated terrain giving rise to deep tropical weathering, where the depth of weathering can extend from 20, and up to 120 metres or more. These saprolitic masses can significantly impact on the performance of pit slopes and are generally characterized as silts with relic structures.

The saprolitic materials could be classified as a very stiff soil tending to a very weak rock. The weathering profile of the saprolites is controlled by both the parent rock and major structural features. Relic discontinuity structures, such as bedding/foliation are retained within the weathered fabric. The intact strength is highly variable but generally less than 15 MPa. From the geotechnical testing carried out it was found that the geotechnical properties of the saprolites encountered were highly variable, as a result of differences in the intensity of weathering and its anisotropic nature. Some in situ samples were also difficult to test as they were in a transition zone between a saprolite and very weak to weak rock.

Records show that the majority of instabilities in the saprolites, occurred during the rainy season, which is an important driving force in the development of these instabilities. Relic structures within the saprolites also contribute significantly to the performance of the slope, and kinematic instabilities (planar, wedge and toppling), more usually associated with failures in rock, can be observed in these materials.

This paper addresses geotechnical properties of saprolites and driving forces which impact on slope performance. Included are case studies from several mining operations in the central African region with analyses of failure mechanisms in these saprolitic masses.

1 Introduction

The Central African Copperbelt is one of the most significantly mineralized Neoproterozoic basins on earth, preserving a spectacular scale of mineralization. The majority of DRC and Zambian copper deposits are contained within the 900km-long Lufilian Arc, a Pan-African fold belt that links with the Damaran Belt of Namibia and within which the Katanga Supergroup-hosted Copperbelt is developed.

The climate of the region is sub-tropical with a cool dry season from May to October and a warm, wet season from November to April. Climate data collected from the region indicates that the annual average rainfall is between 1220mm to 1420mm.

Saprolitic soils, commonly found in tropical regions of the world, are derived from in-situ rock weathering where the original rock texture, fabric, and structure are retained (Massey and Pang 1988). Open pit mining is commonly used to exploit the African Copperbelt deposits. The vast majority of the slopes are excavated through these deep weathered saprolites.
2 Regional geology

The Central African Copperbelt is an arcuate belt of late Proterozoic sediment-hosted copper deposits. The belt is coincident with the Lufillian arc, a major tectonic province characterised by generally north-directed fold and thrust structures.

The Copperbelt deposits occur within the Mine Series at the base of the Late Proterozoic Katangan Supergroup, and can be grouped into two broad associations that fall on either side of the Zambian-Congo border. The Zambian deposits are generally hosted in the lower most portions of the Mine Series, namely the Lower Roan Group clastic sediments, while the Congolese deposit are generally hosted in the Upper Roan Group dolomitic rocks.

Figure 1. Tectonic setting and structure of the Lufillian fold belt (after Selley et al., 2005): (a) Tectonic setting of Central and Southern Africa, (b) Tectonic zones of the Lufillian fold belt, Zambian Copper Belt (ZCB) and Congolese Copper Belt (CCB), (c) Schematic cross section of the Lufillian fold belt.
3 Controls on the geotechnical properties of saprolites

There are a number of factors that control the properties of Saprolites. In some cases Saprolite properties can differ over the space of just a few metres due to such factors such as a change in parent rock type, fabric or mineralogy. These variables are discussed further below:

- **Climate**: rainfall patterns and temperature control the rate of weathering. Higher rainfall and temperature increase the rate of weathering by improving the conditions for chemical reactions to take place.

- **Time**: the longer that weathering processes have been taking place influences the degree and depth of weathering of the parent rock.

- **Lithology**: the mineralogy of the parent rock type will influence the chemical reactions that take place and the new minerals that are formed as a result of weathering. For example, a carbonaceous phyllite may weather to a graphitic saprolite, and a micaceous schist may weather to a chloritic saprolite. A quartzite may continue to contain silica, but the cement or bonds between grains are likely to have become weakened as a result of weathering. The parent rock type will therefore have an influence on the speed of weathering and strength of the resulting saprolite. Where parent rock types are interbedded or layered the saprolite may contain alternating hard and soft layers. This also introduces anisotropy in the saprolite.

- **Fabric and mineralogy**: the fabric of the parent rock type will often be preserved in the resultant saprolite. Saprolites formed from rock types such as schists and phyllites will often preserve the foliation and schistosity of the parent rock. Just as the metamorphic rock can preserve layering from the original sedimentary rock in the form of clay or silica rich layers, this layering may also be preserved in the saprolite by, for example, harder silica rich layers and softer clay rich layers. This will also cause the saprolite to behave anisotropically.

- **Structure**: structure can have a major influence on the strength and behaviour of saprolites. In the same way that the fabric of the parent rock can be preserved in the saprolite, discontinuities can also be preserved. Discontinuities that are orientated unfavourably in relation to the slope will have a negative influence on the stability of the slope and are more likely to promote kinematic failure. In some cases the infilling of discontinuities may be less susceptible to weathering that the rock itself. Quartz infilled veins may retain the quartz whilst the intact rock becomes weathered to a very soft soil like material. The cohesion between the rock and the joint infill will still reduce greatly due to the degradation of the rock material. Often the mineralogy of the discontinuity surface or infilling of the parent rock is such that when the saprolite is formed the joint now becomes harder that the intact saprolite. This does not necessarily mean the discontinuity increases the strength of the mass as a whole since the cohesion between the discontinuity surface, or infill, and intact saprolite is also likely to have been weakened by a weathering.

- **Regional and large scale structures**: faults and fracture zones that promote the movement of groundwater through the rock can have a significant influence on the depth of weathering and therefore the thickness of saprolites. In the Central African Copperbelt, saprolites can be found extending 120m or more in depth from surface, where faults or shear zones are located. Early in the formation of saprolite, fluid movement may have been by way of fracture flow along discontinuities. Saprolite formation is therefore most rapid in the presence of high concentrations of discontinuities or major discontinuities, such as permeable faults or shear zones. Between these areas the parent rock may still be fresh or only slightly weathered. This can make the profile of the depth of the transition between weathered and fresh very variable, even leaving blocks of fresh or slightly weathered rock floating in the soft saprolite. In extreme cases, such as is found often on the copperbelt, dolomite layers may be almost completely removed by dissolution when intersected by a shear zone or fracture leaving a cavity containing just
accessory minerals such as mica between boulders of fresher rock. Overlying saprolites may then collapse into the voids left between the boulders.

- **Topography:** Topography influences surface water drainage patterns and can therefore influence how and where surface water is introduced into the subsurface as groundwater. In the African Copperbelt topographical lows often coincide with highly fractured and faulted areas or areas with rocks more susceptible to weathering. Topography and geology therefore combine to mutually promote and increase rate and depth of weathering and therefore saprolite thickness.

### 4 Geotechnical properties

The saprolitic materials could be classified as a very stiff soil tending to a very weak rock. Historically saprolitic material has been treated as highly weathered rock mass and assigned a rock mass classification (generally less than 25 on the Geological Strength index). However, back analysis of instabilities suggests that their behaviour could not be adequately explained by traditional rock failure criteria (Hoek-Brown or Baron Bandis). It was found that conventional rock mass classification techniques over-estimated the equivalent Mohr-Coulomb shear parameters specifically on comparisons to intact laboratory test results. The material was found to be more a transitional material between rock and soil which exhibited variable but low intact strength, while retaining relic geological structural feature. Geotechnical data has been collected from two operating open pits, sites 2 and 3, and from three feasibility studies for the design of open pit slopes, sites 1, 4 and 5. Tests on samples collected from the five investigations included Uniaxial Compressive Testing, Triaxial Testing, Shear Box Testing and Foundation and Indictor testing.

From the geotechnical testing carried out it was found that the geotechnical properties of the saprolites encountered were highly variable, as a result of differences in the intensity of weathering and its anisotropic nature. Some in situ samples were also difficult to test as they were in a transition zone between a saprolite and very weak to weak rock. Typically the saprolites grade as a clayey silt, with a variable fine sand content. Typically dry densities ranging from 1 550 to 1 725 kg/m$^3$. In terms of the Unified Classification system the saprolites were quite variable, generally classifying as a SC, CL or ML soil.

Specifically analysing the shear testing results the cohesion of the saprolites occur over a wide range of values, for site 4 the cohesion ranged from 17 to 111 kPa, while for site 3 the cohesion ranged from 13 to 87 kPa (shown in Figure 2). The internal angle of friction was more consistent across the sites generally ranging between 20 and 30 degrees (shown in Figure 3).

![Figure 2. Range of Cohesion (kPa) values for five sites across the Copper Belt from shear testing.](image-url)
Figure 3. Range of Internal Angle of Friction (degrees) values for five sites across the Copper Belt from shear testing

Uniaxial compressive strength testing (UCS) was carried out on intact samples during the feasibility investigation for site 5. The samples were collected from near surface to a depth of approximately 60 metres (extend of weathering nearing the transition zone). From 0 to 20 metres the results were consistent with the UCS below 10 MPa (Figure 4). At depths greater than 20 metres the UCS results are scattered and values range from 2 MPa to 50 MPa.

Figure 4. Uniaxial Compressive Strength (MPa) versus Depth (m) from intact saprolite samples

5 Examples of failure modes in Central African Copperbelt saprolites

Descriptions of failures observed in mines of the African Copperbelt are presented below. Due to the variable nature of the saprolites of the Central African Copperbelt, the failure characteristics can be diverse. Often, the mode of failure has more in common with failures in rock than in soil.
5.1 Planar and wedge type failure

Some localised folding of metamorphic rocks in a mine in the domes region of the Zambian Copperbelt caused the dominant discontinuity and foliation direction contained within the saprolite to be unfavourably orientated with respect to the slope face. The parent rock types were schists and phyllites. Planar and wedge failures of single benches were first observed near the toe of the slope early in the wet season of November 2006. A year later during November 2007, the onset of the wet season caused further planar and wedge failures and rotation of the saprolite mass in the slope. Over several months the failed area of the slope then continued creeping and rotating into the pit. Due to the localised nature of the folding a major stability problem was not anticipated and had to be dealt with on site as mining progressed. As the slope was within a cutback it could subsequently be mined out. It did however present short term challenges as the failed material reduced the available mining area below the slope, and therefore the accessibility of ore. Attempts to remove the material at the toe of the slope led to more material accumulating in its place as the rate of creep increased. It was therefore decided to work around the failed material until the failed material was removed by the next cutback.

Figure 5. Planar / wedge failure in the first few days of the deterioration of the slope, bench height is 5m.

Figure 6. Slope face one year after the initial planar failure at the toe, total slope height is 40m.
5.2 Toppling failure

Another failure in the same mine was caused by toppling of saprolite schist. The foliation was sub horizontal, but minor folding meant that foliation in the area of the failure was dipping at a low angle out of the slope face, forming basal planes to the toppling blocks. Near vertical relic joints were steeply dipping at an oblique angle into the face, forming release planes.

![Toppling failure in Saprolites, benches are 5m high.](image)

5.3 Failure at Saprolite – Rock contact

This failure occurred at the contact of the saprolite and rock. The rock type was a biotite rich marble. Dissolution weathering of the marble caused much of the volume of marble to be removed, leaving a very loose mica sand in its place. The result was that a circular failure occurred in the upper two 5m benches of weak residual marble. The failure occurred in January 2008, approximately mid way through the wet season.

![Circular failure of the loose mica sand saprolite adjacent to the fresh to slightly weathered marble.](image)
6 Summary and conclusions

The geotechnical properties of the saprolites encountered in the African Copper Belt are highly variable, as a result of differences in the parent rock type, intensity of weathering and anisotropy. Traditional soil and rock mechanics methods were found to be inadequate in explaining the behaviour of saprolites, specifically in materials which were transitional between a very stiff soil and a very weak rock. It would be impossible to assign absolute values for a design of a saprolite slope as the geotechnical parameters change not only with depth but also along the strike of the slope. A comprehensive laboratory testing program is recommended when deep weathered saprolites are encountered.

Records show that the majority of instabilities in the saprolites, occurred during the rainy season, which is an important driving force in the development of these failures. Relic structures within the saprolites also contribute significantly to the performance of the slope, and kinematic failure, more usually associated with failures in rock, can be observed in these materials.

7 References


