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Analysis of Shear and Consolidation Behaviour of a Clay Foundation Below a TSF

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ABSTRACT

Historically, the analyses of tailings storage facilities (TSFs) have primarily focused on understanding the characteristics of tailings, while often overlooking a comprehensive evaluation of the foundation, as seen at Mount Polley in 2014. The Global Industry Standard on Tailings Management (GISTM) Requirement 5.4 stresses the importance of comprehensively addressing all potential failure modes.

Numerous platinum TSFs in Southern Africa are underlain by residual clay, specifically a residual mafic rock from the Bushveld Complex. Similar soils, known as "tropical black clay soils", are found in other regions of the world. Surprisingly, there's limited public information on testing and modelling the behaviour of this clay foundation.

This paper presents a case study that employs a novel approach to assess the impact of loading from tailings deposition on the underlying clay foundation of an upstream TSF. The analysis investigates how shear behaviour and consolidation characteristics of the clay foundation change with varying TSF heights and construction rates. The approach includes quantifying excess pore water pressures and their influence on the clay foundation's effective stress.

The analyses primarily employ traditional limit equilibrium methods to assess TSF stability and foundation behaviour, with the potential to expand to numerical modelling.

The study concludes that excess pore water pressures will significantly affect the Factor of Safety (FoS) of a TSF, particularly with adverse consolidation characteristics and increasing TSF height. This is primarily due to the low permeability and changing consolidation coefficient (cv) of the clay layer as the surcharge load increases. Furthermore, the research reveals that, depending on the rate of rise, tailings deposition may induce excess pore water pressures, potentially reducing the FoS.

The ability to quantify excess pore water pressures using this novel approach enables a more accurate estimation of the FoS for facilities underlain by low-permeability materials, either residual or transported.

Keywords: TSFs; clay foundation; consolidation; excess pore water pressure.

1. Introduction

In the context of TSFs (Tailings Storage Facilities), emphasis has historically been placed on the shear strength parameters and behaviour of the tailings, with little to no testing and modelling of the founding materials on which the TSF is constructed. Requirement 5.4 in the Global Industry Standard on Tailings Management (GISTM) states that one should: “Address all potential failure modes of the structure, its foundation, abutments, reservoir (tailings deposit and pond), reservoir rim and appurtenant structures to minimise risk to as low as reasonably practicable (ALARP).”

Many platinum TSFs in Southern Africa are underlain by residual clay (residual mafic rock of the Bushveld Complex),with similar soils present in other parts of the world.

This paper aims to show the importance of quantifying the effect of excess pore water pressures in clay foundations through fieldwork, laboratory testing and analysis. Whereby a novel approach was used to assess a generic platinum TSF on the Bushveld Igneous Complex (BIC) in South Africa.

2. Fieldwork, Laboratory Testing & Material Parameters

2.1. Geology

The Bushveld Igneous Complex (BIC) occupies an oval-shaped area in the northern areas of South Africa. The 2-billion-year-old BIC is divided into four limbs: the northern, southern, eastern, and western limbs. The prevalent platinum group metal ore bodies known as the Merensky Reef and Upper Group 2 (UG2) are mined on the eastern and western limbs.

The BIC comprises the Rustenburg Layered Suite, the Lebowa Granite Suite and the Rooiberg Group and is overlain by Karoo sediments. Some of the most highly expansive soils in South Africa are the black and grey subtropical clays that developed as residual and transported soils from the mafic and ultramafic rocks of the Rustenburg Layered Suite. For comparison, similar soils from other parts of the world are known as “tropical black clay soils”. Most subtropical black clays were formed by the in-situ decomposition of mafic and ultramafic rocks as is predominantly the case of the clays discussed herein.

The geology of the area comprises gabbro-norite and pyroxenite of the Rustenburg Layered Suite of the BIC. Several platinum tailings storage facilities in southern Africa have been constructed on these residual gabbro-norite soils.

2.2. Fieldwork

Test pitting around the perimeter of the TSF was undertaken. The profile at the site generally consists of transported silty sand, overlying residual gabbro-norite clay. The clay is underlain by medium-hard rock gabbro-norite. Several small rock outcrops were observed.

The residual norite clay was encountered in all the test pits. The thickness of the clay varies between 0.4m and 1.8m. The consistency varies slightly but was described as soft to stiff. The clay was observed to be slickensided and shattered with fissures. The clay is calcified sporadically and the degree of cementation ranges from very weakly cemented to cemented. Calcrete nodules were encountered in some test pits.

2.3. Laboratory Testing

A range of routine and advanced tests were undertaken by specialist accredited facilities. These tests were conducted on disturbed and undisturbed soil samples, where the undisturbed soil samples consisted of block samples. Testing included:

- Particle size distribution and Atterberg limit determination.
- Oedometer (1-dimensional consolidation) testing
- Consolidated undrained triaxial testing
- Triaxial permeability testing
- Ring shear testing

2.4. Material Parameters

The engineering characteristics of black clays can typically be described as having a clay content higher than 30 percent and sometimes as high as 60 percent, of which montmorillonite is usually the predominant clay mineral. Liquid Limits (LL) are all exceptionally high (typically in the range of 50 to 110) and Plasticity Indices (PI) often measured in excess of 30.

The consolidation characteristics of the clay describes the behaviour when it is subjected to a surcharge pressure and excess pore water pressures are dissipating. The coefficient of consolidation (c_v, measured in m^2/year) is not a material parameter and varies depending on the effective vertical stress (σ'_v, measured in kPa) that the soil is subjected to. Based on several oedometer test results the following material specific relationship was established:

$$c_v = 424.51\,\sigma'_v{}^{(-1.341)} \tag{1}$$

The coefficient of consolidation can also be used to describe the permeability of the clay at the different effective vertical stresses. This can be used to explain that at higher vertical effective stresses (when the coefficient of consolidation is low) the dissipation of excess pore water pressures is slower due to decreased permeability.

The drained shear strength parameters of the clay were established by undertaking several iso-tropically consolidated undrained triaxial tests. The shear strength parameters determined for the tailings and clay are summarised in Table 1.

Table 1. Material Parameters Used in Limit Equilibrium Analyses

Material	**Unit Weight (kN/m^3)**	**Friction Angle (°)**	**Cohesion (kPa) (from lab results)**	**Cohesion (used in models)**
Tailings	22	33	0	0
Clay	18	19.5	23.6*	0*

*Triaxial testing undertaken was on samples described as calcified. The cementation caused by the calcification is probably the reason for the cohesion. Test pitting indicated that the calcification around the dam was not consistent. Therefore, for further analyses and calculations, the clay cohesion is assumed to be zero.

Figure 1 below illustrates that the clay does experience some post peak strength loss, but the clay did not fail in a brittle way. This is illustrated by calculating a brittleness index (IB) of 0.32 at higher confining pressures.

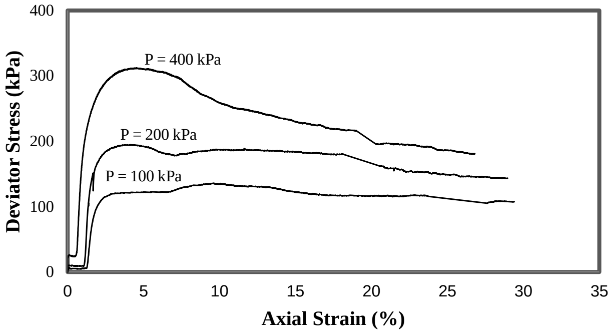

Figure 1. Clay Stress-strain curves

3. Methodology

The clay parameters and characteristics, detailed in the previous section, were used in calculations and analyses to determine the behavioural characteristics of the clay layer. The investigation primarily included accurately computing the excess pore water pressures generated in the clay layer as the height of a TSF is increased. This was done by considering the consolidation characteristics of the clay, as well as the deposition strategy in terms of Rate of Rise (RoR) of the TSF.

Once the excess pore water pressures in the clay foundation were quantified, limit equilibrium slope stability analyses were used to model the clay under partially drained conditions. This assisted in understanding the influence of the clay foundation on the Factor of Safety (FoS) of the TSF. The procedure and methodology of which is detailed in this section.

3.1. Slope Stability and Limit Equilibrium Analysis

A generic model with a slope of 1 in 3 (18.4°) was analysed. TSF heights of 10 m to 128 m were analysed at 10 m vertical height intervals.

Limit equilibrium slope stability software was used to analyse the slope resistance against failure, and to calculate the FoS, with special consideration of the effects that the clay foundation has on this resistance. It should be noted that the base case scenario consists of slopes that were assessed with the clay under partially drained conditions and the tailings under drained conditions. A second case was then assessed to illustrate the clay and tailings under drained conditions.

3.2. Excess Pore Water pressure generation

There are multiple ways in which excess pore water pressures may be generated in a clay foundation. For the purpose of this study, only the case in which excess pore water pressures are generated by a load placed on a saturated soil layer was considered. The method of conversion for use in the limit equilibrium model will still apply no matter the method of generation of the excess pore water pressures. At the time of placement, the magnitude of excess pore water pressure in the saturated soil layer is equal to the surcharge pressure. The excess pore water pressure will then dissipate over a period of time as a function of the permeability and the drainage path length of the layer.

For this case study, the excess pore water pressures generated in the clay foundation will be considered only. The surcharge pressures will consist of the slurry deposition onto a TSF. The deposition of slurry is modelled using a varying RoR approach which simulates the effect of altering the RoR of a TSF, as a mining house ramps up production. The RoR used for the analysis can be seen in Table 2.

Table 2. Value of RoR at different heights of the TSF

Heights from which the RoR is applicable (m)	Rate of Rise (m/year)
0 – 65	1.5
65 - 128	2.5

The dissipation of excess pore water pressures in a soil layer is governed by the soil's permeability and the shortest drainage path of the layer. From the fieldwork of the case study, the clay layer is considered to have single drainage (there is permeable material above, but not below the clay layer) and the drainage path is equal to the thickness of the clay layer. The thickness of the clay layer (determined from the test pit profiles recorded during the field work) was measured to be a maximum of 1.8 m thick.

The excess pore water pressures in the clay foundation were calculated using the parameters listed in Table 3.

Table 3. Summary of parameters used for excess pore water pressure calculations

Parameter	Value	Comment
Coefficient of consolidation (c_v)	0.032 – 2.022 m^2/year	Determined using the oedometer test results. The range of c_v values is due to the difference in effective stress levels at different elevations of the TSF.
Drainage path length	1.8 m	Determined as the thickness of the clay layer due to the presence of single drainage path conditions.
Pressure induced by each deposition cycle	2.75 kPa (0 - 65m) 4.58 kPa (65m - 128m)	The pressures were calculated using a yearly RoR of 1.5 m/year and 2.5 m/year to account for a hypothetical change in deposition strategy. These RoR values were then multiplied by a platinum tailings density of 22 kN/m^3.
Time between deposition cycles	30 days	

Using the parameters listed in Table 3, the excess pore water pressures generated in the clay foundation were calculated using Terzhagi's theory of one-dimensional consolidation. The equation used is given as:

$$u_e = \sum_{n=1}^{n=\infty} \frac{2u_i}{n\pi} (1 - cosn\pi) \left(sin\frac{n\pi z}{2d}\right) exp\left(-\frac{n^2\pi^2 c_v t}{4d^2}\right) \quad (2)$$

Where:

ue – Total excess pore water pressure
ui – Initial excess pore water pressure
d – Drainage path length
cv – Coefficient of consolidation (1D)
z – Depth within soil layer
t – Time

This equation was used to estimate the excess pore water pressures generated in the clay foundation at different heights as time progressed. A simple code was written in Microsoft Excel's VBA to run iterations of the equation. The excess pore water pressures were calculated for each height increment scenario that was modelled, i.e. 10 m vertical height intervals from heights of 10 m to 128 m. During the life of any TSF, the excess pore water pressures will undergo multiple cycles of generation and dissipation as tailings is alternatively deposited and left to dry. For this case study, as the number of cycles increases so will the magnitude of excess pore water pressure. This is due to the process of excess pore water pressure generation occurring faster than the dissipation. This is shown in Figure 2.

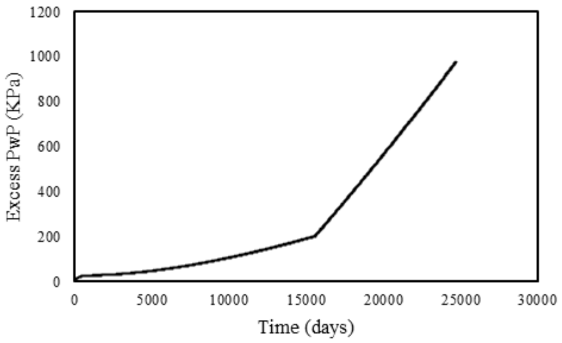

Figure 2. Maximum excess pore water pressure with time

It is evident in Figure 2 that the excess pore water pressure rapidly increases during the initial stages of loading the clay. The excess pore water pressure then proceeds to follow an exponential curve as time progresses. After approximately 16 000 days, the RoR is changed from 1.5 m/year to 2.5 m/year. At this point, the excess pore water pressure curve follows a steeper projection as time progresses. The exponential shape of the curve is still partially visible but has reduced to more of a straight line. At the final height of 128 m, the excess pore water pressure has increased to a maximum of 978.16 kPa.

It should be noted that Figure 2 shows the maximum excess pore water pressure in the clay. This is at the impermeable boundary surface.

3.3. B-bar value Determination

After the excess pore water pressure has been determined for the clay layer, a constant is required to relate a surcharge pressure to the generation of these excess pore water pressures for input into the limit equilibrium software. This constant value is known as the B-bar ($\overline{\mathrm{B}}$) value and can be numerically expressed as follows:

$$\overline{\mathrm{B}} = \frac{\Delta \mathrm{u}}{\Delta \sigma_{\mathrm{v}}} \tag{3}$$

Where, $\overline{\mathrm{B}}$ is the constant B-bar value, $\triangle$u is the change in pore pressure and $\triangle\sigma_v$ is the change in vertical stress.

To include the calculated excess pore water pressures in the limit equilibrium software, the term $\overline{\mathrm{B}}\triangle\sigma_v$ should equal $\triangle$u. A B-bar value should, therefore, be chosen such that this expression holds true. For ease of analysis, the procedure adopted for this study consisted of assuming a B-bar value of unity and adjusting the height of the surcharge layer to a layer thickness that is equal in weight to the desired excess pore water pressures. A conservative approach was undertaken whereby the maximum excess pore water pressure within the clay layer was used in expression (3).

Using this approach, the desired excess pore water pressures can be assigned to any specific region of the clay layer for calculation of the FoS using the limit equilibrium models.

3.4. Thickness of tailings generating excess pore pressure in the clay

In order to account for the excess pore water pressure within the clay in a limit equilibrium model, the method described in this section was followed.

The thickness of the tailings layer directly relates to the generation of excess pore water pressures in the clay. This tailings layer forms a part of the overall TSF geometry and will be referred to as the surcharge layer from this point on. The calculation of the thickness of the surcharge layer follows on from the discussion of the calculation of the B-bar value.

The calculation of the tailings layer thickness can be done by making use of Equation (2) and setting the B-bar value equal to one. The change in pore pressure and vertical stress are, therefore, set equal to one another. The surcharge layer thickness can then be calculated with known excess pore water pressure and tailings unit weight values.

Due to the geometry of most TSFs, the clay will not experience a constant excess pore water pressure for each height scenario. This is due to the outer slope of the TSF and its distribution of stress to the foundation material. The clay layer outside the toe of the TSF will not generate any excess pore water pressures as no surcharge pressure is exerted on this region of the foundation strata. The clay layer just inside the toe of the TSF (below the outer slope of the TSF) will experience an increase in excess pore water pressure until the slope above the clay has reached its final geometry. From this time, the excess pore water pressure in the clay will dissipate at a rate corresponding to the coefficient of consolidation, until the excess pore pressures are equal to zero. The clay layer beneath the basin of the TSF will experience the highest excess pore water pressures as the height of the TSF increases with deposition. It should be noted that the case study under consideration is an upstream constructed TSF. However, the same procedure may be applied to all TSF construction methods with special consideration to how the clay foundation is being loaded with time.

The model representing what is described above is shown in Figure 3. In this figure, the purple layer is the surcharge layer that is responsible for the generation of excess pore water pressures. The decrease in thickness of the surcharge layer towards the outer toe of the TSF visually illustrates the decrease in the excess pore water pressures present in the clay towards the outer toe of the TSF.

It should be noted that the layer referred to as the “surcharge” layer does form a part of the geometry of the TSF and is not an additional layer. The surcharge layer is merely a layer of tailings with the same material properties as the surrounding tailings, with the only difference being that the effective stresses induced by this surcharge layer has been allowed to generate excess pore water pressures in the clay foundation layer.

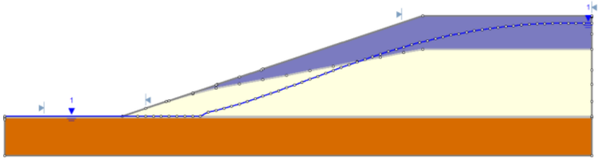

Figure 3. Representation of surcharge layer (purple) for the final height scenario

4. Results

4.1. Limit Equilibrium Results

The base case scenario consists of slope stabilities that were assessed with the clay under partially drained conditions and the tailings under drained conditions. A second case was then assessed to illustrate the clay and tailings under drained conditions. The tailings and other soils were assessed purely under drained conditions as it was deemed to be outside the scope of this paper. The results of the slope stability analyses can be seen in Table4 and Figure 4.

Table 1 presents the material properties used in the limit equilibrium analyses.

Table 4. Factor of safety for different height scenarios (with $u_{e} = 0$ kPa)

Height Scenario (m)	**FoS - Base Case (Partially Drained Conditions)**	**Maximum Excess Pore Pressure in Clay – Base Case (kPa)**	**FoS - Second Case (Drained Conditions)**
10	1.32	31.8	1.41
20	1.48	46.9	1.51
30	1.57	70.7	1.59
40	1.62	101.7	1.63
50	1.63	138.8	1.64
60	1.66	181.1	1.66
70	1.66	263.2	1.68
80	1.66	380.1	1.69
90	1.59	499.8	1.65
100	1.54	622.0	1.61
110	1.47	746.7	1.57
120	1.42	873.6	1.53
128	1.34	978.2	1.49

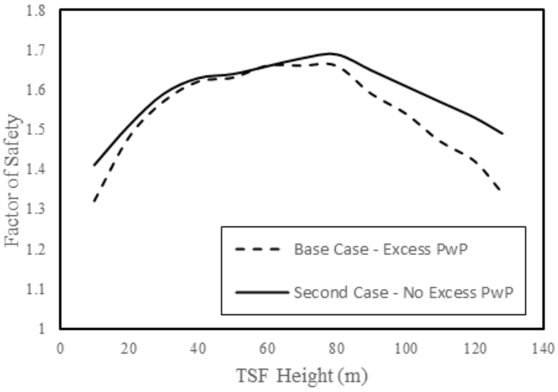

Figure 4. Summary of the slope stability factor of safety for each height

It is evident from Table 4 and Figure 4 that the FoS for the case in which no excess pore water pressures are present in the clay layer (second case) are higher than the FoS for the case in which excess pore water pressures are present in the clay layer (base case). This is primarily due to the reduction in strength of the clay layer under partially drained conditions compared to a clay layer under drained conditions.

Furthermore, it should be noted that for a few of the height scenarios presented in Table 4 and Figure 4, the FoS calculated for the base case and the second case are similar. This is likely attributed to the position of the slip surface in relation to the clay in which the pore pressures have been generated. If the clay in which the critical slip surface passes through contains little to no excess pore water pressures, then the FoS will be similar to that of the scenario in which the clay is under drained conditions.

4.2. Sensitivity Analysis – Rate of Rise

This section serves to assess the sensitivity of parameters that typically remain uncertain in models and are deemed to have a relatively significant influence on the results of an investigation. For this case study, only the sensitivity of RoR was assessed.

In order to assess the sensitivity of RoR, this parameter was changed after a TSF height of 65 m to analyse the influence on the FoS of the TSF. The base case model, detailed in Section 3.1, had a RoR of 1.5 m/year until a TSF height of 65 m was reached. Thereafter, a 2.5 m/year RoR was used up to and including a TSF height of 128 m.

This sensitivity analysis will assess the implications of slightly decreasing the RoR (to 2 m/year) or increasing the RoR (to 3 m/year) at heights greater than 65 m. By decreasing or increasing the RoR of a TSF, the excess pore water pressures generated in the clay layer will decrease or increase, respectively. The generation of excess pore water pressures in the clay is, therefore, directly proportional to the RoR of a TSF. This is illustrated in Figure 5 below.

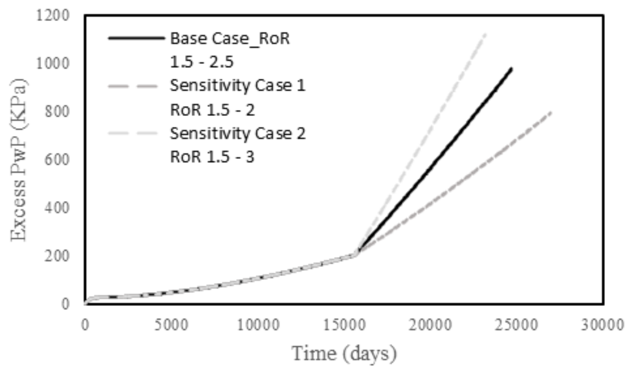

Figure 5. Excess pore water pressures for different RoR scenarios

From Figure 5, it is evident that with an increase in RoR there is an increase in the generation of excess pore water pressures in the clay. It should also be noted that in the cases where the RoR was lower, the final height of 128 m was only reached after a greater number of days. The maximum excess pore water pressures generated in the clay for each scenario can be seen in Table 5.

Table 5. Summary of maximum excess pore water pressures for different RoR scenarios

Model Scenario	Initial Rate of Rise (m/year)	Final Rate of Rise, after 65 m (m/year)	Maximum Excess Pore Water Pressure in Clay (kPa)
Base Case	1.5	2.5	978.2
Sensitivity Analysis 1	1.5	2.0	793.9
Sensitivity Analysis 2	1.5	3.0	1120.7

The calculations of excess pore water pressures in the clay were used to determine the thickness of the surcharge layers for use in the limit equilibrium slope stability models, as described in Section 3.4. Models were then analysed for the various heights of the TSF for each of the model scenarios. Figure 6 illustrates three different slope stability models which represent the TSF case study at 128 m for each of the respective RoR scenarios. The base case scenario has been included for ease of reference.

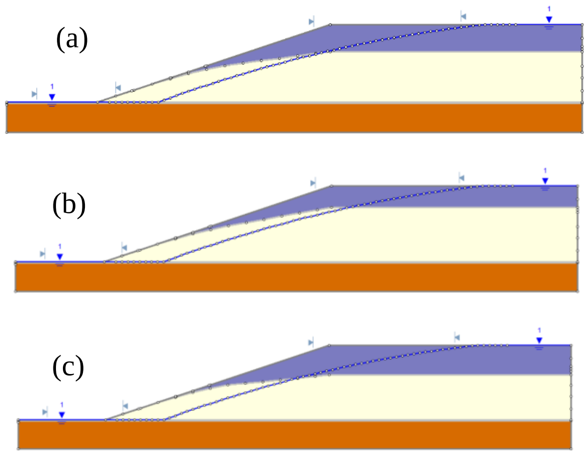

Figure 6. Model geometry for different RoR scenarios. (a) Base Case: 1.5 - 2.5 m/year (b) Sensitivity 1: 1.5 - 2 m/year (c) Sensitivity 2: 1.5 - 3 m/year

If Figure 6 is assessed carefully, a clear distinction between the thicknesses of the surcharge layers (purple layer) is evident. This is due to the difference in the desired generation of excess pore water pressures for each case. The higher the required excess pore water pressure in the clay, the thicker the surcharge layer.

Using the abovementioned slope stability models, Figure 7 illustrates the values of FoS that were calculated for each case. The sub-scenarios in which excess pore water pressures and no excess pore water pressures were considered can also be seen in Figure 7.

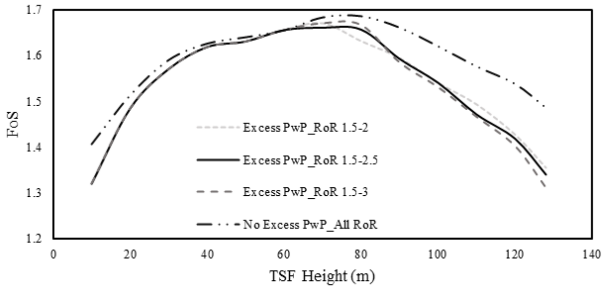

Figure 7. Summary of slope stability factors of safety for the base and sensitivity cases

5. Discussion and Analysis of Results

Based on the results, summarised above, the following was noted:

- The generation of excess pore water pressures in the clay layer is a function of the RoR (and subsequent properties of surcharge load), the stress dependent cv value, the clay thickness and the drainage conditions;
- Values of excess pore water pressures can be quantified and represented in limit equilibrium slope stability models;
- An increase in RoR will result in higher excess pore water pressures generated in the clay;
- Excess pore water pressures in the clay (partially drained conditions) result in a lower FoS when compared to the case in which no excess pore water pressures (drained conditions) are present;
- The higher the excess pore water pressures in the clay layer, the lower the overall FoS;
- As per the results of the sensitivity analysis, it can be concluded that changing the RoR (deposition strategy) will influence the FoS. An increase in the RoR over the life of a TSF will reduce the FoS for each 10 m height interval, when compared to the base case scenario.

6. Conclusions

It was concluded that excess pore water pressures in the clay foundation significantly affect the FoS of the TSF, particularly at greater height scenarios. This is primarily due to the low permeability and stress dependent coefficient (cv) of the clay layer as the surcharge load increases. It was further shown that, depending on the RoR, deposition onto the TSF may induce excess pore water pressures which could lead to a reduced FoS.

Based on the fact that the generation of excess pore water pressures reduces FoS, it is significant that these pressures may be quantified using the novel approach described in this paper. The FoS for other facilities underlain by residual or transported low permeability materials may, therefore, be estimated more accurately. The use of this technique may also be implemented in studies conducted on similar, low permeability, materials.

Furthermore, it should be noted that laboratory testing and fieldwork plays a major role in accurately quantifying the excess pore water pressures induced in low permeability materials.

The technique described within this paper is for using limit equilibrium techniques (only) to consider the effects of excess pore water pressures in a foundation. The inclusion or consideration of excess pore water pressures in foundation materials can also be done using a coupled finite element analysis.

7. References

ICMM, August 2020. Global Industry Standard on Tailings Management, s.l.: GlobalTailingsReview.org.

Oelofse et al., 2020. Assessment of undrained behaviour in black turf clay, Johannesburg: SRK Consulting.