A case study on the stability of an Ash Dump Facility

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ABSTRACT: This case study evaluates the impact of stacking arrangements on slope stability for the southern extension of the Majuba Ash Dump Facility (ADF). The study incorporates available geotechnical data to assess local and global slope stability, considering factors such as safe edge distances (SED), sensitivity to material density and shear strength parameters and pseudo-static loading. Failure surface analysis is conducted using limit equilibrium design and Rocscience's Slide2 software. The results show that stacking methodologies can either compromise slope stability or enhance it, with specific challenges posed by clayey residual shale and clayey hillwash materials found across the site. The over-consolidated nature of founding soils was found to influence settlement, shear strength, and stability, particularly under sequential consolidation of stacking tiers. Increasing tier heights reduced slope stability, while targeted toe loading improved local and global safety factors. This paper adds to the body of knowledge on ADFs and provides insights into optimising stacking strategies to achieve improved slope stability, for both interim slopes and final closure designs.

1 INTRODUCTION

The slope stability of ash dump facilities (ADFs) is important to minimise adverse consequences to the environment and the safety of personnel and infrastructure located in close proximity to the ADF. Given the growing energy demands of South Africa, optimising the storage and placement of ash, a by-product of coal-fired power generation, becomes a critical challenge. Often times the original design philosophy is not applied during operations, where stacking philosophies may be changed to suit. Effective management of ash dump stability not only ensures operational safety but also promotes sustainable practices in waste management.

This paper presents a case study of the southern extension of the Majuba Ash Dump Facility (ADF), a "dry" ash facility, where alternative stacking arrangements were explored to assess their influence on slope performance. The study highlights how factors such as soil material strength parameters, founding soil conditions, and seismicity affects drained and undrained soil response, and govern the stability and performance of ADF slopes. By identifying stacking tiers susceptible to local and global failures, the study emphasises the importance of informed design and operational strategies aligned to design.

A key aspect of the investigation was the characterisation of the representative founding soils, predominantly clayey, residual shale and clayey hillwash, and their impact on settlement and overall slope stability. Allowing for consolidation of stacking tiers emerged as an important factor in understanding slope performance over time. Furthermore, the study examined cutback options to ensure that sensitive slopes remained within their required safety thresholds, effectively mitigating slope failure risks.

The study employed limit equilibrium software Slide2 by Rocscience™, to conduct sensitivity analyses of material densities, pseudo-static loading conditions, and non-circular failure surface search methods. Safe edge distances (SEDs) to ensure operational safety for stackers, conveyors, and associated infrastructure, were considered. The findings of this study emphasise the importance of targeted toe loading and strategic stacking methodologies in improving local and global factors of safety (FoS). By quantifying the magnitude and spatial extent of these enhancements, the results provide insights for optimising stacking strategies and enhancing slope stability. This paper aims to contribute to the broader understanding of geotechnical and operational considerations critical to the sustainable management of ADFs.

2 BACKGROUND AND SITE DESCRIPTION

2.1 *Geology and site conditions*

The southern extension of the Majuba ADF, located in the semi-humid region of Mpumalanga, with a Weinert Climatic N-value of less than 5 (Weinert, 1980), is underlain by clayey hillwash and clayey, residual shale of the Volksrust Formation, Ecca Group, Karoo Supergroup. The normally consolidated saturated clayey residual shale is often characterised by low shear strength which negatively influences slope stability. The current over-consolidated state of the clayey residual shale is assessed as it is prone to change state as the ash deposition loads the material. The over-consolidated nature of the soil is attributed to historical climatic conditions, including cycles of wetting and drying, the weight of previously deposited geological layers that have since eroded, and the impact of glacial activity during past ice ages (Rajapakse, 2016). Glaciers exerted vast pressure on the underlying soils, with the overburden contributing to their over-consolidated state. This glacial influence is suspected to have further enhanced the stiffness of the soils, but consideration of the soils being loaded to a normally consolidated state under loading by the new ADF, needed to be assessed.

The new ADF extension is approximately 80m high, constructed of coal ash with natural bulk unit weight between 11.4kN/m^3 to 15.6kN/m^3, with the ash's typical moisture content at 20%. The subsoil's estimated pre-consolidation stress tending closer to the current effective vertical stress exerted on the subsoil, due to the additional ash mass deposited thereon. When that happens, the in-situ soil would transition to a normally consolidated state. This realisation affects the stress ranges specified for the shear testing to ensure that realistic shear strength parameters are incorporated into the analyses. For this study, the slope stability sections were zoned for over-consolidated and normally consolidated behaviour and their consolidation and shear strength parameters applied accordingly.

2.2 *Stacking philosophy*

The stacking philosophy focuses on maintaining consistent and proportional face progression to minimise the risk of operational failures caused by temporary or interim slope geometries. Figure 1 presents a general stacking arrangement with two stackers able to stack in both directions, i.e. backstack and frontstack.

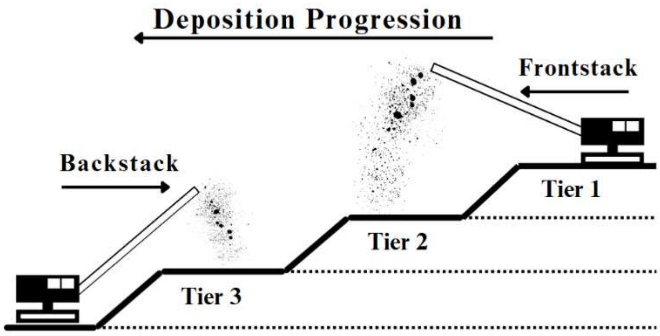

Figure 1. Stacking arrangement with associated tiers

Sensitivity analyses were conducted on different tier heights to find the optimal sequence and geometry for deposition, where the aim was to mitigate the development of deep-seated failure mechanisms occurring during operations.

3 APPROACH AND METHODOLOGY

3.1 *Data collection*

To develop the ground models for the respective sections in the north-south orientation, the use of historical test pit and borehole data was used, augmented with dynamic probe super heavy (DPSH) tests and additional test pits conducted more recently. This enabled the development of a more comprehensive model and representation of the underlying stratigraphy of the site. Consolidated Undrained Triaxial laboratory testing was done on disturbed and "undisturbed" samples to ascertain soil characterisation and shear strength parameters. Table 1 presents the primary ground parameters.

Table 1. Primary ground strength parameters

Material	Internal Drained Friction Angle ϕ' (°)	Cohesion Intercept, c' (kPa)
Ash	33	40*
Clayey Residual Shale	35	8
HDPE Liner/Clay Interface	22.4	54.8
HDPE Liner/Ash Interface	33.2	39.4

* Higher than the expected ranges of cohesion for coal ash, likely influenced by apparent factors such as soil suction and cementation over time. Hence conservatively assumed to be zero within slope stability ground models.

3.2 *Analytical tools and modelling*

Limit equilibrium software, Slide2, by Rocscience, was used to assess the slope stability of the ADF. Structural interfaces such as the double textured HDPE geomembrane liners, including geomembrane/clay and geomembrane/ash interfaces, were included in the models. The Limit Equilibrium Method (LEM) by Morgenstern-Price (Morgenstern and Price, 1965), was employed. This method was chosen because it satisfies both force and moment equilibrium. Advanced optimisation techniques, including Simulated Annealing (SA) and Cuckoo Search (CS) algorithms, were integrated to efficiently identify critical slip surfaces by refining failure paths in complex scenarios. Using modelling software, these methods facilitated comprehensive sensitivity analyses, evaluating the effects of varying material properties, loading conditions, and geometric configurations on slope stability.

3.3 *Slope stability criteria*

The slope stability of the ADF extension was evaluated against the following Factor of Safety (FoS) criteria: (a) Static drained (no seismicity). This case relates to a monitored, operational case where no sudden loading takes place (rather "slow loading") and conditions are drained, with a required FoS of at least 1.3 (b) Static undrained loading (no seismicity). This case relates to a short-term and quick loading scenario, where monitoring is taking place, but where pore pressure increases due to short-term loading occur in low permeability layers (particularly the clayey foundation layers), with a required FoS of at least 1.3 (c) Undrained conditions, with seismicity. This case relates to a short-term loading with seismic loading scenario. Pore pressures occur in low permeability layers (particularly the clay foundation layers), with a required FoS of at least 1.1. In the absence of any specified seismic loading by the client, a conservative pseudo static load based on a conservative Peak Ground Acceleration (PGA) of 0.1g, is applied based on SANS10160 (Part 4 – Seismic Loading). A site-specific seismic study may yield more appropriate and likely lower values.

To ensure that operating equipment (stackers and conveyors) and personnel remain safe from slope failure, a SED for each bench was determined. This was done by identifying the critical failure surfaces in relation to the criteria stated earlier. Slide2 software's built-in function to exclude specific slip surfaces was utilised to remove those failure surfaces emerging as "critical", but that are deemed to be manageable during operation. "Shallow" failures were defined as those with a vertical slice depth of 5 to 10m, while "deeper" failures were defined as those exceeding 15m. These were used to define the SED distance. Failures within 5–10m depths were deemed manageable through routine maintenance, given that their mechanisms were confined within the SED area. Smaller, shallow slips occur regularly and are attributed to short-term oversteepening of the ash due to soil suction. These short-term over-steepenings are disregarded in the SED distance allocation and are not critical.

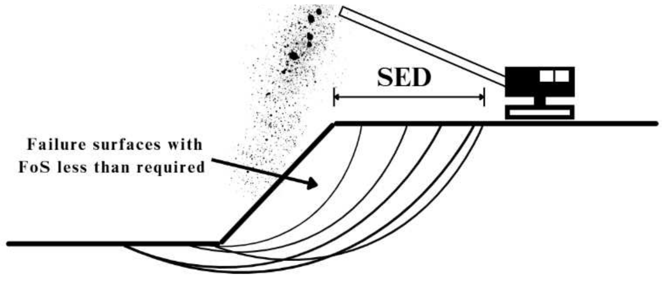

Figure 2. Schematic of SED determination from failure surfaces

3.4 *Applying historical imagery*

Historical satellite imagery, using Google Earth Pro™, was used to enhance the geotechnical campaign. With limited construction reports and as-built information available, interpretation was necessary to assess localised areas potentially more susceptible to weaker founding soils. The extent of ash deposition over the area of interest was determined using historical imaging. For example, the southeastern quadrant of the site was identified in the desktop study as a possible wetland or clay pan (see Figs 3 and 4).

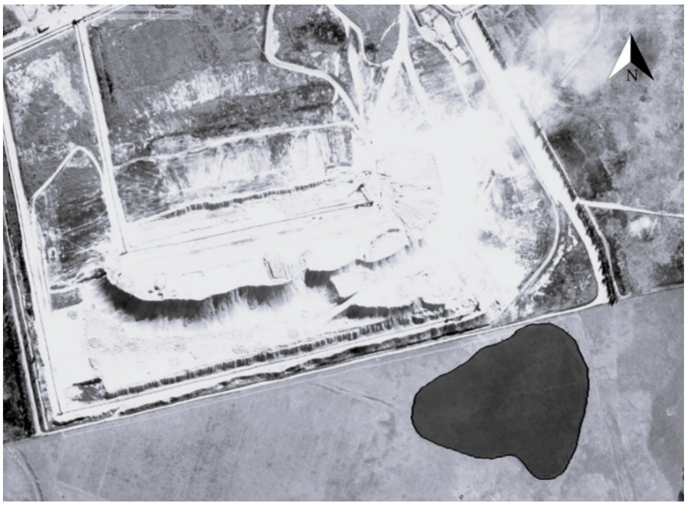

Figure 3. Reconnaissance approach of identifying possible areas of interest for geotechnical campaign. Identified area of interest outlined. May 2017.

Figure 4 illustrates the covering of the identified wetland area in later ashing operations. Knowing this, the area could be targeted for geotechnical investigation.

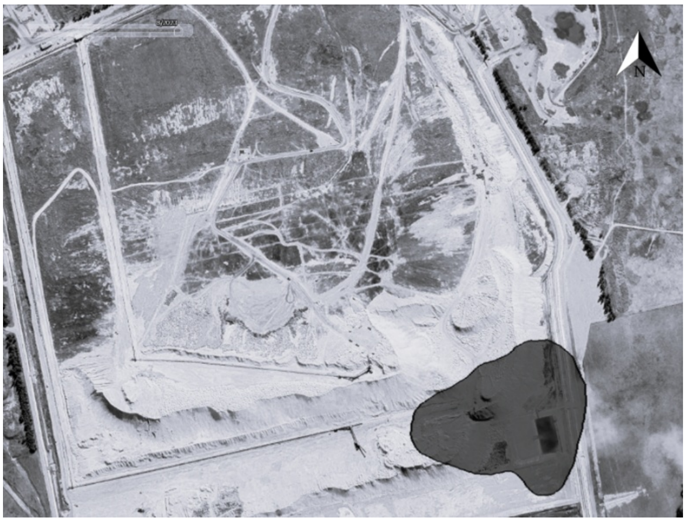

Figure 4. ADF extending across the identified wetland. August 2023.

The geotechnical campaign confirmed the value of historical imagery, with test pits and DPSH tests revealing extensive clayey residual shale and clayey hillwash. These findings were used to model the localised softer foundation as a weak zone, highlighting the potential for localised failure mechanisms. Consequently, the area was targeted for slope stability analyses.

4 FINDINGS

4.1 *Sensitivity to unit weight and shear strength parameters*

The bulk unit weight of the ash was found to range between 11.4 kN/m3 and 15.6 kN/m3. Sensitivity analyses were conducted to assess the impact of the variability of unit weight and shear strength on slope stability, considering (a) a case where shear strength remains constant; and (b) a case where shear strength changes across the range of unit weight. The analyses indicated that the governing factor of the sensitivity analysis was not the unit weight range of the ash alone, but rather the combination of unit weight and applicable shear strengths. The failure mechanisms developed with a bulk unit weight of 15.6 kN/m3, were compared to the ash with a bulk density of 11.4kN/m3, with no significant effect on FoS, as long as shear strength parameters were equal for the two cases. However, when keeping the unit weight constant for the two cases and lowering the angle of friction from 33° to 30°, and assuming that the cohesion intercept of the ash is zero (conservative approach), the effect on slope stability was notable and influenced the propagation and development of larger deeper failure mechanisms. Hence, rather than adopting a conservative approach (e.g., using a higher density and lower shear strength), the results emphasise the need to better map the ash body to assign appropriate density and shear strength combinations to specific zones within the ADF.

4.2 *Targeted toe loading*

The principle behind targeted toe loading is the provision of additional mass at the base of slopes where failure is most susceptible. This additional mass helps counteract driving forces by increasing resisting forces and expanding the shear zone. Targeted toe loading also aids in consolidating softer, saturated foundation layers in newly extended areas ahead of the advancing embankment. This reduces the risk of excess pore pressure build-up during ashing, which could otherwise lead to a loss of strength and potential slope failure. Figure 5 illustrates the principle of reinforcing susceptible toe regions, which can be compared to Figure 2.

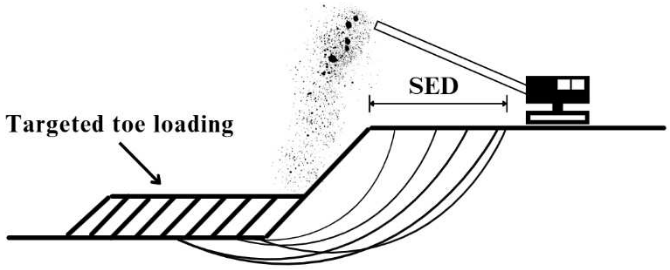

Figure 5. Approach of targeted toe loading.

Determining the appropriate magnitude and configuration of targeted toe loading is critical to enhancing stability without introducing further adverse effects to slope stability. Variables such as the width and height of the targeted toe loading govern stability. Overloading the toe can redistribute potential failure mechanisms, destabilising upper stacking tiers and affecting the SED. Additionally, rapid application of loads without allowing excess pore water pressures to dissipate may result in undrained conditions in saturated materials, increasing instability risks. To mitigate these challenges, toe loading was recommended to be applied incrementally, allowing gradual consolidation and dissipation of pore pressures, with continuous monitoring to adjust operations as required.

The application of toe loading was assessed to determine its effectiveness in improving the stability of the ADF, as well as the point at which it could adversely affect slope stability. Sensitivity analyses were conducted on the geometries of the targeted toe loading, and the results are summarised in Table 2.

Table 2. Slope stability results

Section	Scenario	Factor of Safety (FoS)	
		Without toe loading	Targeted toe load
Section A	Drained	1.4	1.6
	Undrained	1.1	1.3
	Pseudo Static	0.8	1.1

Toe support was only utilised if no other adverse mechanisms were induced. As illustrated in Figure 8, operational equipment was at risk due to the most likely failure mechanisms encroaching on its location. Figures 6 and 7 present the initial circumstances compared to the amended geometries with the addition of targeted toe loading, which mitigated the susceptibility of failure through weaker founding soils (clayey residual shale and hillwash).

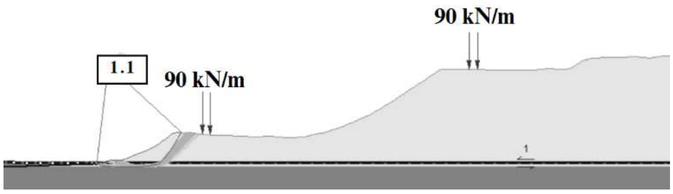

Figure 6. Slope stability before targeted toe loading, operational equipment at risk (Peak Undrained case). Showing all failure surfaces with FoS below 1.3.

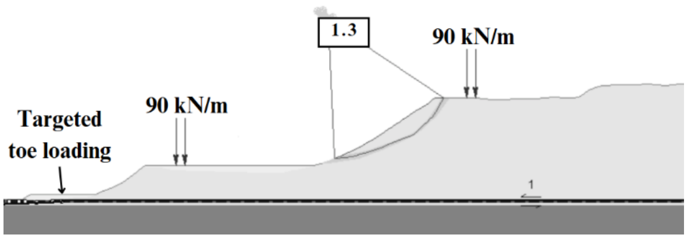

Figure 7. Stability after targeted toe loading, operational equipment not at risk (Peak Undrained case). Showing all failure surfaces with FoS equal to 1.3.

By adding a 5m height of material at the toe of the embankment across a width of 45m, the slope stability of the ADF was improved to meet design thresholds. The 5 m toe load effectively eliminated toe failure susceptibility, while newly identified failure mechanisms in the uppermost tier were deemed insignificant for temporary ADF slopes, as they did not encroach on the Safe Edge Distance (SED).

4.3 *Safe Edge Distance (SED)*

The stackers apply a load of 90kN/m across each of its two tracks, which are located 6m apart. The SED as illustrated in Figures 2, 6 and 7 represents the distance away from edge of the ADF slope, within which a zone where a higher likelihood of slope instability exists that may pose risk to stackers, conveyors, and operational staff. The SED needed to be > 15m to include any local over-steepening. This was practical as the stacker's boom reach was approximately 26m.

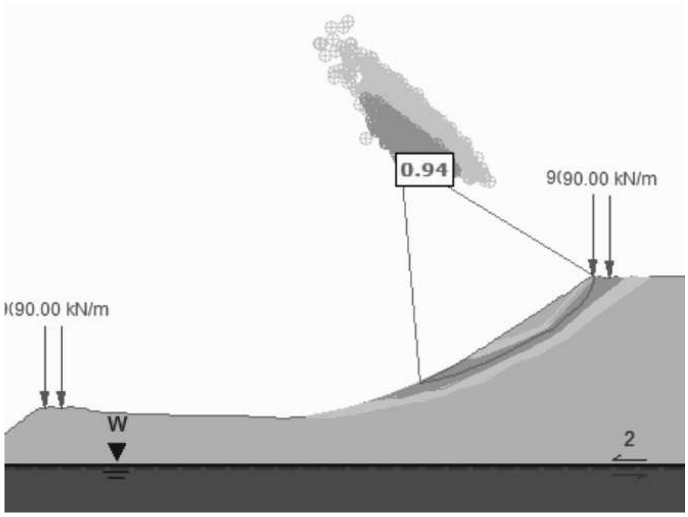

Figure 8. Encroachment into SED, operational equipment at risk (Pseudo-static case). Showing all failure surfaces with FoS below 1.1.

The local oversteepening illustrated below in Figure 9, was an alternative approach to determine the applicable SED. Each tier was divided into thirds to define the base flow and over-steepened areas: the top third was predominantly over-steepened, the middle third was in a purely frictional state at the angle of repose, and the bottom third was less steep, representing the base flow of the ash. The middle third said to be the angle of repose of the ash, which was extrapolated to the crest to determine the suitable SED, this methodology did not satisfy the requirements for the operational equipment safety. A sensitivity analysis was rather adopted to determine the applicable SED for each scenario.

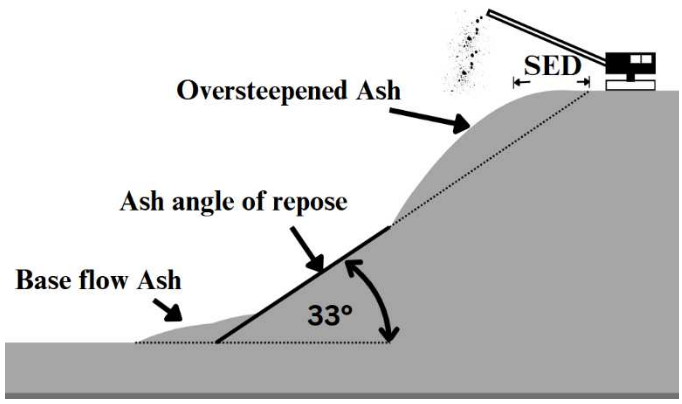

Figure 9. Alternative approach to determine SED. Considered not satisfactory.

4.4 *Allowing for Consolidation*

Due to the saturated, clayey soils occurring in the ADF footprint, undrained behaviour could occur if the area is loaded too quickly. Allowance had to be made to allow pore pressure dissipation by managing the ashing process by limiting the lift height and varying the location of ashing. In this way operational and slope stability requirements could be met. The consolidation time required for the dissipation of excess pore pressure due to the additional 65kPa induced by the 5m ash tier height over the respective progression areas was determined to be 46 days.

4.5 *Monitoring*

Conducting regular geotechnical monitoring to track settlement and stability trends over time assists management of the ADF. With deviations from stacking design geometries likely to occur, it is important to ensure interim slopes are within the allowable operational stability thresholds. The installation of key monitoring infrastructure, such as vibrating wire piezometers (VWPs) to monitor phreatic surface variations, and tilt meters to detect minor slope movement, is good practice to ensure stability and safety of operational equipment and staff.

5 CONCLUSIONS

This study highlights the importance of integrating geotechnical and operational considerations to optimise the slope stability of ash dump facilities. The southern extension of the Majuba ADF presented challenges, including localised weak zones due to historical wetland conditions, variable ash deposition patterns, and the need to ensure operational safety within the SED. These challenges were addressed through a combination of targeted geotechnical investigations, historical imagery analysis, adaptive slope stability modelling and monitoring. Key interventions included the addition of scenario specific toe loading applied across varying widths to eliminate failure mechanism propagation. The findings demonstrate that these measures improve slope stability, ensuring compliance with design thresholds and operational safety requirements. These insights contribute to safer and more sustainable practices at the Majuba ADF and provide a framework for addressing similar challenges in other ADF projects. They emphasise the value of targeted interventions and adaptive analytical approaches. The output of the modelling software is just as good as the user defined inputs and the interpreted ground model. It is important to consider all available historical geotechnical data and construct the most representative model such that the in-situ conditions are best represented. Where possible, planning ash deposition on new areas early enough such that there is sufficient time for consolidation of the material to take place and to minimise the rapid buildup of excess pore water pressure with limited dissipation is valuable.

6 RECOMMENDATIONS

Based on the findings, the following recommendations are proposed.

- Definition of the ground conditions is important. Soils that at lower over-consolidation ratios, may become normally consolidated when loaded during ashing. Laboratory and in situ testing should therefore account for this in the stress ranges tested.
- Historical satellite imagery could prove useful to identify areas to target in the ground investigation to ensure that driving mechanisms are addressed.
- Stacking methodologies may change through the life of an ADF. They should, however, always fit the local ground conditions and the drivers of slope stability to avoid unforeseen failures.
- Where soft ground exists, targeted toe loading as part of the ashing process can be used to provide stability for the advancing slope and to consolidate softer soil strata.
- Ensure SEDs for operational equipment to maintain safety during ash stacking operations.
- Monitor the slopes to ensure the design and operational philosophies always remain aligned.

ACKNOWLEDGMENTS

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