# Optimization Techniques for Failure Surface Identification in Dry Stacking Tailings: A Comparative Study

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ABSTRACT: This study evaluates the stability of a dry-stacked tailings storage facility using limit equilibrium analyses in Slide2. Eight scenarios were modeled, combining two search algorithms (Auto Refine Search and Cuckoo Search), static and pseudo-static loading conditions, and the presence or absence of a water table at the foundation–tailings interface. The results showed that the water table had negligible influence on safety factors, supporting the assumption of drained behavior and effective internal drainage. In contrast, pseudo-static loading significantly reduced stability, highlighting the importance of incorporating seismic effects in design. Both algorithms yielded nearly identical results under static conditions, while under pseudo-static conditions the Cuckoo Search identified slightly higher safety factors and deeper slip surfaces. Across all scenarios, critical slip surfaces developed predominantly between berms, suggesting that geometry and drainage play a central role in governing failure mechanisms. These findings provide insights into the influence of loading conditions and search strategies on the stability assessment of dry-stacked tailings facilities.
KEYWORDS: Tailings Stability, Failure Surface Identification, Cuckoo Search, Auto Refine Search, Geotechnical Optimization.

RESUMO: Este estudo avalia a estabilidade de uma instalação de disposição a seco de rejeitos por meio de análises de equilíbrio limite no software Slide2. Foram simulados oito cenários, combinando dois algoritmos de busca (Auto Refine Search e Cuckoo Search), condições de carregamento estático e pseudoestático, e a presença ou ausência de nível d'água na interface fundação–rejeito. Os resultados indicaram que o nível d'água teve influência desprezível nos fatores de segurança, confirmando o comportamento drenado e a eficiência do sistema de drenagem interna. O carregamento pseudoestático, por sua vez, reduziu de forma significativa a estabilidade, destacando a necessidade de considerar efeitos sísmicos no projeto. Ambos os algoritmos apresentaram resultados semelhantes sob condições estáticas; entretanto, sob carregamento pseudoestático, o Cuckoo Search identificou fatores de segurança ligeiramente superiores e superfícies críticas mais profundas. De modo geral, as superfícies de ruptura se desenvolveram entre bermas, sugerindo que a geometria e a drenagem governam os mecanismos de instabilidade em sistemas de empilhamento a seco.

PALAVRAS-CHAVE: Estabilidade de Rejeitos, Identificação de Superfícies de Ruptura, Cuckoo Search, Auto Refine Search, Otimização Geotécnica.

# 1 INTRODUCTION

The geotechnical stability of tailings storage facilities (TSFs) has become a growing concern worldwide, particularly in the aftermath of catastrophic failures with severe environmental and social consequences (Massignan and Sánchez, 2024). In response, dry stacking of tailings has emerged as a safer alternative to conventional hydraulic disposal, since it reduces the risk of liquefaction and large-scale collapse, especially in seismic or high-rainfall regions (Su et al., 2024).

A critical challenge in the stability assessment of dry-stacked TSFs lies in the identification of realistic failure surfaces. The stratified, compacted, and partially saturated nature of these deposits results in anisotropic and heterogeneous behavior, with potential weaknesses at lift interfaces and from compaction inconsistencies (Bruschi et al., 2023; Doi et al., 2023). Traditional limit equilibrium methods often assume simplified, circular geometries, which may not represent actual failure mechanisms.

To overcome these limitations, numerical tools have incorporated optimization algorithms capable of exploring complex solution spaces and avoiding local minima. In particular, Auto Refine Search (ARS) and Cuckoo Search (CS) have gained attention for their ability to capture non-circular or compound slip surfaces more efficiently and accurately (Shah Malekpoor et al., 2024; Soranzo et al., 2022). Despite their increasing application (Chen et al., 2020; Hussen et al., 2024; Phoon et al., 2022), no systematic studies have compared their performance in the context of dry stacking, where unsaturated behavior and construction-induced heterogeneities strongly influence stability.

This study addresses this gap by evaluating and comparing ARS and CS in the stability analysis of a dry-stacked TSF through limit equilibrium modeling. The objective is to assess their relative strengths and limitations in predicting critical slip surfaces under layered, partially saturated conditions, providing insights to improve design and risk assessment practices.

# 2 METHOD

This study evaluates the stability of a dry stacked tailings facility through limit equilibrium analyses, considering both static and seismic conditions. A geotechnical-geological cross-section of a fictional structure was defined based on typical material properties found in dry stack deposits and underlying foundation soils, as demonstrated in Figure 1.

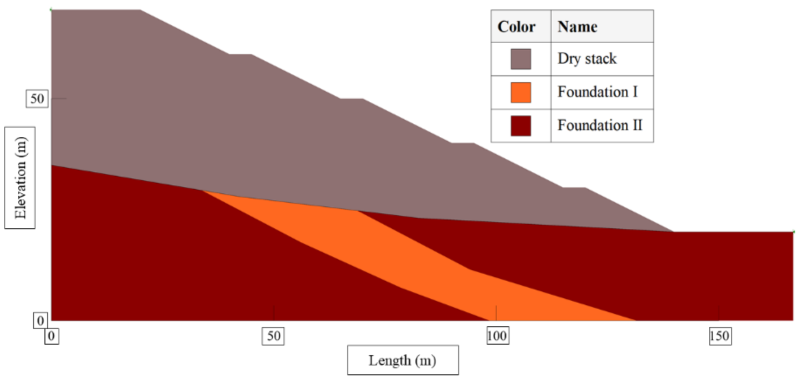


Figure 1. Geotechnical section applied in the study.

## 2.1 Geotechnical model

The geotechnical parameters adopted for the stack and foundation materials were defined under drained conditions, consistent with the low degree of saturation typical of dry-stacked facilities. Values of unit weight, cohesion, and friction angle were selected based on engineering practice and reference ranges commonly used for similar materials. As this study is intended as a numerical simulation, no laboratory testing was performed. Nevertheless, it is acknowledged that uncertainties may arise from heterogeneity, placement conditions, and fabric effects, which can influence the adopted values. The parameters are summarized in Table 1.

Table 1. Geotechnical parameters adopted for the stability analyses.

| Material | Dry unit weight (kN/m³) | Cohesion (kPa) | Friction angle (°) |
|---|---|---|---|
| Dry stack | 23.0 | 3.0 | 29.0 |
| Foundation 1 | 20.0 | 6.0 | 28.0 |
| Foundation 2 | 20.0 | 8.0 | 31.0 |

The assumption of drained conditions is justified by the presence of a designed engineered drainage system, which effectively minimizes porepressure within the tailings stack. This drainage system limits the degree of saturation and thereby mitigates the potential buildup of excess pore pressures, an important factor in maintaining stability.

### 2.2 Limit Equilibrium Analysis

Stability analyses were performed in Slide2 (Rocscience) using Morgenstern-Price limit equilibrium method to evaluate safety factors for potential failure surfaces. Two optimization algorithms were applied: Auto Refine, a deterministic refinement procedure, and Cuckoo Search, a metaheuristic capable of exploring complex search spaces to identify global minima. The analysis allowed for non-circular slip surfaces, capturing the heterogeneous behavior of the tailings stack and its foundation interface. The phreatic surface was modeled at the foundation–tailings contact to represent confined groundwater conditions and the effectiveness of the drainage system in maintaining low saturation. Seismic loading was incorporated through pseudo-static analysis with a horizontal coefficient of 0.10 g, an estimated value based on prior engineering practice. As this study represents a numerical simulation rather than a design case, the adopted parameter provides a reasonable basis for comparative assessment. Factors of safety were reported to three decimal places to enable consistent comparison between scenarios.

### 2.3 Stability scenarios

Eight scenarios were developed to evaluate the stability of the dry stack under different conditions, as summarized in Table 2.

Table 2. Stability analysis scenarios.

| Scenario | Search method | Loading condition | Water table presence |
|---|---|---|---|
| I | Auto Refine Search | Static | Yes |
| II | | | No |
| III | | Pseudo-static | Yes |
| IV | | | No |
| V | Cuckoo Search | Static | Yes |
| VI | | | No |
| VII | | Pseudo-static | Yes |
| VIII | | | No |

The inclusion of the water table only at the foundation interface reflects the facility's drainage design, which effectively prevents saturation within the tailings stack. This modeling assumption is critical for realistically representing seepage and pore pressure effects, which are essential parameters influencing the overall stability of dry stacked tailings facilities.

## 4 RESULTS

The results of the stability analyses for the eight modeled scenarios are presented in Table 3, which includes both the computed factors of safety and the corresponding processing times. The scenarios combine two search algorithms (Auto Refine Search and Cuckoo Search), static and pseudo-static loading conditions, and the presence or absence of a water table modeled at the interface between the foundation and the tailings stack.

Table 3. Safety factors and processing time results for the analyzed scenarios.

| Loading condition | Water table presence | Auto Refine FS | Cuckoo FS | Variation (%) |
|---|---|---|---|---|
| Static | Yes | 1.381 | 1.393 | 0.87% |
| Static | No | 1.38 | 1.393 | 0.94% |
| Pseudo-static | Yes | 1.105 | 1.159 | 4.89% |
| Pseudo-static | No | 1.105 | 1.159 | 4.89% |

The presence of the water table had a negligible effect on stability, with safety factors differing by less than 0.001 between saturated and dry conditions. This supports the assumption of drained behavior in dry-stacked facilities and confirms the role of internal drainage in limiting pore pressure buildup.

Under static loading, both Auto Refine Search and Cuckoo Search produced nearly identical results, with factors of safety of 1.381 and 1.393, respectively. In contrast, pseudo-static loading introduced significant reductions, with Auto Refine decreasing to 1.105 and Cuckoo to 1.159. These values reflect the increased driving forces associated with seismic loading and underscore the importance of including such conditions in stability evaluations.

The divergence between algorithms was more evident in the pseudo-static cases: Auto Refine, a deterministic local method, tended to converge toward shallow, circular surfaces, while Cuckoo Search, through its global Lévy flight strategy, identified deeper and more irregular slip surfaces. This broader exploration explains the slightly higher safety factors obtained with Cuckoo Search and indicates its greater robustness in capturing representative seismic failure mechanisms.

Figures 2 through 9 illustrate the critical slip surfaces obtained for each of the eight modeled scenarios, which combine different search algorithms (Auto Refine Search and Cuckoo Search), loading conditions (static and pseudo-static), and water table presence (present or absent). Despite these variations, the failure surfaces across all scenarios appear remarkably similar, primarily developing between berms within the dry-stacked tailings. This consistency suggests that the overall geometry and geotechnical properties of the tailings structure govern the slip surface location, with limited sensitivity to the search method or water table modeling under the given conditions.

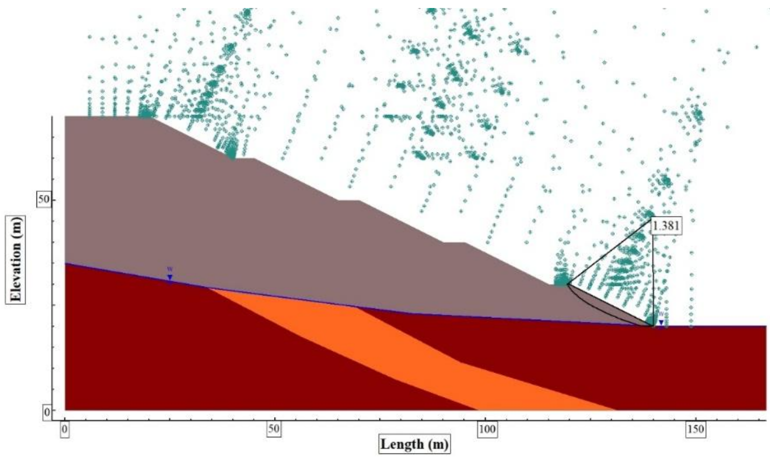


Figure 2. Stability analysis scenario I: Auto Refine Search Method, static loading with water table.

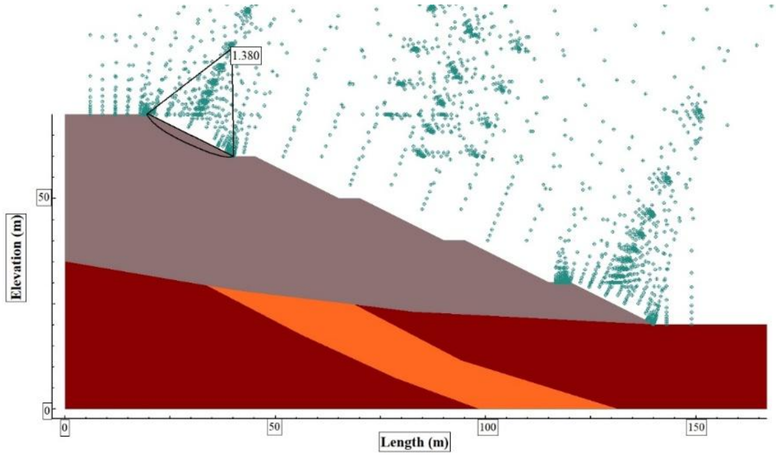


Figure 3. Stability analysis scenario II: Auto Refine Search Method, static loading without water table.

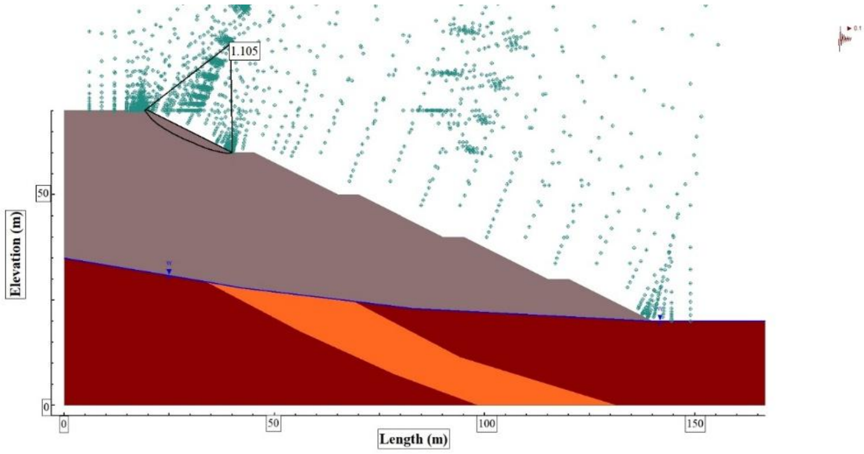


Figure 4. Stability analysis scenario III: Auto Refine Search Method, pseudo-static loading with water table.

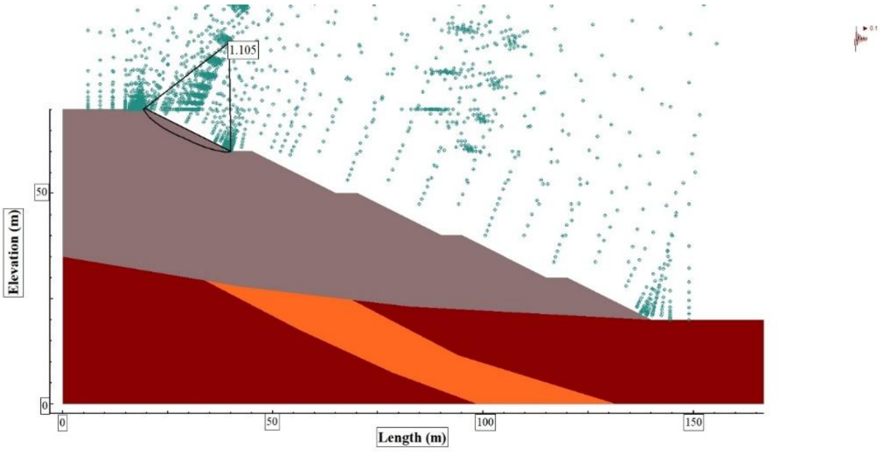


Figure 5. Stability analysis scenario IV: Auto Refine Search Method, pseudo-static loading without water table

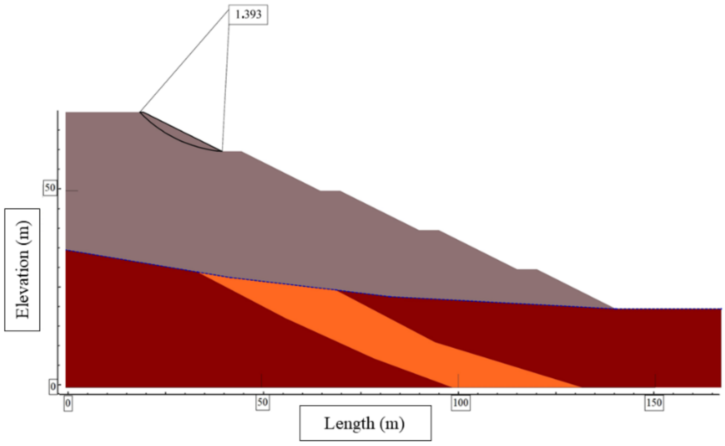


Figure 6. Stability analysis scenario V: Cuckoo Search Method, static loading with water table.

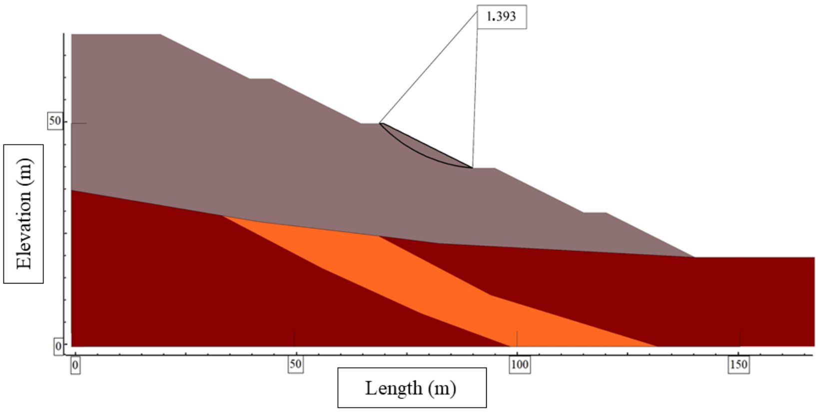


Figure 7. Stability analysis scenario VI: Cuckoo Search Method, static loading without water table.

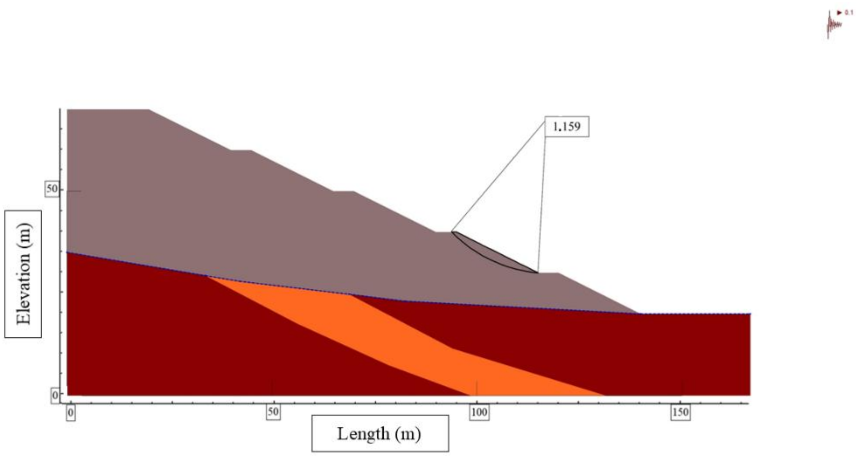


Figure 8. Stability analysis scenario VII: Cuckoo Search Method, pseudo-static loading with water table.

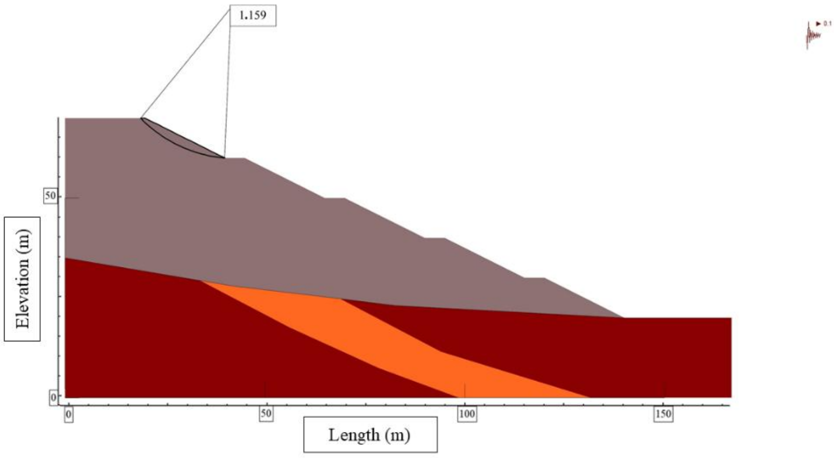


Figure 9. Stability analysis scenario VIII: Cuckoo Search Method, pseudo-static loading without water table

The similarity in slip surfaces reflects the modeling setup, where the water table at the foundation–tailings interface simulated an effective drainage system, leading to negligible differences in stability. Under pseudo-static loading, however, seismic forces reduced safety factors and highlighted differences between algorithms. Auto Refine Search tended to identify shallow, circular surfaces, while Cuckoo Search located deeper and more irregular slip surfaces, mobilizing larger portions of the stack. This broader exploration explains the slightly higher safety factors obtained with Cuckoo Search and indicates its greater robustness in capturing representative seismic failure mechanisms. Overall, geometry and drainage govern stability under drained static conditions, but algorithm selection becomes more relevant when seismic effects are considered. Extreme water table rises, or more complex seismic inputs could alter these patterns and merit further investigation.

## 6 CONCLUDING REMARKS

This study evaluated the stability of a dry-stacked tailings facility through limit equilibrium analyses considering static and pseudo-static loading conditions, two search algorithms, and the presence or absence of a water table. The results showed that the water table location at the foundation–tailings interface had negligible influence on safety factors, supporting the assumption of drained behavior under typical operating conditions. Pseudo-static loading, on the other hand, consistently reduced stability compared to static cases, highlighting the need to include seismic effects in design assessments.

Regarding the search algorithms, both Auto Refine Search and Cuckoo Search produced nearly identical results under static conditions. Under pseudo-static conditions, Cuckoo Search identified slightly higher safety factors and slip surfaces with deeper toe penetration, indicating differences in the way each algorithm explores the solution space. Despite these distinctions, the critical slip surfaces were generally consistent across scenarios, developing predominantly between berms. This suggests that geometry and drainage play a central role in controlling stability in dry-stacked systems, while the choice of search algorithm may become more relevant under seismic loading.

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