PROBABILISTIC VULNERABILITY ANALYSES OF TWO PROFILES IN AN ACTIVE PIT

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ABSTRACT

This paper presents a probabilistic vulnerability analysis of two pit profiles within an active mine in Austral Africa. The profiles exhibit differing geological conditions, necessitating a nuanced assessment of their stability under varying operational and care scenarios. The study employs a prior published quantitative semi-empirical methodology to evaluate the evolution of annualized probability of failure (PoF) under different factors of safety (FoS) and levels of maintenance. The analysis encompasses four hypothetical scenarios representing varying degrees of care, maintenance, and dewatering activities for each profile. As expected, results indicate that maintenance practices, particularly dewatering, significantly influence slope stability, with neglect leading to elevated PoF levels. The study extends across multiple time horizons, from yearly assessments to long-term projections spanning 5, 10, 20, and 50 years.

Findings reveal that while increasing FoS generally reduces PoF, scenarios with reduced maintenance and FoS exhibit persistent vulnerabilities, especially over longer time frames. Profiles in more difficult geological conditions, demonstrate heightened vulnerability, underscoring the importance of tailored maintenance strategies. Comparisons with benchmark values derived from industry standards provide further insights into the effectiveness of current maintenance practices. This analysis reaffirms the significance of the current standard of care within the examined pit. Moreover, the proposed approach, complemented by Bayesian updates, holds promise for informing long-term and closure designs, facilitating risk-informed decision-making, and supporting efforts to achieve ALARP (As Low As Reasonably Practicable) conditions.

1 INTRODUCTION

This paper presents the probabilistic vulnerability analysis of two profiles (P1, P2) of a presently active open pit mine in Austral Africa. The two profiles differ due to the respective prevalent geological conditions. The vulnerability analysis consists in showing the evolution of the annualized probability of failure (PoF) under varying factors of safety (FoS) along the profiles and under different, decaying levels of care. These are simulated as follows: i) "as is" present operational situation, ii) absence of monitoring, maintenance, inspections, but still active depressurization, iii) two stages where depressurization is abandoned and the FoS firstly decrease to 80% of their initial values, and then plunge to 60% (of course with a limiting value set at a metastable condition, i.e. 1). Thus, the intricate dynamics of mine pit slope stability under varying conditions is explored, utilizing a previously published probabilistic analysis method called ORE2_Slopes (Contreras et al., 2024) to assess slopes' probabilities of failure and manage their associated risks. Indeed, mine pit slopes differ significantly from natural slopes due to human-induced alterations associated with mining activities:

- Anthropogenic Alterations: Mine pit slopes are artificially created through excavation activities for mining purposes, contrasting with natural slopes formed by geological processes over extended periods.
- Steepness and Scale: Mine pit slopes often feature steeper angles and larger scales compared to natural slopes.
- Geotechnical Characteristics: The composition and structure of mine pit slopes may vary due to the excavation process and the presence of mining-related materials such as overburden, waste rock, and tailings.
- Hydrogeological Influence: Mining activities can modify hydrogeological conditions surrounding mine pit slopes, affecting groundwater flow patterns, aquifer recharge rates, and water quality.

These differences introduce uncertainties and pose significant challenges to personnel safety and mining infrastructure integrity. To address these challenges, we leverage ORE2_slopes as a robust tool for risk assessment and management support. Indeed, ORE2_Slopes allows for systematic evaluation of slopes and facilitates and informed decision-making within mining operations (Oboni, Oboni (2017 a,b; 2019; 2020 a,b). This semi-empirical and easy to use method follows the workflow as depicted in Figure 1 has proven to deliver comparable results (Contreras et al., 2024) to more complex geomechanical approaches, using a similar number of subjective judgments and assumptions.

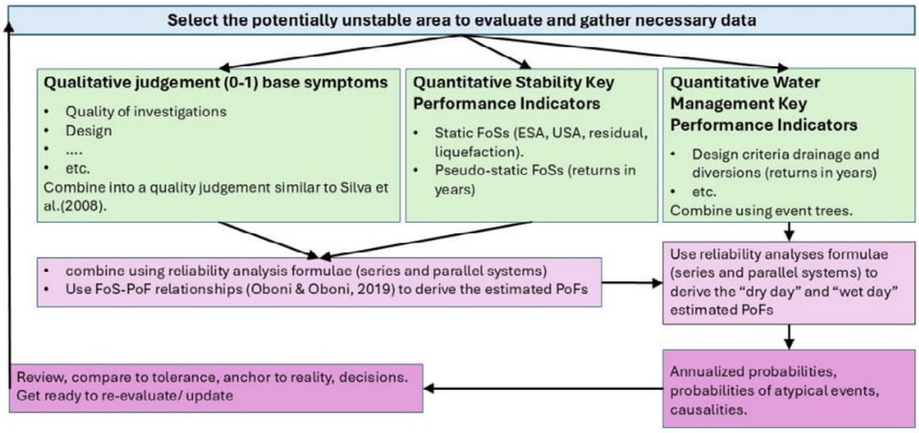

Figure 1: Conceptual framework of the ORE2_Slopes methodology

2 THE SCENARIOS

As mentioned in the introduction four hypothetical scenarios, each simulating distinct levels of care, maintenance and dewatering activities were developed per profile, as follows:

1. Dewatered and Maintained "as is": this scenario entails regular dewatering and maintenance activities and therefore depicts present slope stability conditions.
2. Dewatered with No Maintenance: this scenario explores the implications of releasing monitoring and inspections maintenance activities while maintaining present dewatering efforts.
3. No Maintenance, no Dewatering: the phreatic levels rise is assumed in this hypothetical scenario to reduce the FoS to 80% of its original value, in the absence of maintenance and dewatering measures. In each application the decrease of the FoS must be evaluated by the engineers.
4. Further Reduction of FoS with neither Maintenance nor Dewatering: extending the previous hypothetical scenario, this exacerbates the reduction in the FoS to 60% of its original value, emphasizing the vulnerability of mine pit slopes under neglect or closure conditions. In each application the decrease of the FoS must be evaluated by the engineers.

In actual cases, for each profile, each scenario and each local FoS derived by the engineers along the profiles, the annualized probability of failures must be evaluated using ORE2_Slopes. Given the large number of cases to analyze it becomes immediately apparent that using a light probabilistic method of analysis, rather than a complex geomechanical one alleviates the burden and swiftly delivers a global understanding of the situation allowing for risk informed decision making.

2.1 TIME HORIZONS, POSSIBLE BAYESIAN ADJUSTMENTS

Furthermore, the analysis was extended across varying time horizons, including yearly assessments and long-term probabilistic projections spanning 5, 10, 20, and 50 years. To model the probability distribution inherent in these scenarios, the Poisson distribution was used, chosen for its suitability in capturing the probability of events in various time spans on the basis of an initial annualized evaluation. Indeed, the Poisson distribution serves as a foundational tool for modelling event occurrences within fixed intervals. It is imperative, however, to recognize the conditions under which the Poisson distribution remains valid. Indeed, events are:

- assumed to occur independently, without influencing one another within the observed interval and at constant rate over time and space.
- expected to be rare relative to the length of the observation interval and countable as whole numbers.
- counted over a fixed and consistent interval, maintaining uniformity in the analysis and their probability remains consistent across all intervals, reflecting homogeneity in their occurrence.

While these conditions provide a foundational framework for our analysis, it is important to acknowledge their inherent limitations. For instance, the assumption of event independence may not always hold true in geotechnical systems, and the constancy of event rates may vary over time due to external factors or system dynamics. Despite these challenges, the Poisson distribution serves as a valuable initial estimate, offering insights into the probability of occurrences. To address the limitations and refine the analyses over time, in the future we will also propose a Bayesian updating approach. Indeed, by integrating new data and adjusting our model parameters, we will be able to iteratively improve the accuracy and reliability of our predictions. This adaptive framework will ensure that our analysis remains robust and reflective of real-world conditions throughout the life of the pit.

3 RESULTS

Through this type of study, we aim to provide valuable insights into the dynamic interplay between factors influencing mine pit slope stability, maintenance strategies, and risk management practices, ultimately contributing to the stability and sustainability of mine pit slopes. In this study the annualized probabilities of failure were systematically compared to benchmark values described in Contreras et al. (2024) originally described by Oboni and Oboni (in 2013 they worked for a major world insurance company delivering benchmarking criteria for mining pit slopes. Oboni and Oboni considered literature data, a portfolio of 40 pits in Latin America and third-party semi-empirical correlations). The benchmark values appear as horizontal lines in the figures below.

Figures 2, 3 display respectively the results of the vulnerability analysis for profiles P1 and P2 with "one year" time horizon. As it can be seen, in Profile P1, Figure 2, scenarios 1 and 2 (dewatered and maintained, respectively dewatered and not maintained) the PoF tends to decrease as the FoS increases, consistent with expectations for slope stability across all maintenance scenarios (orange and blue curves). However, in scenarios 3 and 4 (no maintenance and reduced FoS) the PoF remains consistently high, even within shorter time horizons. This clearly demonstrates the paramount influence of dewatering for the stability of the profile.

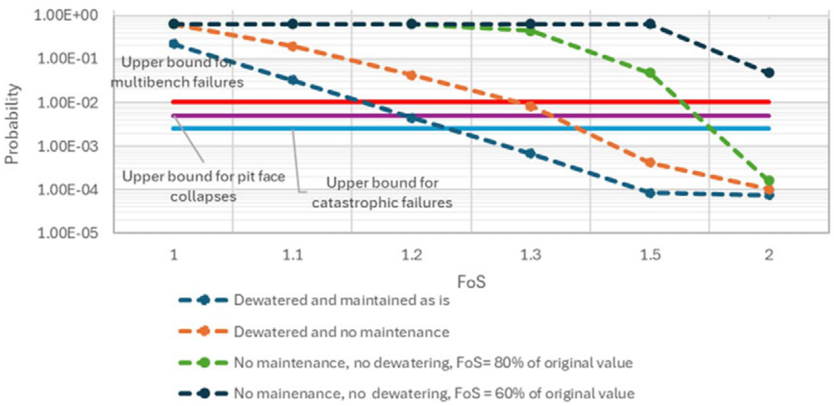

Figure 2: Results of the vulnerability analysis for profile P1 with "one year" time horizon.

Similar results were found for profile P2, Figure 3, which however, features higher vulnerability than profile P1, as expected.

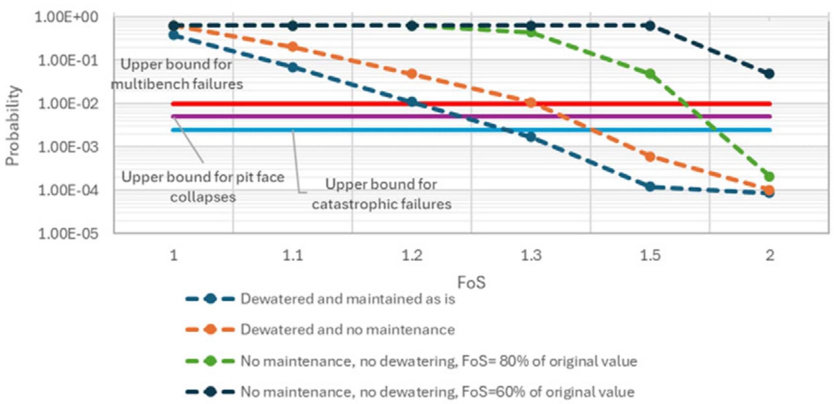

Figure 3: Results of the vulnerability analysis for profile P2 with "one year" time horizon.

As profile P2 is more critical than P1 in the "as is" conditions, the results show the increased importance of the standard of care and dewatering for a more critical profile, confirming the processes that the owner/operator has engaged and maintains in the considered pit.

3.1 P1 RESULTS FOR ALL TIME HORIZONS

Below we show (Figures 4,5,6,7) the Poisson projections for profile P1, respectively for scenario 1 to 4 for the 1,5,10,20 and 50 year intervals. Figure 4 shows that the initial FoS should be at least 1.4 to ensure compliance with the benchmarks under any scenario 1. The threshold increases to 1.6 for scenario 2 (Figure 5).

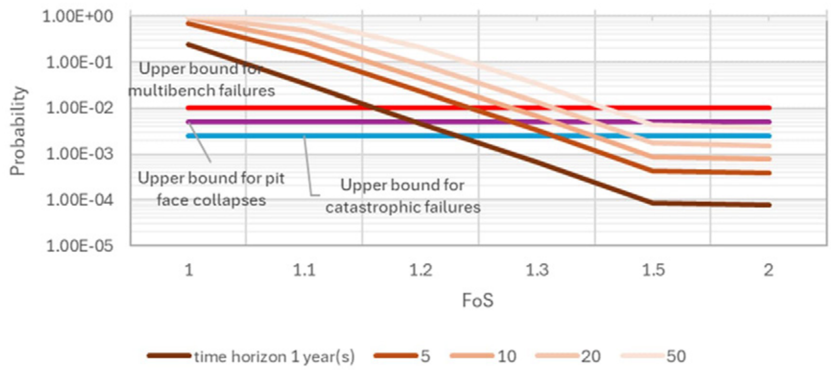

Figure 4: 1,5,10,20 and 50 years Poisson projections for profile P1, scenario 1 (dewatered and maintained as is). The initial FoS should be at least 1.4 to ensure compliance with the benchmarks under scenario 1.

Finally, Figure 6, scenario 3, and Figure 7, scenario 4, indicate respectively the following:

- Scenario 3: an initial FoS=1.4 would lead to PoF of 30% over an interval of 5, years, respectively 90% over 50 years.
- Scenario 4: an initial FoS=1.4 would lead to PoF larger than 80% at all time horizons.

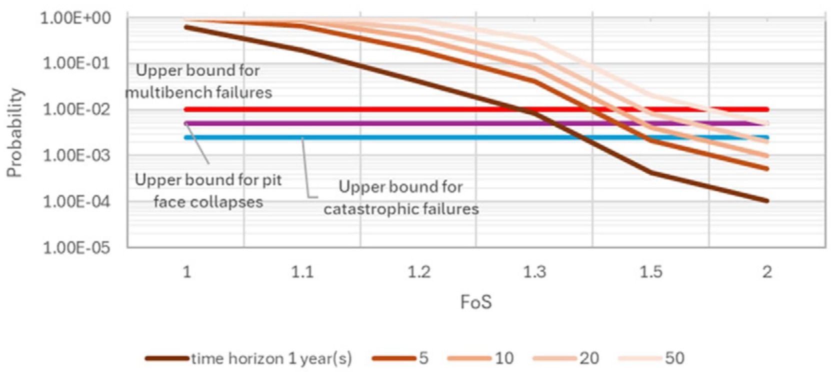

Figure 5: 1,5,10,20 and 50 years Poisson projections for profile P1, scenario 2 (Dewatered with No Maintenance). The initial FoS should be at least 1.6 to ensure compliance with the benchmarks under scenario 2.

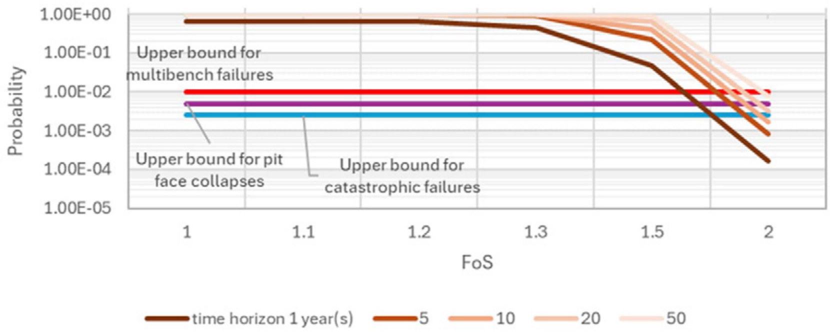

Figure 6: 1,5,10,20 and 50 years Poisson projections for profile P1, scenario 3 (No maintenance, no dewatering, FoS=80% of original value). Initial FoS=1.4 would lead to PoF of 30% over an interval of 5, years, respectively 90% over 50 years.

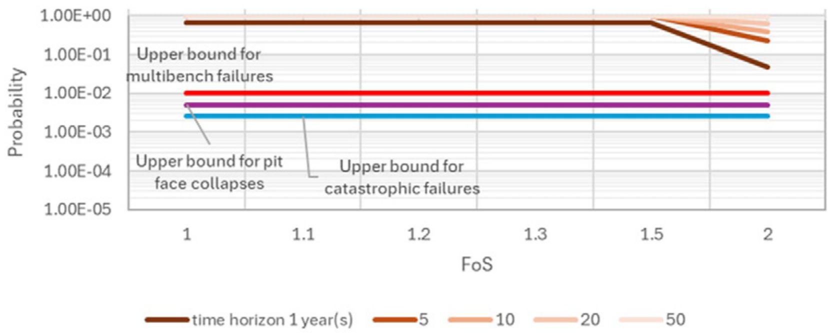

Figure 7: 1,5,10,20 and 50 years Poisson projections for profile P1, scenario 4 (No maintenance, no dewatering, FoS=60% of original value). Initial FoS=1.4 would lead to PoF larger than 80% at all time horizons.

The time horizon analysis for profile P1 delivers the following summarized results:

- At 5 years the general trend is to see lower PoFs for larger FoSs, however, the PoF remains relatively high for scenarios with no maintenance and reduced FoS, indicating sustained probability over the 5-year period.
- At 10-20 years, the PoF continues to decrease with increasing FoS across all scenarios, nevertheless, scenarios with no maintenance and reduced FoS exhibit elevated PoFs, emphasizing long-term implications associated with neglecting maintenance practices.
- Finally, at 50 years scenarios with no maintenance and reduced FoS display persistent high PoFs.

3.2 P2 RESULTS

Similar results were found for profile P2, which however, features more vulnerability than P1 due to its more critical geological conditions, as expected (Figures 8, 9, 10, 11).

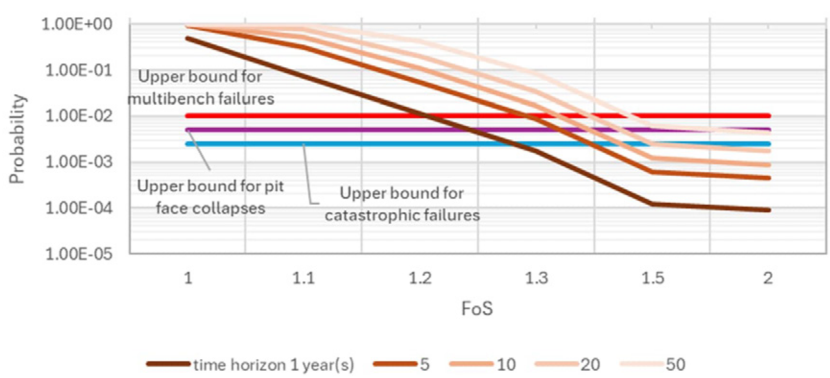

Figure 8: 1,5,10,20 and 50 years Poisson projections for profile P2, scenario 1. Initial FoS=1.4 would lead to PoF within benchmarks with the exception of the 50 years horizon.

- Figure 8 shows the 1,5,10,20 and 50 year Poisson projections for profile P2, scenario 1. Initial FoS=1.4 would lead to PoF within benchmarks with the exception of the 50 year horizon.
- For the same set of time horizons Figure 9 shows that an initial FoS=1.4 would see all PoF above the benchmarks with 10E-02≤PoF≤10E-01 (PoF between 1% and 10%) over the respective time horizons.
- Figure 10 shows again the 1,5,10, 20 and 50 year Poisson projections for profile P2, but for scenario 3. An initial FoS=1.4 would see all PoF above the benchmarks with 1.5E-01≤PoF≤9E-01 (PoF between 15% and 90%) over the respective time horizons.

Finally, Fig. 11 shows the Poisson projections for profile P2, scenario 4. An Initial FoS=1.4 would see all PoF above the benchmarks with PoF≥7E-01 (PoF larger than 70%) over the respective time horizons.

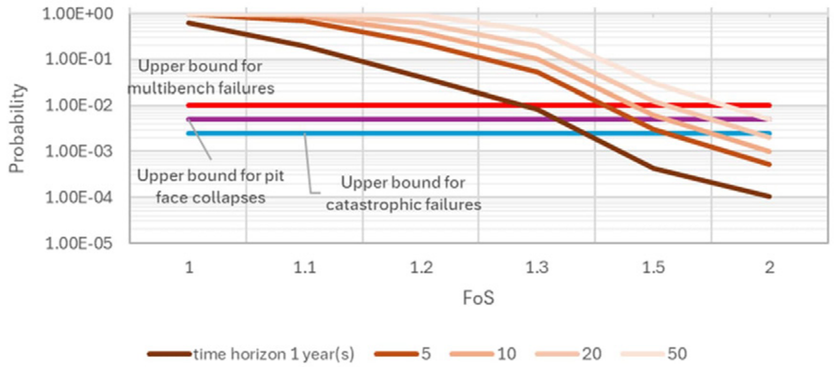

Figure 9: 1,5,10,20 and 50 years Poisson projections for profile P2, scenario 2. Initial FoS=1.4 would see all PoF above the benchmarks with 10E-02≤PoF≤10E-01 (PoF between 1% and 10%) over the respective time horizons.

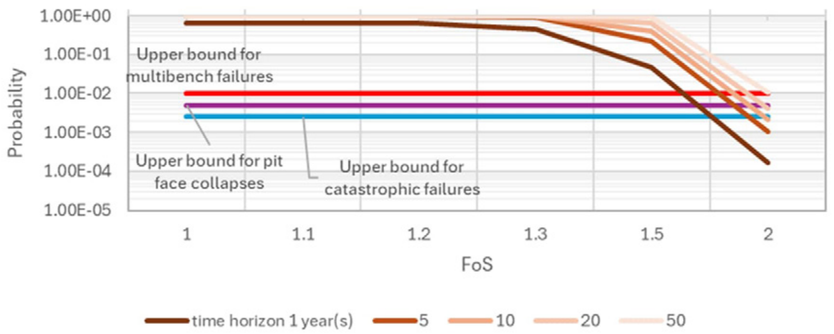

Figure 10: 1,5,10,20 and 50 years Poisson projections for profile P2, scenario 3. Initial FoS=1.4 would see all PoF above the benchmarks with 1.5E-01≤PoF≤9E-01 (PoF between 15% and 90%) over the respective time horizons.

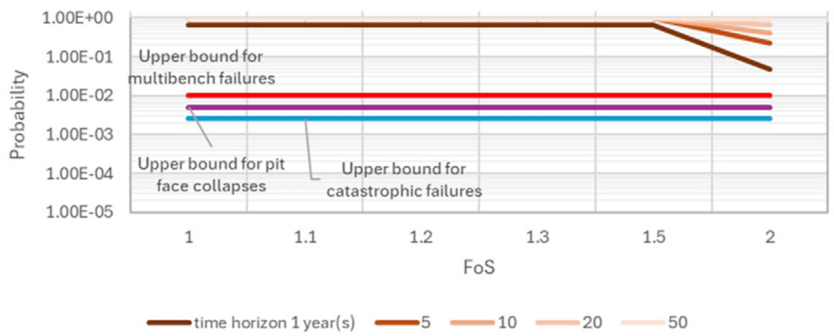

Figure 11: 1,5,10,20 and 50 years Poisson projections for profile P2, scenario 4. Initial FoS=1.4 would see all PoF above the benchmarks with PoF≥7E-01 (PoF larger than 70%) over the respective time horizons.

4 CONCLUSIONS

The vulnerability analysis presented in this paper confirmed the pertinence of the level of care adopted by the owner/operator at the considered pit, under present conditions for both considered profiles.

The approach will allow, especially if paired with Bayesian updates to support long term and closure designs with rational, quantitative analyses. The same approach can support the search for minimum ALARP conditions, based on the most modern definition of the term.

CRediT authorship contribution statement

Franco Oboni: Writing - original draft. **Cesar H. Oboni:** Writing – review & editing.

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