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Analysis of the Validated Transition Failure Criterion Model for Slope Stability in the Final Wall of a High-Sulphidation Epithermal Open-Pit Mine

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ABSTRACT

Open-pit slope stability in hydrothermally altered and clay-rich settings remains a critical challenge in geotechnical design. Conventional criteria, such as the Mohr–Coulomb and Generalized Hoek–Brown (GHB) models, often fail to accurately represent the intermediate soil–rock behavior of transition materials. This study applies and validates the Validated Transition (VT) criterion, a refinement of the GHB model, within a Finite Element Method (FEM) framework to evaluate slope stability in the final wall of a high-sulphidation epithermal open-pit mine. Transition rock properties were derived from Point Load Index (PLI) correlations with Uniaxial Compressive Strength (UCS), ensuring a representative characterization of hydrothermal clay-altered lithologies. Numerical simulations were performed to compare slope responses under the VT, GHB, and Mohr–Coulomb (MC) formulations. Results show that the VT model provides the highest consistency with radar-monitored displacements, achieving up to 93% agreement in low- to medium-strength rock masses, while GHB and MC produced lower correlations. This demonstrates that the VT model more effectively captures the deformation behavior of transitional rock masses, improving predictive reliability over conventional approaches. Beyond the studied case, the VT–FEM approach establishes a methodological framework that can be extended to other open-pit mines with similar geomechanical conditions. The findings emphasize the importance of transition material-specific failure criteria, supporting optimized pit design and cost-effective wall management aligned with safety standards.

Keywords: slope stability, validated transition criterion, finite element method, rock mass strength classification, generalized hoek-brown criterion

INTRODUCTION

Recent research has highlighted the complexity of open-pit slope behavior in highly weathered, clay-rich, or hydrothermally altered igneous rocks, particularly in high-sulfidation epithermal open-pit mines. For example, Alemayehu et al. (2025) studied an Ethiopian open-pit cut through basalt and claystone. They found that the interlayering of hard (basalt) and soft (claystone) units controlled slope performance using finite element method (FEM) analysis to assess slope stability. The study showed that reducing bench angles dramatically increased the safety factor [1]. Such findings underscore the need for careful geotechnical appraisal in settings where phyllic alteration has produced clay-rich zones (R0–R2 rock classes) that weaken the rock mass.

Determining an appropriate failure criterion is a fundamental aspect of geotechnical engineering, as it is crucial for analyzing slope stability and predicting the deformation of rock masses [2]. Rocks are typically categorized into two main strength classes: weak rocks (R0 to R2), with UCS values ranging from below 1 MPa up to 25 MPa, and hard rocks (R3 to R6), with UCS values exceeding 25 MPa [3]. However, soil or soft material is classified into S1–S6 classes with UCS < 0.25 MPa [3].

The Generalized Hoek-Brown (GHB) criterion is commonly employed to derive and estimate rock mass strength [4]. This criterion remains the standard for rock masses, as it relates intact rock strength to rock mass strength via the Geological Strength Index (GSI) [5]. The GHB criterion is an extension of the original Hoek–Brown (HB) criterion, which was initially developed for intact rock and later generalized to include rock mass properties. As a non-linear, empirically derived model, it accounts for the complex behavior of rock masses by incorporating parameters such as the GSI, which represents the reduction in strength due to discontinuities, indicating that failure criteria are significantly influenced by rock structure [6]. Recent developments have also introduced improved empirical models to predict the strength of both soft and hard rock masses, enhancing the understanding of deformation behavior before and after yielding [7], [8]. These approaches emphasize the necessity of comprehensive rock mass characterization, including GSI and detailed structural analysis [9].

In contrast, the Mohr-Coulomb (MC) failure criterion is widely used for soils or soft materials [10]. This linear model relates shear strength to normal stress through parameters such as cohesion and internal friction angle, making it suitable for analyzing soil behavior under various loading conditions [11]. However, neither model alone effectively addresses the intermediate "soil-to-rock" continuum. Recent studies have aimed to bridge this gap. For instance, a combined probabilistic MC and HB formulation for Himalayan rock masses concluded that a GSI-based HB model yields more realistic compressive strengths than a direct MC–HB hybrid [12]. In other words, explicitly including GSI in the HB criterion provided higher and more suitable compressive strength values for the transition rock masses. Similarly, the HB envelope reformulated to incorporate a ductility parameter that captures the brittle–ductile transition stress of rock masses under varying GSI and confining stress [13]. Their model demonstrates how high-GSI rock masses can sustain increased confinement before yielding, effectively extending the HB framework into more ductile behavior regimes.

Present empirical approaches for slope stability analysis, while widely applied, may not sufficiently represent the non-linear post-yield behavior of rock masses across different competence levels [14]. The HB failure criterion, initially developed for intact and jointed rock masses, has undergone significant refinement to account for transition rock mass conditions [15]. Its modified forms allow for better estimation of both peak and residual strength, particularly when validated against site-specific conditions [16]. These refined criteria have increasingly been tested against experimental and field data. Triaxial tests on naturally fractured limestone were conducted and demonstrated that the m parameter in HB must be modified by fracture characteristics, introducing new crack parameters into m and showing that confining pressure and fracture distribution strongly affect rock-mass strength [17]. This work reinforces the need for parameter calibration under conditions of severe jointing or weathering. Numerical analyses that integrate these criteria have shown promise in their application. For instance, the GHB criterion was applied in a

3D slope model of the Angouran open pit, where the model was calibrated with local rock mass properties to ensure that simulated displacement patterns closely matched field monitoring data, resulting in a coefficient of determination of $R^2 = 0.96$ [5]. This agreement between observed and predicted deformation highlights the importance of using site-specific strength parameters in HB-based analyses.

Additional empirical models have been proposed, with a validated Transition failure criterion equation derived from the GHB model, specifically applied to fissured clay materials and sedimentary rock located in South Kalimantan, characterized as weak rock with low strength [18]. The proposed model is evaluated by comparing actual field deformation conditions with numerical model predictions [18]. However, the proposed failure criterion needs to be validated for igneous rock, particularly hydrothermal clay-altered rocks, as the rock mass exhibits similar characteristics, with the rock strength classified as R0–R2 [19].

This present study focuses on applying and validating the transition relationships of the modified Hoek-Brown failure criterion in analyzing the slope stability of a high-sulfidation epithermal final wall open-pit mine. It also evaluates the reliability of this failure criterion by comparing FEM displacement predictions with slope monitoring data. The outcome is expected to enhance slope design optimization, address the current lack of site-specific validations of empirical criteria for weak rock masses, and provide a framework for applying validated empirical criteria of transition rock mass in open-pit slope design [20].

THEORY

The GHB failure criterion is widely used in geotechnical engineering to model the strength and failure behavior of rock masses. Developed as an extension of the original HB criterion, it incorporates both the effects of rock mass properties and in-situ stress conditions, providing a more comprehensive framework for assessing rock stability [2]. The GHB criterion provides a comprehensive analysis of heterogeneous and non-homogeneous rock masses, where variations in rock quality, structural features, and geological conditions significantly influence the determination of failure mechanisms [15].

The Transition equation is a combination of the GHB criterion, which represents the behavior of rock materials, and the MC criterion, which represents the behavior of soil-like materials [14]. The Transition equations are presented in Equations 1 to 4.

$$\sigma_1 = \sigma_3 + \sigma_{ci}\left(m_b \frac{\sigma_3}{\sigma_{ci}} + s\right)^a \quad (1)$$

$$\frac{m_b}{m_i} = e^{\frac{GSI-100}{28-14D}} \quad (2)$$

$$s = e^{\frac{GSI-100}{9-3D}} \quad (3)$$

$$a = \frac{1}{2} + \frac{1}{6}\left(e^{\frac{-GSI}{15}} - e^{\frac{-20}{3}}\right) \quad (4)$$

$$UCS_{rm} = UCS_i . s^a \quad (5)$$

In this context, m_i represents the HB material constant, while D denotes the disturbance factor accounting for the degree of damage or stress relaxation within the rock mass. Where UCS_i refers to the intact uniaxial compressive strength obtained from laboratory testing, and UCS_{rm} denotes the rock mass uniaxial compressive strength derived by reducing UCS_i to account for rock mass conditions. UCS_{rm} is calculated by setting the value of σ_3 to zero in the GHB equation

(Equation 1), with relationship in Equations 2 to 4, resulted in Equation (5) [15].

The Transition equations are applied to rock materials with a UCS range of 0.5–15 MPa. As illustrated in Figure 1 and 2, a lower UCS value corresponds to a smaller reduction in rock mass strength, meaning that the UCS_{rm}/UCS_i ratio approaches one. The parameters UCS_{rm}/UCS_i and GSI exhibit a gradual transition from GHB failure criterion to the Mohr-Coulomb model, corresponding to a shift in material behavior from rock-like to soil-like properties. The formulations are as follows:

$$f_t \begin{cases} 1, \sigma_{ci} \leq 0.5\ MPa \\ e^{\frac{-(UCS-0.5)^2}{25}}, \sigma_{ci} \geq 0.5\ MPa \end{cases} \tag{6}$$

$$s' = s + (1 - s)\ f_t(\sigma_{ci}) \tag{7}$$

$$a' = a + (1 - a)\ f_t(\sigma_{ci}) \tag{8}$$

$$m_b' = \frac{[m_b + (m_i - m_b)\ f_t(\sigma_{ci})]}{(4a' - 1)} \tag{9}$$

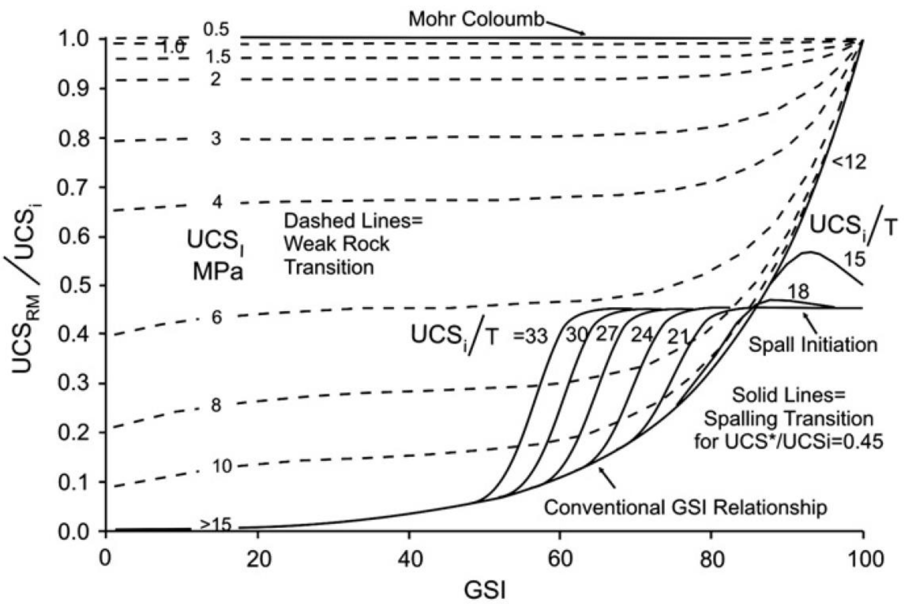

Figure 1. The transition behavior equation model [14].

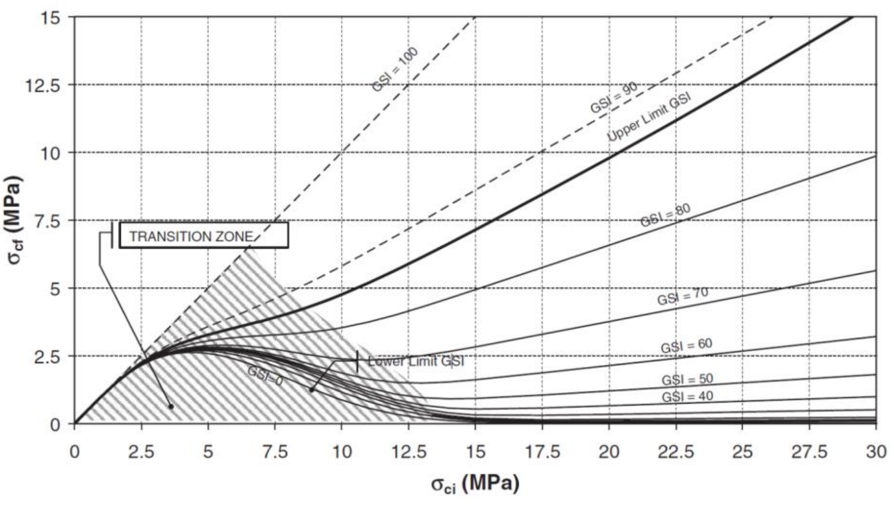

Figure 2. UCS_{rm} Chart on the transition zone.

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A Validated Transition (VT) failure criterion derived from the Generalized GHB model, primarily developed for weak transitional materials (Equations 10 to 13) [18]. However, this criterion has not been widely applied or validated beyond its initial context, leaving uncertainties regarding its broader applicability. Therefore, this study seeks to extend the validation of the VT model to a different geological setting, providing a critical assessment of its reliability for slope stability analysis in transitional rock masses. The validated transition is formulated as follows:

$$f_{vt} \begin{cases} 1, \sigma_{ci} \leq \ 0.5\ MPa \\ e^{\frac{-(UCS-0.5)^2}{25}}, \sigma_{ci} \geq \ 0.5\ MPa \end{cases} \quad (10)$$

$$S" \ = \ s + (0.2 - s)\ f_{vt}(\sigma_{ci}) \quad (11)$$

$$a" = a + (1 - a) f_{vt}(\sigma_{ci}) \quad (12)$$

$$m_b^" = \frac{[m_b + (m_i - m_b)\ f_t(\sigma_{ci}]}{(5.5a' - 1)} \quad (13)$$

Note:
σ_{ci} : UCS of intact rock (MPa)
m_i, s, a : Input parameter of rockmass
e : Exponential value (2.72)

In this study, the VT equations are applied with the specific objective of evaluating their performance in high-sulfidation epithermal open-pit conditions. While the transition model itself has been widely applied and validated, including evaluations by Carter, Diederichs, and Carvalho (2008). The VT formulation is tested here to examine whether it can provide consistent and reliable results under the geological conditions of this case study.

METHODOLOGY

The study area is located in Pesanggaran Subdistrict, Banyuwangi Regency, East Java (8°37'9.12"S, 114°2'13.30"E). The location of the study area is shown in Figure 3. The study site is at high-sulphidation epithermal open-pit mine, where the Batuampar Formation is the dominant geological unit, followed by the Alluvial Formation and the Andesite-Granodiorite Formation. The distribution of these rock formations is illustrated in Figure 3. The Batuampar Formation, which predominates in the high-sulphidation epithermal open-pit mine area, comprises dacite, basaltic andesite, and includes tuff, volcanic breccia, limestone, and lava. However, within Pit C, only breccia-type rock is present [21].

To determine the compressive strength of intact rock, UCS_i (σ_{ci}), this study employs empirical correlations that relate the Point Load Index (Is_{50}) to UCS. The Point Load Test (PLT), introduced and standardized by Broch and Franklin (1972), is a practical and widely adopted method for assessing rock materials, providing both an estimate of strength and a classification system based on the Point Load Index ($I_{s(50)}$) [22]. The test applies concentrated loading on a specimen at two opposing points, and the resulting index value (Is_{50}) can be converted into UCS through established empirical relationships. Various researchers have developed conversion factors for different rock types and conditions: Kohno and Maeda (2012) for hydrothermally altered rocks (Equation 14) [23], Bieniawski (1975) for igneous rocks in general (Equation 15) [24], and Schrier (1988) specifically for breccia within igneous rocks (Equation 16) [25]. Collectively, these correlations provide a systematic framework for estimating UCS from PLT results, thereby enabling a more reliable representation of intact rock strength in geotechnical analysis. The equations applied in this study are as follows:

$$\sigma_{ci} = 16.41\, I_{s(50)} \text{ (Kohno \& Maeda, 2012)} \tag{14}$$

$$\sigma_{ci} = 22\, I_{s(50)} \text{ (Schrier, 1988)} \tag{15}$$

$$\sigma_{ci} = 23\, I_{s(50)} \text{ (Bieniawski, 1975)} \tag{16}$$

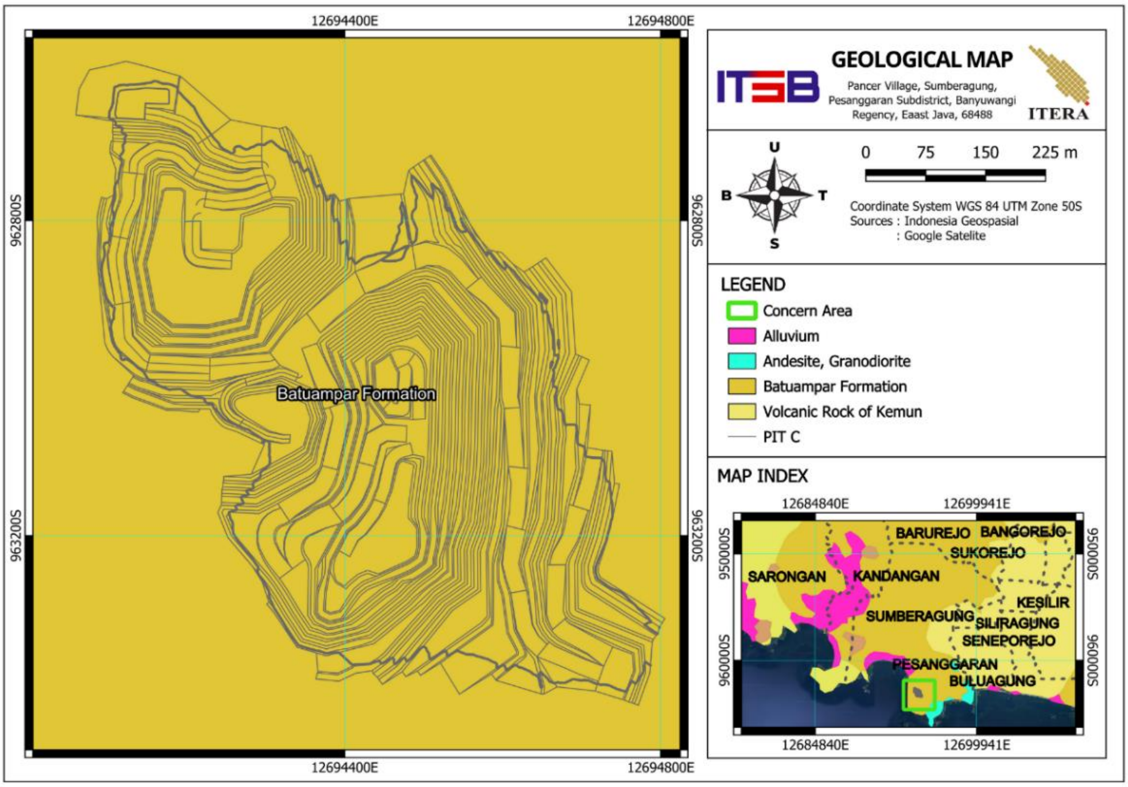

Figure 3. Research location and regional geological map research area.

The strength characteristics of intact rock in the study area were evaluated using an empirical approach based on Point Load Index (PLI) testing (Table 1), which was then converted to Uniaxial Compressive Strength (UCS) using appropriate standard correlations for the dominant rock types. The PLI sample location on the final slope pit design is presented in Figure 4. The analysis revealed a wide range of rock strength classifications, from extremely low strength (<1 MPa) to very high strength (>100 MPa), indicating significant geological heterogeneity across the site. This variation is attributed to factors such as the presence of altered and fractured zones, as well as more competent, massive rock units.

Table 1. Point Load Index strength classification.

Classification	**Is_{50}**
Extreme Low	≤ 0.03
Very Low	> 0.03 to 0.10
Low	> 0.10 to 0.30
Medium	> 0.30 to 1.00
High	> 1 to 3
Very High	> 3 to 10
Extremely High	> 10

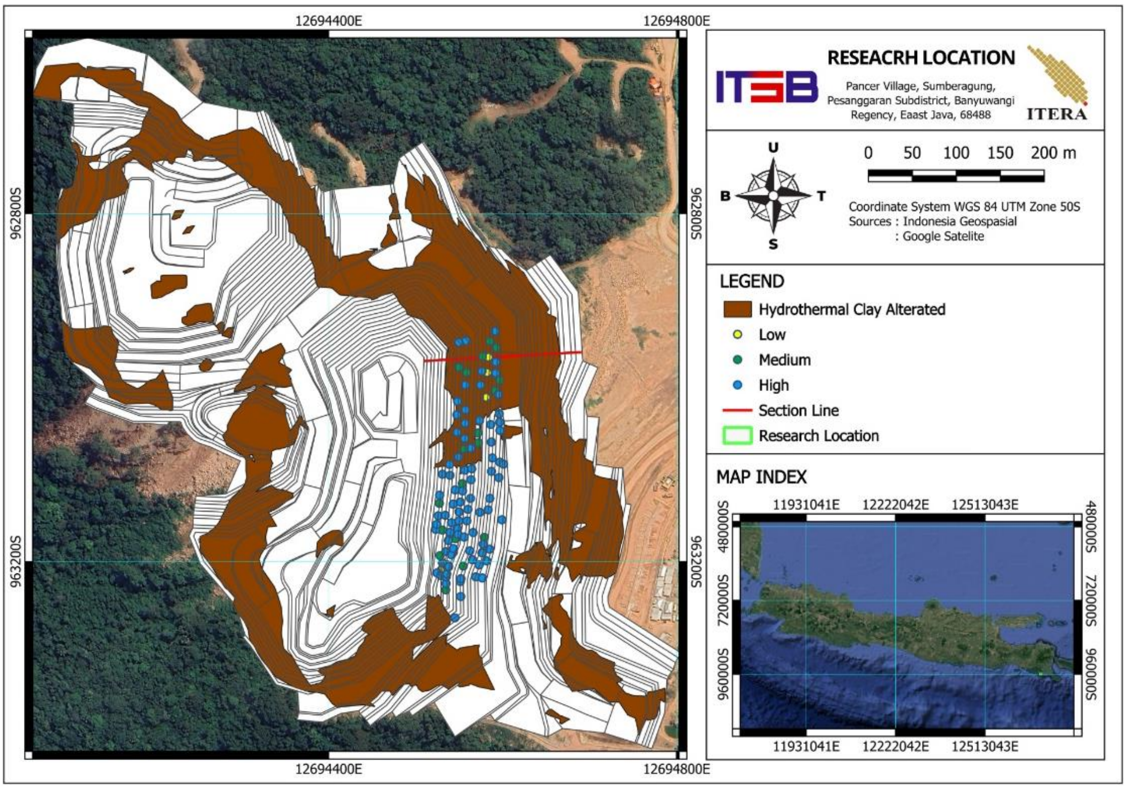

Figure 4. PLI sample location and final slope pit design (Plan View).

According to the rock strength classification of Broch and Franklin (1972), intact rocks with low (L), medium (M), and high (H) strength are categorized as transition materials—having uniaxial compressive strength (UCS) values ranging from 0.5 to 15 MPa—based on empirical approaches proposed by Kohno & Maeda, Bieniawski, and van der Schrier. In contrast, intact rocks with very low (VL) strength are classified as the transition materials only when using the methods of Kohno & Maeda and Bieniawski. Meanwhile, extremely low (EL) strength rocks are classified as such solely using Bieniawski's empirical Equation.

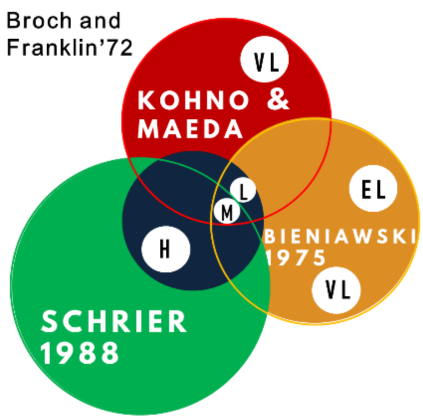

Figure 5. The transition material (UCS 0.5–15 MPa) based on the PLI strength classification of Broch & Franklin (1972) [22], with empirical PLI–UCS correlations from Kohno & Maeda (2012) [23], Bieniawski (1975) [24], and Schrier (1988) [25].

The transition material with a UCS range of 0.5–15 MPa is represented by the black-shaded area in the PLI classification of Broch & Franklin (1972), covering the low, medium, and high classes after applying empirical PLI–UCS correlations (Figure 5). According to Schrier (1988), materials in the medium and high PLI classes fall within the transition material category, as their converted UCS values are in the 0.5–15 MPa range. Similarly, Bieniawski's (1975) correlation shows that low and medium PLI classes correspond to the transition materials, while the correlation by Kohno & Maeda (2012) also places low and medium PLI classes in the transition material range. These results indicate that across different empirical correlations, several PLI classes consistently convert into the UCS range of 0.5–15 MPa, defined as the transition material.

The updated geotechnical parameters were obtained through a systematic program of laboratory testing and geological wall mapping at the high-sulphidation epithermal open-pit mine (Table 2). These data represent the most reliable characterization of in-situ rock mass conditions currently available for the site. This comprehensive dataset forms a robust basis for subsequent numerical modeling and slope stability assessment under transition rock mass conditions.

Table 2. Breccia geomechanical properties.

Parameter	Mean	Min	Max	Standard Deviation
ρ (Ton/m^3)	24	21	27	3.20
m_i	19	-	-	-
GSI	51.67	40	65	9.56
σ_{ci} (MPa)	9.02	2.56	14.88	4.73
E_m (GPa)	1547.72	894.43	3430.82	864.72
υ	0.27			

In general, the materials within the pit are classified into two categories for geotechnical analysis: non-hydrothermal clay-altered and hydrothermal clay-altered materials. The slope configuration in the final wall of the high-sulphidation epithermal open-pit mine is based on a single slope design criterion, which varies according to the rock alteration type, as illustrated in Table 3.

Table 3. Single slope configuration.

Alteration	Batter Face Angle (°)	Catch Bench Width (m)	Bench Height (m)
Non-Hydrothermal Clay Altered	75	7.8	15
Hydrothermal Clay Altered	65	4.2	7.5

The inter-ramp angle and overall slope angle vary depending on the geotechnical domain, which is based on the rock mass properties, slope stability analysis, and the presence of geological structures. In the area

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under investigation, the inter-ramp angle is 45°, while the overall slope angle is 39°.

Slope monitoring in the study area has been conducted using radar and prism readings from the RTS (Robotic Total Station) equipment, which can be utilized for validation purposes. This involves comparing the results from slope monitoring with the total displacement outcomes from the slope stability analysis model simulation. Essentially, the application of the Transition equation requires validation to ensure its accuracy. During the study period, the displacement readings from the slope monitoring instruments, particularly radar monitoring, reached 37 mm at the critical strain.

FEM is applied in this study to evaluate slope stability, producing three main outcomes:

(1) the Strength Reduction Factor (SRF);
(2) a comparison between observed and simulated deformations; and
(3) a UCS_i versus UCS_{rm} comparison chart used to assess the effect of the Transition equation.

The slope stability analysis was performed on the actual final slope in October 2024 with the azimuth direction is N 273° E Pit C, and the analysis was divided into three phases:

(i) using the original GHB material;
(ii) using material based on the Transition equation; and
(iii) using the Transition equation material with validation (Validated Transition).

In phase (iii), the validation involves ensuring that the model's deformation aligns with the observed deformation. This alignment is achieved by adjusting the constants in the Transition equation, while maintaining the Equation's overall structure, until a match with the actual deformation is obtained.

RESULTS AND DISCUSSION

Based on the Point Load Index (PLI) data from the research area, it was found that more than 50% of the sampled points fall within the transition material category, with samples evenly distributed across the site. This indicates that the majority of the material in the study area can be classified as transition material. Subsequently, numerical modeling using FEM will be conducted by entering UCS parameters into three failure criteria models: the VT, GHB, and MC. This modeling aims to compare the resulting displacements and SRF, which will then be evaluated against actual displacement measurements obtained from slope monitoring tools such as radar.

The input parameters used in the numerical model are presented in Table 4. Moreover, transition materials are analyzed using the Validated Transition of the GHB failure criterion, with parameters determined based on the rock strength classification, as presented in Table 5. The modeling conducted in the previous assessment employed the Mohr-Coulomb failure criterion, which is generally more applicable to soft materials characterized by the MC parameters with cohesion (c) 25 kPa, friction angle (ϕ) 38° (Figure 6).

The numerical simulations performed using the FEM reveal that both the SRF and the resulting displacement values exhibit notable variability depending on the selected failure criterion and the rock strength classification. As shown in Figure 7, each of the three failure models, GHB, VT, and MC, produced distinct displacement values across rock masses categorized as low, medium, and high strength.

Table 4. Input parameter numerical modelling.

Parameter	**Rock Strength**		
	Low	**Medium**	**High**
Modulus Young	1250	2260	3158
GSI	53	52	49
UCS	3.6	7.9	8.3
υ	0.27	0.27	0.27
m_i	19	19	19

Table 5. GHB and VT failure criterion parameter.

Parameter Failure Criterion		Rock Strength		
		Low	Medium	High
	m_b	0.69	0.66	0.51
GHB	s	4.10^{-4}	5.10^{-4}	2.10^{-4}
	a	0.5	0.5	0.5
	m_b"	5.87	6.45	6.70
VT	s''	0.84	2.99	8.74
	a''	2.59	7.92	22.13
	t	0.36	0.79	0.83

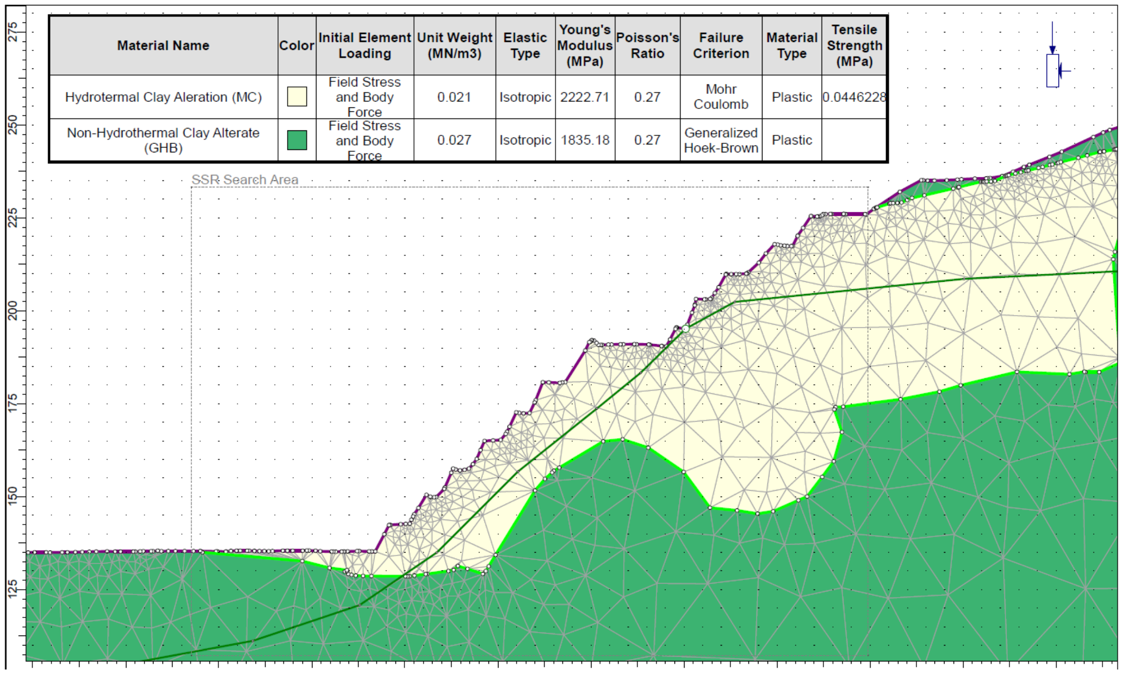

Figure 6. Cross section numerical model.

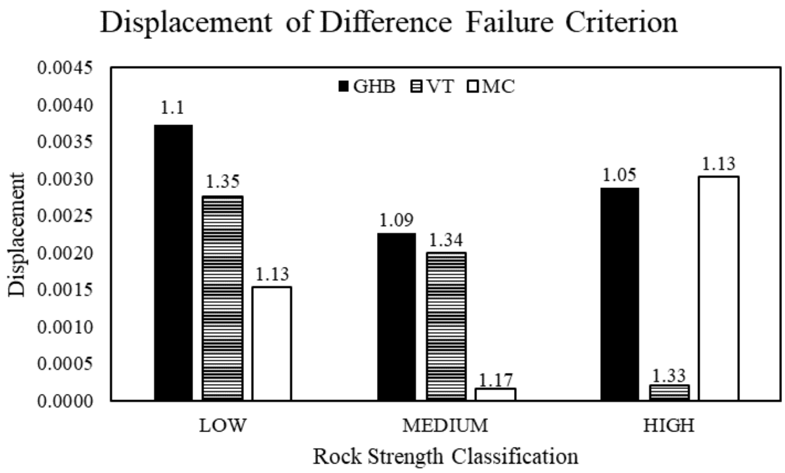

Figure 7. Comparison of displacement and SRF based on rock strength classification.

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A critical observation from the modeling results is that the VT failure criterion, while demonstrating good agreement in predicting displacement for low-strength and medium-strength rocks, appears unsuitable for high-strength rock materials, as it tends to significantly underestimate displacement values compared to the GHB and MC models. This indicates that the mechanical assumptions embedded in the VT criterion may not fully capture the failure mechanisms or deformation characteristics typical of high-strength rock masses.

These findings limited subsequent analyses, particularly those comparing model-predicted and field-measured displacements obtained from slope monitoring radar to low- and medium-strength rock classifications. This selective focus enhances the reliability of the model validation process and ensures that the comparison of numerical and observed displacements is based on geomechanically consistent conditions.

The slope monitoring radar primarily measures surface displacement. In the analysis, the vertical axis (Y-axis) represents distance, where the 70-meter mark corresponds to the boundary of the numerical model, i.e., the actual surface where displacement is recorded. Therefore, to evaluate the accuracy of the numerical models, the calculated displacements at the 70-meter distance must be directly compared with the surface displacement measurements obtained from the slope monitoring radar.

The comparison reveals varying degrees of agreement between modeled and observed displacements, depending on the failure criterion used (Figure 8). The model employing the MC failure criterion shows a correspondence of approximately 68% with the radar-observed displacement. The model utilizing the GHB criterion demonstrates a slightly higher agreement at 75%. Notably, the model applying the VT failure criterion achieves the highest level of consistency, with a 93% match to the actual surface displacement data.

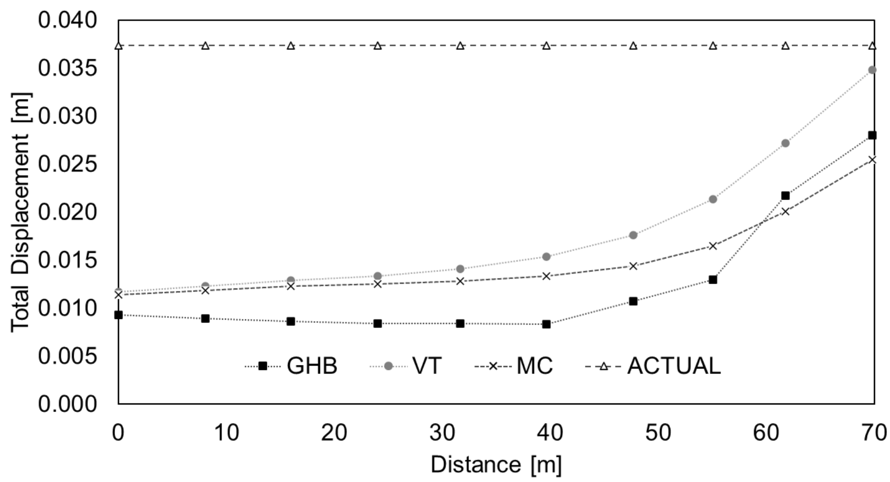

Figure 8. Comparison of displacement responses based on different failure criteria.

These results suggest that the VT criterion provides a significantly more accurate representation of slope behavior under current geological and geomechanical conditions, underscoring the importance of selecting an appropriate failure model for reliable slope stability analysis. When compared with previous studies on weak sedimentary transition materials, such as fissured clay, similar trends were observed: the use of the GHB criterion produced a displacement gap of 31% relative to field data, whereas the validated transition formulation reduced this gap to only 4%, with corresponding SRF values of 1.28 and 1.44, respectively [18]. This comparison reinforces the robustness of the VT approach for transition rock masses. Nevertheless, the present study is limited to a single high-sulphidation epithermal case, and its broader applicability requires further validation. Given its strong agreement with field data, the VT–FEM framework also shows potential for application in other open-pit mines with comparable transition lithologies, hydrothermal alteration zones, or fissured clay materials, where conventional criteria often underperform.

CONCLUSION

The FEM simulations clearly demonstrate that the choice of failure criterion strongly influences slope stability outcomes, particularly in predicting displacement behavior across different rock strength classifications. The study highlights that more than half of the investigated materials belong to the transition class, making the application of a tailored failure criterion essential. Among the criteria evaluated, the VT model consistently achieved the highest accuracy, reproducing radar-monitored displacements with up to 93% agreement in low- and medium-strength rocks.

Furthermore, these results validate the findings of other studies on transition materials, such as fissured clay. This reinforces the VT model's broader applicability across diverse geological settings. This confirmation highlights the model's value as a reliable tool for assessing slope stability, which supports safer and more effective mine planning in complex rock mass conditions

This research demonstrates that the application of the VT criterion within a FEM framework substantially improves the accuracy of slope stability predictions in transition rock masses, achieving strong validation against field-monitored displacements. While the analysis is based on a single high-sulphidation epithermal case study and excludes high-strength rock classes where VT underperforms, the methodological approach holds broader relevance. Specifically, the integration of VT-based failure criteria and FEM modeling can be adapted to other open-pit mines characterized by transition lithologies, hydrothermally altered zones, or fissured clay materials. By extending validation across such comparable geological contexts, the findings provide a foundation for more robust guidelines in slope design, ultimately supporting safer, optimized, and cost-effective pit wall management.

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