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Numerical characterization of tapering features in non-uniform weak interlayers for proposed slope stability geometry

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Abstract

Folding and subsequent pinching out are common geological features in geologically active areas. This gives layers a non-uniform thickness, especially for a multilayer slope with a weak interlayer. Thickness non-uniformity is often disregarded in stability analysis to simplify slope models. However, the geometrical variability of rock masses always exists, and the impact is inevitable; therefore, it is not to be discounted. This research systematically established a geometric correlation framework to understand how tapering configurations in weak interlayer influence slope stability in layered rock masses. Analytical and numerical methods are implemented using the RocScience code. Statistical analysis was also performed to assess the significance and correlation of tapering configurations to slope stability conditions. It was found out that Tilting Intensity ($\rho \geq 0.736$) and Thickness Gradient ($\rho \geq 0.743$) consistently exhibited the strongest ($\alpha = 0$) negative correlation with critical strength reduction factors and slip surface radius, respectively, confirming that taper steepness and vertical irregularity are the dominant geometrical destabilizers in non-uniform weak layers. Moreover, stratigraphic unevenness not only exerts a direct destabilizing influence but also modulates the sensitivity of other geometrical parameters, such as the aspect ratio, by a factor of 2 units ΔFS recorded at the highest elevation. The findings of this study carry several practical and scientific implications for slope design, geomechanical modeling, and geological interpretation in complex stratified rock masses.

1. Introduction

Folding and subsequent pinching out are common geological features in geologically active areas. One example is in a mineralized zone, where a magma intrusion causes regional rock mass deformation. This is the case of a pyrometasomatic deposit, where its deposition is known to come from a magma source making its way upward on the shallower subsurface (Haldar, 2018). Magma intrusion as a dike cuts its way through the different elasticities of preexisting rock layers. Elasticity behavior determines how rock mass deforms from different intrusion forces (Shu et al., 2025). In that sense, every rock exhibits a certain degree of yielding prior to failure, allowing accommodation to intrusive processes. The degree of yielding causes the elasto-plastic rock mass to fold, pinch, or taper to varying extent. From a geometrical point of view, a tapered bed exhibits non-uniform thickness in two dimensions.

Non-uniformity of bed thickness has never been the focus of slope stability research, largely due to the prevailing notion that its influence on slope stability is minor compared to the effects of its mechanical properties and basic geometrical attitude (dip and dip direction). As a result, this aspect is often disregarded or implicitly accepted as part of the natural geological variability. Many researchers explicitly acknowledge this issue as a limitation in their analyses, particularly in relation to simplifying geometrical assumptions of rock mass under investigation. Consequently, a research gap exists in the limited examination of such geometrical non-uniformity. Therefore, there is a clear need to address these geometrical limitations in slope stability analysis.

Review of Related Literature

Much of the slope stability research has focused on a uniform thickness of a weak interlayer in the slope. For instance, it has been repeatedly shown that a "daylighting" weak interlayer puts the slope at risk of failure (Wyllie et al., 2004). The thickness of the weak interlayer has also been shown to be inversely proportional to slope stability. The greater the uniform thickness of the weak layer, the greater the chance of deformation (Li et al., 2025; Valentino, 2023). Moreover, the dip angle also intensifies instability, as the weak layer is more steeply positioned on the slope face, where it can attain a lower factor of safety (Crusoe Jr et al., 2016). Other academic advances in geometrical parameters of the slope concern the location of the weak layer. It has been shown in numerous studies that, aside from the "daylighting" scenario of the weak layer, even when it is hidden within the slope body, its influence on global slope stability increases as it approaches the slope face. This is further intensified by its orientation, whether vertical, inclined, or horizontally emplaced (Azarafza et al., 2021; Girardi et al., 2023; Rodríguez-Ochoa et al., 2015; Valentino, 2023). Other studies use actual stratigraphic delineation from exploration data to simulate a 2D slope model, but they focus on different aspects of slope stability, such as seepage effects (Jia et al., 2024; Patel and McMechan, 2003) and dynamic analyses (Abdela et al., 2025; Cai et al., 2021), and therefore do not address the degree and features of tapering.

Aside from major structural characteristics, such as bedding attitude and thickness, many other studies have also focused on fracture characteristics, applying techniques such as statistical and Voronoi analyses (Boukarm et al., 2024; Ma et al., 2025), and observing how these contribute to failure mechanisms. Although these studies are essential for determining slope stability, they primarily highlight the local failure mechanisms and suggest a commonly defined type of failure. Fracture physical characterization has long been established and defined by spacing, persistence, aperture, block sizes and shapes, and fracture density (Wyllie et al., 2004). This information is translated into empirical scoring suggested by pioneers in the field (Barton, 1972; Palmström and Stille, 2015), which have been widely accepted as standard means of qualifying rock mass stability. Among previous research, none have gone further to investigate the contribution of non-uniform geometry to the behavior of the slope. Although, some studies have explicitly mentioned that this aspect is part of the study limitations (Boukarm et al., 2024; Ma et al., 2025), this does not negate the fact that tapering phenomena and total pinching are almost always present as geological features of major structures, especially in mineralized areas and therefore deserve to be investigated to increase the effectiveness of slope stability analysis.

Significance and Objectives

The non-uniformity of the tapered layer is often disregarded in slope stability modelling simulations. It has been a common practice in geotechnical engineering to simplify models for rapid assessment of slope safety. This includes assuming the interlayer to be uniform in thickness and laterally persistence. However, such simplified model fail to capture the actual geological scenario. Dealing with a natural in situ slope involves inherent geological complexity, especially in geologic areas with mineralization. One author acknowledged in his analysis that non-uniform thickness was present in his study but could not be quantitatively defined, and therefore identified this as a limitation of the study (Valentino, 2023).

Oversimplification compromises robustness and may lead to misrepresentation, causing damage in the long run. While it is beyond reasonable doubt that slope configuration and structural geometry play a critical role in governing slope stability, geotechnical engineers often to unintentionally disregard the slope's sensitivity to irregular geometry and non-uniform thicknesses. Given this, the author suspects that this may be due to a lack of a robust description of these geometrical characteristics. There is no established quantitative standard for recording or describing the degree of tapering of the interlayer. This is one of the reasons why researchers often fail to observe or quantify the effect of the non-uniformity of the tapered weak interlayer, and instead resolve the issue by simplifying models or by identifying the phenomenon as a study limitation. The present research aims to propose measurable tapering parameters to determine whether they have a significant relationship with slope stability analysis.

The objective of this study is to establish five characteristic features of weak interlayer tapering: 1) Aspect Ratio, 2) Symmetrical Ratio, 3) Tilting Intensity, 4) Thickness Gradient, and 5) Wedge Area, and to determine which of these Tapering Configuration Features (TCFs) show significant connection and sensitivity to commonly used stability criterion, namely the Critical Shear Strength Reduction Factor (CSRF). In support of the analysis, the numerical calculation of Maximum Total Displacement (MTD) and analytical determination of slip surface radius will be included as supplementary results to investigate the intensity and spatial extent of potential failure influenced by the TCFs.

After determining these three stability indicators, an attempt will be made to fit linear correlation functions, and the statistical significance of the relationships will be determined as the final step. Statistical correlation analyses will also be performed on the average dip angles and the exposed vertical thickness of the Weak Middle Layer (WML) to examine whether the widely recognized linear relationship with the stability criterion remains valid for non-uniform or tapering thicknesses. Stress contours will also be present to support and substantiate the findings.

2. Data and methods

Setting up Base Model

Inspired by the geological setting of the pyrometasomatic skarn deposit in the tropical island arc of the Philippines (Fig. 1a), this setting will serve as the basis for constructing a 2D model for the subsequent analysis. The Philippines, with its volcanic terrain and tropical climate, remains geologically active, with volcanism, sedimentation, burial, and erosion forming the prevailing geological cycle (Becker and Martin, 1901), as evidenced by an alternating sequence of volcanic and sedimentary rocks (Fig. 1b-1c). In addition to volcanic and sedimentary rocks, dike and sill intrusions, as sources of local mineralization, contribute to the folding and tapering of pre-existing rocks and create a new set of metamorphically altered rocks (Haldar, 2018).

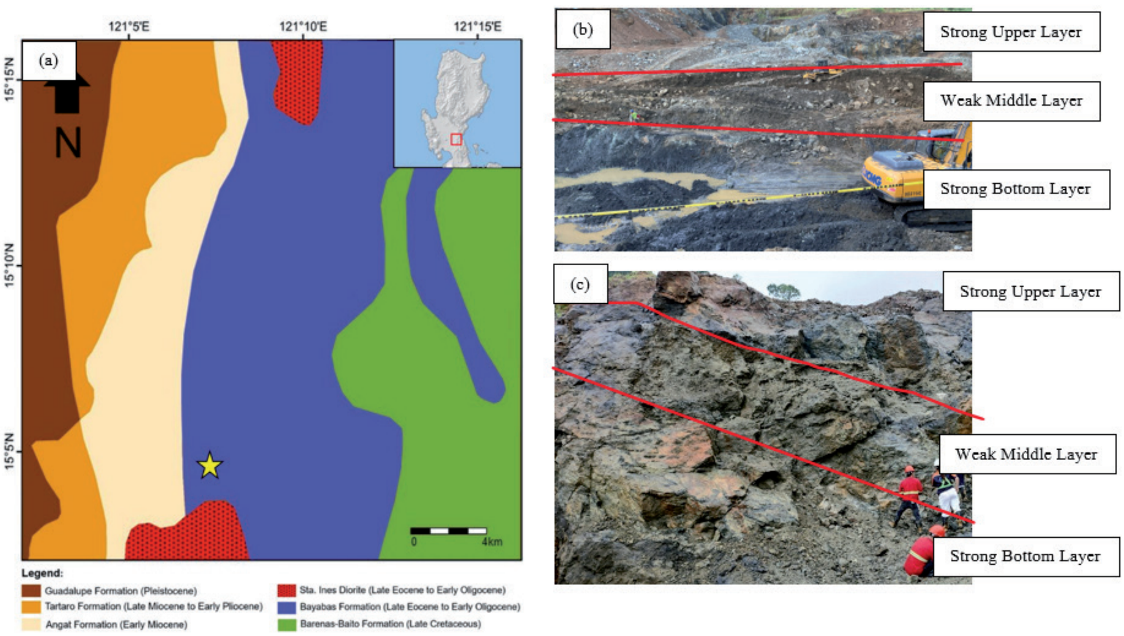

Figure 1. Geological map of skarn deposit in Bulacan, Philippines, with on-site photographs of multilayered slope (b-c). The star symbol marks the sampled area. Modified from Mines and Geosciences Bureau (2010).

Focusing exclusively on the tapering feature, the model will be simplified to only two major rock types: volcanic and clastic units, where the volcanic unit is assigned as the top layer (TL), the clastic (sedimentary) unit as the middle layer (ML), and a second volcanic unit as the basement layer (BL) of the excavated slope (Fig. 2). The sedimentary middle-layer unit is treated as the weak layer and is assumed to be the most affected by pinching-out or tapering resulting from active geological processes, while the remaining rock units are treated as hard rock. Hence, the composition of the slope mass is a strong-weak-strong multilayer rock system. Coupled with the well-known adverse effect on slope stability of having a weak interlayer (Rodríguez-Ochoa et al., 2015; Valentino, 2023), the effects of folding and pinching out phenomena are concentrated on this middle rock unit.

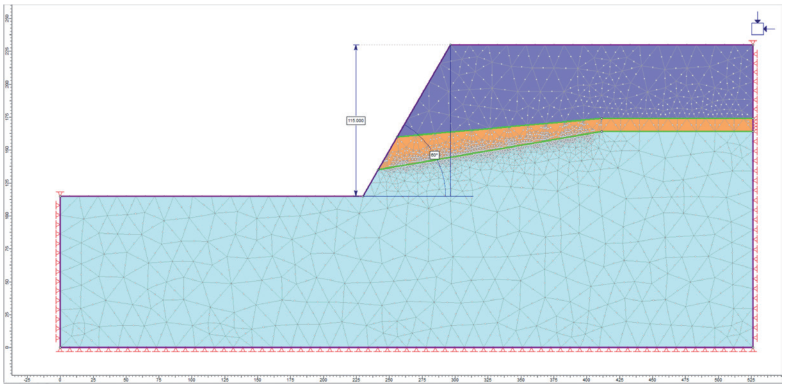

Figure 2. Numerical set-up of the 2D geological slope model

A 2D geometrical model of the slope and the geological structures is constructed using Rocscience RS2 software (Fig. 2). Maximum Total Displacements (MTD) are computed using Finite Element Numerical Method (FEM) for pseudo-continuum material model, which is considered appropriate for mineralized slope. The shear strength reduction (SSR) capability in RS2 is activated to obtain the CSRF for each tapering configuration. The slope geometry, inspired by the typical surface mine dimensions (60° OSA and 115m slope height) (Fig. 2) is kept constant throughout the analysis to isolate the effect of 5 TCFs.

As such, weak interlayer dimensions are systematically adjusted to induce varying degrees of TCFs, and all these are recorded individually to yield sufficient experimental data suitable for statistical analysis. However, the level of TCFs is controlled solely by daylighting conditions and by dipping into the slope face to induce instability through stress redistribution, guided by well-established concepts from past studies (Wyllie & Mah, 2004). Including opposite-dipping configurations or a fully hidden weak layer would otherwise dilute the dataset and render the analysis inconclusive.

Physicomechanical properties (Table 1) of each rock unit of the slope were derived through engineering judgement based on a series of field observations and guided by material properties indices proposed by Hoek and Brown (2018) to reflect the strong-weak-strong mechanical characteristics of the individual rock units. Furthermore, the Hoek-Brown failure criterion is also adopted to represent the elasto-brittle-plastic behavior of a mineralized slope.

Table 1. Geomechanical properties of the multi-layered slope

Rock Unit	Unit Weight (γ, MN/m^3)	Uniaxial compressive strength (σ_c, MPa)	Young's Modulus (E, MPa)	Geological Strength Index (GSI)	Intact rock material constant (mi)	Excavation disturbance factor (D)
Top Layer (TL)	0.026	90	3417.4	60	35	0.8
Middle Layer ML)	0.024	60	719.3	30	20	0.7
Basement Layer (BL)	0.027	100	6517.2	80	25	1.0

The ground surface is set free to move, while the side and bottom subsurface boundaries are assigned axial fixation, given that the ratio of the vertical (Y) dimension is set to 2H and the horizontal (X) dimension is set to 4H to minimize the influence of external boundaries on the tapered bed. The tapering and dipping of the middle layer are extended only to half the horizontal extent of the right-side boundary to allow sufficient space for the tapered structure to accommodate the applied internal and external stresses. This approach is commonly used to isolate the tapered layer from the effects of the external boundary constraints. Gravity loading and insitu stress conditions are then activated to simulate loading and stress redistribution associated with the active mining operation.

Assumptions, Scope, and Delimitation

The analysis in this study is limited to dry, static environmental conditions to focus solely on the geometric effects of the proposed tapering features on the slope's stability. Furthermore, it is assumed that only generalized regional stresses are at play, allowing for simplified fixed boundary conditions and equal stress ratios in both principal directions. In this study, it is also assumed that the failure plane develops only along the slope face; therefore, an auto-refine search algorithm is selected to determine the critical slip surface radius using the SLIDE2 software.

Establishing Proposed Five-Tapering Configuration Features (TCFs)

An attempt is made to describe each TCF, its importance, and the corresponding equation for quantitative measurement, as listed below:

1. Aspect Ratio (AR) (Fig. 3a) - represents taper sharpness, with calculation based on the concept used in finite element solvers to compute the aspect ratio of triangular mesh elements (Altair Engineering, Inc., 2022), which is the ratio between the longest edge of an element and either its shortest edge or the shortest distance from a corner node to the opposing edge. In this study, it is defined as the lower contact length divided by the exposed width on the slope face (Equation 1). The lower contact length can only be determined with the help of a 2D geological cross-section, whereas the exposed width can be directly measured in the field.

$$AR = \frac{Lower\ Contact\ Length}{Face\ Length} \qquad (1)$$

2. Symmetrical Ratio (SR) (Fig. 3b)- compares the lateral spread of the wedge between the hanging-wall and footwall sides to assess failure asymmetry. The wedge geometry represents the non-uniform thickness of the middle layer and indicates whether the weak layer thickness bulges toward the hanging wall or, alternatively, toward the footwall. Guided by the concept of similar triangles, the Symmetrical Ratio is defined as the ratio between the Footwall side (FWR) and the Hanging-wall side (HWR) of the tapered layer (Equation 2).

$$SR = \frac{Footwall\ Ratio}{Hanging\ Wall\ Ratio} \qquad (2)$$

3. Tilting Intensity (TI) (Fig. 3c) – is similar to dip angle but is expressed as the average inclination of the wedge, measured relative to the neutral plane angle (θn), which is defined as the mean of the field-recorded maximum (θu) and minimum (θl) dip angles of the lithology of interest along a single vertical scanline (Equation 3).

$$\theta n = \frac{\theta u + \theta l}{2} \qquad (3)$$

4. Thickness Gradient, TG (Fig. 3d) – is defined as the ratio of the exposed thickness (H_1) to the hidden thickness (H_2) of the weak interlayer (Equation 4). It describes the continuity of non-uniformity as a function of distance and reflects how drastic (higher TG) or gradual (lower TG) the change in thickness of a bed is over a given distance. From the materials science perspective, a thickness gradient supports the assumption that volume changes correlate with the material's temperature gradient (Drukker et al., 2003). Ambient heat is one of the factors that can drive changes in rock mass volume, and such volume changes are relevant during the planning and design stage for engineering intervention.

$$TG = \frac{H_1}{H_2} \quad (4)$$

5. Wedge Size Area (WA) (Figure 3e)- represents the relative volumetric contribution of the weak layer to the overall slope mass. It has long been established that the exposed thickness of a weak interlayer is inversely proportional to its stability. However, it remains unclear whether the total wedge size influences stability even when the exposed thickness is relatively small. The respective significance of wedge size and exposed height in relation to slope stability are subsequently compared.

Most tapering features can be measured directly in the field using compass clinometers and tape measures applied to outcrops, or, where this is not possible, a geological subsurface model derived from exploration data can be used to identify and quantify them.

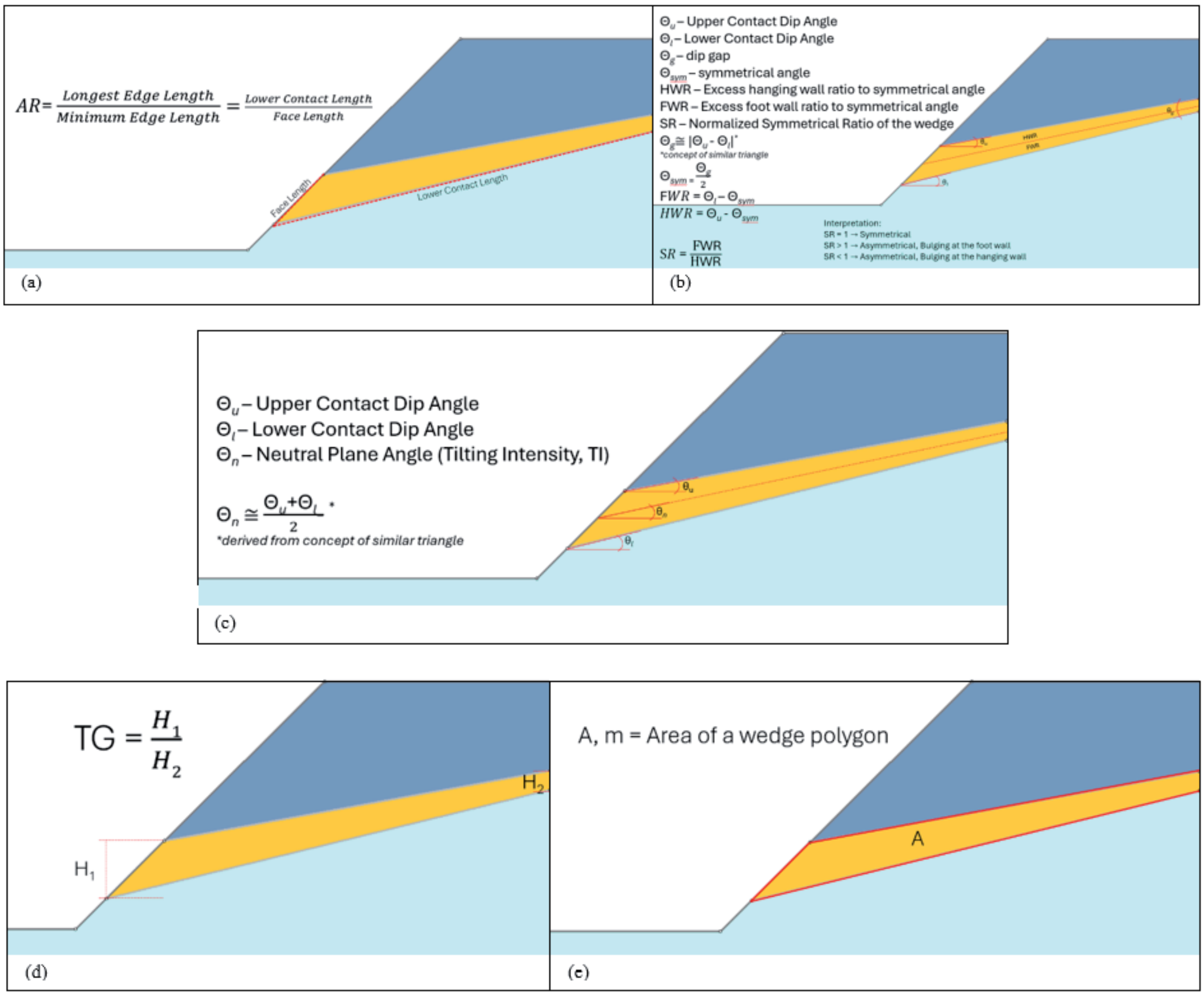

Figure 3. Illustration diagram of calculation method for each TCF: (a) AR, (b) SR, (c) TI, (d) TG, (e) WA

Generation of Hypothetical Data for Statistical Analysis

In the example study area, the thickness of the WML ranges from 10 m to 30 m, and the dip angle ranges from 5° to 33°, directed towards the slope face. Since the ore formed by metasomatism, which is characterized by its irregular distribution and sizes, the pit bottom includes some thickness of basement rock (BL) as part of the slope face and varies significantly from 5 m to 20 m in height. This is also verified through observation of the current mining operation, which compensates for the unevenness of the folded layer in its third dimension. But for completeness, to capture other possible extents, it was decided to widen the range of combinations to 5 – 35 m thickness, from horizontally emplaced beds to 35° dipping towards the slope face, and from 5 m to 25 m of basement rock inclusion at the slope face. Including basement rock in the slope face thickness elevates the location of the WML in the slope. This is also one of the parameters that this research examines.

The dipping configuration of the weak layer reflects a folded bed. Now, to model tapering or pinching-out phenomena, the back-end thickness of the dipping bed will not be similar to its exposed slope face thickness. This changes the uniform thickness to a non-uniform thickness of the middle layer, reflecting a realistic geometrical setup, especially for a mineralized slope. A 5-unit interval is used to generate combinations of the following geometrical parameter: 1) WML slope-face exposed vertical thickness (Hf), 2) WML back-end thickness (Hb), 3) WML upper dip angle (Θu), and 4) BL exposed thickness. As a side note, the back-end thickness can only be measured from the 2D geological model, while other parameters can be obtained from field measurements. From the produced combinations, a semi-systematic selection is applied, capturing the opposite extremes and some in-between scenarios to strengthen the overall results.

Initially, Latin Hyperbolic Sampling (LHS) was performed, but using pure LHS would also add uniform- thickness data, which would distort the statistical analysis, as it should focus only on irregular thickness. Fixing the gaps left by the LHS partitions involved meticulously removing uniform-thickness data and replacing the removed data points with additional intermediate points that capture the actual recorded modality of the sampled area. The treatment was performed to improve the smoothness of the regression/response surfaces.

A Spearman correlation coefficient (ρ) for monotonic correlation with a two-tailed sigma for α-significance will be the adopted statistical treatment for the parametric correlation. It is to be recalled that $\alpha = 0$ is interpreted as the probability that the observed result occurred by chance being 0, and thus it is statistically significant. Moreover, a ρ value closer to 1 indicates a stronger relationship, while a value closer to 0 indicates a weaker relationship; the positive or negative sign indicates the direction of the relationship. Looking at some authors (e.g., Ameratunga et al., 2016; Daoud et al., 2016), for empirical geotechnical correlations, a value ≥ 0.70 is recommended as the minimum correlation coefficient, and since slope safety is a meticulous task, $\rho \geq 0.70$ with $\alpha = 0$ is the adopted acceptance criterion for drawing conclusions. The diagram below summarizes the flow of the research activity (Figure 4).

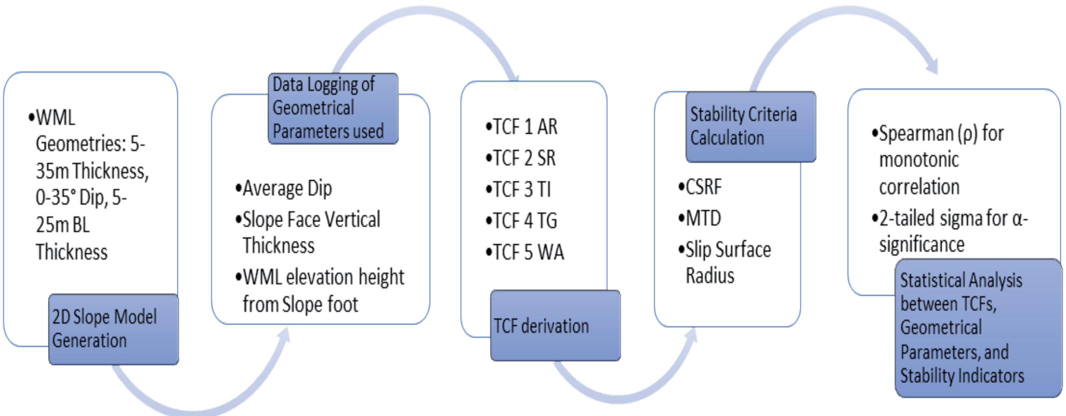

Figure 4. Research activity flow chart

3. Results

A total of 176 tapering combinations were generated; 56 of them have WML positioned 25 m above the slope foot (maximum position), another 56 at 5 m above slope foot (lowest position), while the 48 are at 10 m above slope foot (middle position), and the rest with 15 m and 10 m BL thickness. This was done intentionally to examine the effect of uneven stratigraphy in the third dimension and to achieve wider, more realistic scenarios. The CSRF, maximum total displacements, and slip surface radius were calculated for each of the 176 tapering models. The TCFs of the 176 models were also derived from the proposed equations and are recorded individually, along with the average dip angles and the exposed thickness of the WML. The resultant stability indicators are correlated with the TCFs and the basic geometrical parameters under investigation, and the statistical significance of the investigated relationship was determined. A summary of the statistical analysis for the sample size n = 176 is consolidated in Table 2.

Table 2. Spearman rank correlation (ρ) and α-significance between stability indicators and geometrical parameters for the total data set (N=176)

	CSRF	Maximum Total Displacement	Slip Surface Radius
WML Exposed Thickness	-0.647*	0.504*	-0.333*
WML Elevated Height	0.134177581	-0.071225855	-0.880**
WML Ave. Dip	-0.734**	-0.552*	0.051779251
TCF 1 Aspect Ratio	0.617*	-0.430*	0.426*
TCF 2 Symmetrical Ratio	0.01184899	0.304	0.371
TCF 3 Tilting Intensity	-0.736**	-0.551*	0.05468475
TCF 4 Thickness Gradient	0.014023366	0.093325658	-0.743**
TCF 5 Wedge Area	-0.238*	0.651*	-0.535*

The Spearman rank correlation analysis (Table 2) was conducted to determine the relationships between the slope stability indicators—Critical Strength Reduction Factor (CSRF), Maximum Total Displacement, and Slip Surface Radius—and the geometrical parameters of the Weak Middle Layer (WML) and its Tapering Configuration Factors (TCFs). To ensure statistical reliability, only correlations with coefficients of $\rho \geq 0.70$ and significance level $\alpha = 0.01$ were considered strong enough to support the conclusions.

Under this criterion, the WML Average Dip ($\rho = -0.734$, $p < 0.01$) and TCF 3 Tilting Intensity ($\rho = -0.736$, $p < 0.01$) both exhibit strong negative correlations with the CSRF. This indicates that as the weak middle layer becomes more inclined or experiences greater overall tilting, the computed stability factor consistently decreases. Conversely, a strong positive correlation was observed between the CSRF and TCF 1 Aspect Ratio ($\rho = 0.617$), though it falls slightly below the 0.70 threshold and is therefore considered indicative but not conclusive.

For the Slip Surface Radius, the parameters WML Elevated Height ($\rho = -0.880$, $p < 0.01$) and TCF 4 Thickness Gradient ($\rho = -0.743$, $p < 0.01$) show strong and highly significant negative relationships, suggesting that greater vertical irregularity and sharper thickness gradients within the weak layer correspond to smaller failure radii, implying more localized or shallow failure mechanisms, as shown in Figure 5. No parameters exhibited strong positive correlations with Slip Surface Radius or Maximum Total Displacement at the accepted significance level.

Overall, only four variables—WML Average Dip, TCF 3 Tilting Intensity, WML Elevated Height, and TCF 4 Thickness Gradient—meet the defined strength and significance threshold ($\rho \geq 0.70$, $\alpha = 0.01$). These parameters are therefore identified as the most influential geometrical controls on slope stability indicators in this study.

These statistical outcomes highlight the geometrical parameters that most strongly govern slope stability in the modeled configuration (a slope with irregular layer thickness). The consistently high-magnitude and significant correlations of WML Average Dip, TCF 3 Tilting Intensity, WML Elevated Height, and TCF 4 Thickness Gradient suggest that both the internal inclination of the weak interlayer and the degree of stratigraphic unevenness play dominant

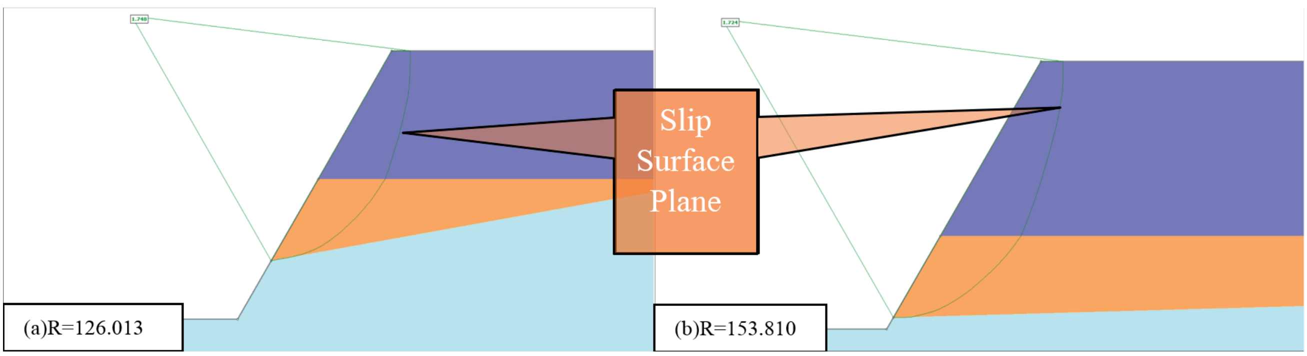

Figure 5. Comparison of the slip surface radius, R, of the slope with a sharper thickness gradient WML in a higher elevated position (a) versus a slope with a more gradual WML thickness gradient in a lower elevated position (b). The slip radii of the global minimum FS are smaller in (a) than in (b), where both slip planes are bounded by the weak layer at a shallower depth as the thickness gradient increases.

roles in determining the overall slope response. In contrast, parameters such as Aspect Ratio and Symmetrical Ratio exert comparatively minor or inconsistent effects. These patterns collectively indicate that slope stability is more sensitive to geometrical irregularities that influence the inclination and continuity of the weak layer than to those affecting its lateral extent or symmetry. The following discussion elaborates on these relationships, examining their mechanical implications and addressing how each parameter contributes to the three main research questions: the influence of taper geometry, the persistence of classical geometrical effects, and the modifying role of stratigraphic unevenness.

Three subsets (Table 3-5) were evaluated separately, each defined by a distinct WML elevated height, while maintaining a consistent elevation within each subgroup to isolate the influence of stratigraphic unevenness.

At the subset with a fixed 25 m WML elevated height, strong negative correlations were observed between WML Exposed Thickness ($\rho = -0.856$) and TCF 4 Thickness Gradient ($\rho = -0.856$) and the Slip Surface Radius, suggesting that thicker and more variable weak layers promote smaller, more localized failure surfaces. TCF 1 Aspect Ratio ($\rho = 0.708$) demonstrated a strong positive correlation with CSRF, implying that a broader taper configuration corresponds to higher computed stability at this stratigraphic level.

Table 3. Spearman rank correlation (ρ) and α-significance between stability indicators and geometrical parameters at fixed 25-meter WML elevated height

n = 56	CSRF	Maximum Total Displacement	Slip Surface Radius
WML Exposed Thickness	-0.664*	0.555*	-0.856**
WML Elevated Height	N/A	N/A	N/A
WML Ave. Dip	-0.647*	-0.495*	-0.048459344
TCF 1 Aspect Ratio	0.708**	-0.478*	0.861**
TCF 2 Symmetrical Ratio	0.699	0.082390168	0.454*
TCF 3 Tilting Intensity	-0.65*	-0.494*	-0.058349173
TCF 4 Thickness Gradient	-0.659*	0.558	-0.856**
TCF 5 Wedge Area	-0.387*	0.709**	-0.734**

*with α=0 but ρ<0.69
**with α=0 and ρ≥0.7

Table 4. Spearman rank correlation (ρ) and α-significance between stability indicators and geometrical parameters at fixed 10-meter WML elevated height

n = 48	CSRF	Maximum Total Displacement	Slip Surface Radius
WML Exposed Thickness	-0.605*	0.466*	-0.828**
WML Elevated Height	N/A	N/A	N/A
WML Ave. Dip	-0.811**	-0.643*	-0.384*
TCF 1 Aspect Ratio	0.557*	-0.270748521	0.735**
TCF 2 Symmetrical Ratio	-0.184274084	0.466**	-0.241373671
TCF 3 Tilting Intensity	-0.811**	-0.643*	-0.384*
TCF 4 Thickness Gradient	0.617*	-0.466*	0.829**
TCF 5 Wedge Area	-0.049740713	0.833**	-0.413*

*with α=0 but ρ<0.69
**with α=0 and ρ≥0.7

Table 5. Spearman rank correlation (ρ) and α-significance between stability indicators and geometrical parameters at fixed 5-meter WML elevated height

n = 56	CSRF	Maximum Total Displacement	Slip Surface Radius
WML Exposed Thickness	-0.711**	0.441*	-0.894**
WML Elevated Height	N/A	N/A	N/A
WML Ave. Dip	-0.727**	-0.570*	-0.213377538
TCF 1 Aspect Ratio	0.658*	-0.470*	0.877**
TCF 2 Symmetrical Ratio	-0.096243114	0.453*	-0.323*
TCF 3 Tilting Intensity	-0.727**	-0.570*	-0.213377538
TCF 4 Thickness Gradient	N/A[1]	N/A[1]	N/A[1]
TCF 5 Wedge Area	-0.383*	0.662*	-0.743**

*with α=0 but ρ<0.69
**with α=0 and ρ≥0.7
[1] Back-end Thickness is 0m to induce tapering for 5 meters exposed thickness, making the Thickness Gradient TCF4 trigonometrically not applicable

In contrast, subsets with higher or lower elevations showed similar trends, but with shifts in magnitude. For all subsets, WML Average Dip ($\rho \approx -0.734$, $p < 0.01$) and TCF 3 Tilting Intensity ($\rho \approx -0.736$, $p < 0.01$) consistently maintained strong negative correlations with CSRF, confirming that increasing inclination of the weak layer and overall wedge tilting systematically reduce stability. WML Elevated Height itself, as shown in the original set in Table 2, exhibited the strongest negative correlation with Slip Surface Radius ($\rho = -0.880$, $p < 0.01$), indicating stratigraphic unevenness as a key controlling parameter on the depth and shape of potential failure surfaces.

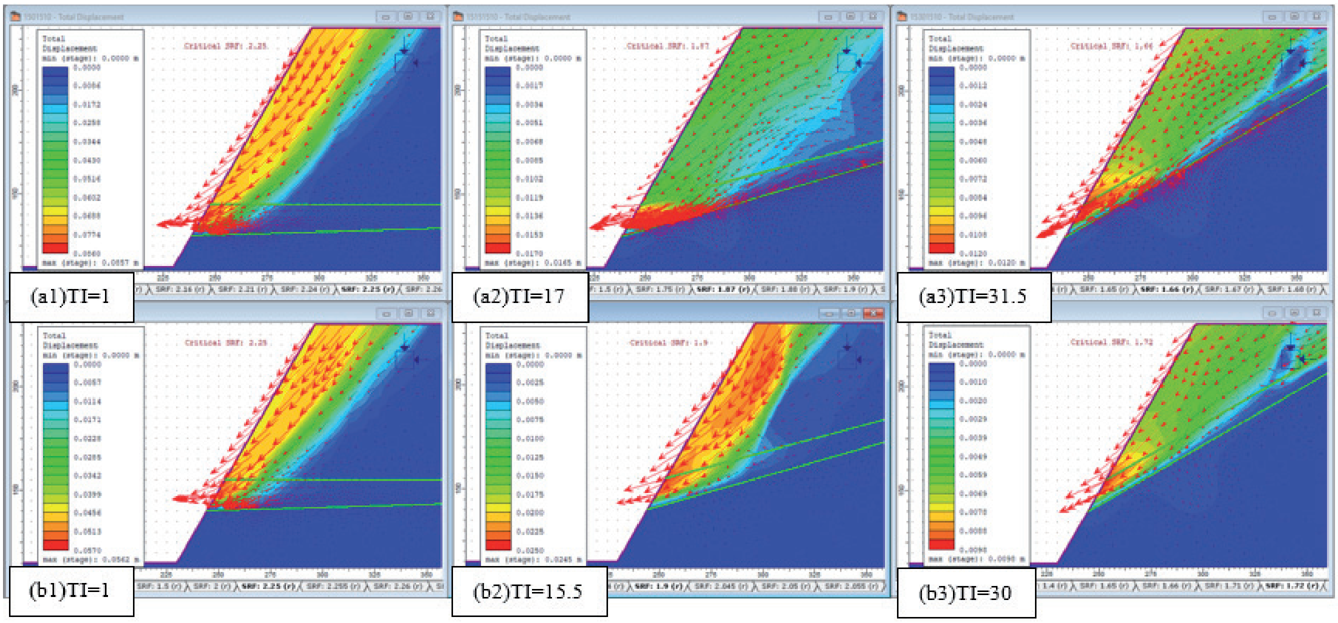

Figure 6. Comparison of total displacement contours with stress vectors of the WML at different tilting intensities, TI (1-2-3) situated at different elevations (a-b). The higher the TI value obtained, the more tilted it gets. At higher tilting intensity (e.g. TI=31.5 and TI=30) stress vectors become deeper and localized, and at higher elevation (b1 to b3), stress coverage becomes shorter.

Overall, four parameters—WML Average Dip, TCF 3 Tilting Intensity, WML Elevated Height, and TCF 4 Thickness Gradient—consistently exceeded the $\rho \geq 0.70$ threshold across the subsets, designating them as the primary geometrical controls on slope stability. Parameters such as Aspect Ratio and Symmetrical Ratio displayed moderate but non-persistent correlations and are therefore regarded as secondary influences under the present modeling conditions.

These subset-based correlations emphasize that the influence of taper geometry on slope stability is not uniform but varies with changes in WML elevation. While certain relationships—such as the negative dependency of CSRF on layer dip and tilting intensity—remain consistent, others, including the stabilizing effect of aspect ratio, appear sensitive to stratigraphic elevation. The repeating dominance of WML elevated height and thickness gradient in controlling slip radius underscores the mechanical significance of stratigraphic unevenness as an independent factor modifying the stability response. The succeeding discussion explores these findings in greater depth, focusing on (1) which tapering configuration factors exhibit the strongest control on stability, (2) whether basic geometrical parameters retain their conventional relationships under non-uniform tapering, and (3) how stratigraphic unevenness mediates these interrelations.

4. Discussion

Influence of Tapering Configuration Factors (TCFs) on Stability Indicators

Across the full correlation set, TCF 3 Tilting Intensity and TCF 4 Thickness Gradient of the wedge-like middle layer consistently exhibit the strongest negative correlations with the stability indicators, particularly CSRF ($\rho = -0.736$, $p < 0.01$) and Slip Surface Radius ($\rho = -0.743$, $p < 0.01$). This implies that taper geometries characterized by higher inclination and steeper vertical gradients are inherently less stable, thereby strengthening the hypothesis that geometrical non-uniformity enhances shear localization and stress concentration along weak interlayers. The persistence of these relationships across all subsets, regardless of WML elevated height, underscores the robustness of Tilting Intensity and Thickness Gradient as primary geometrical controls on slope stability.

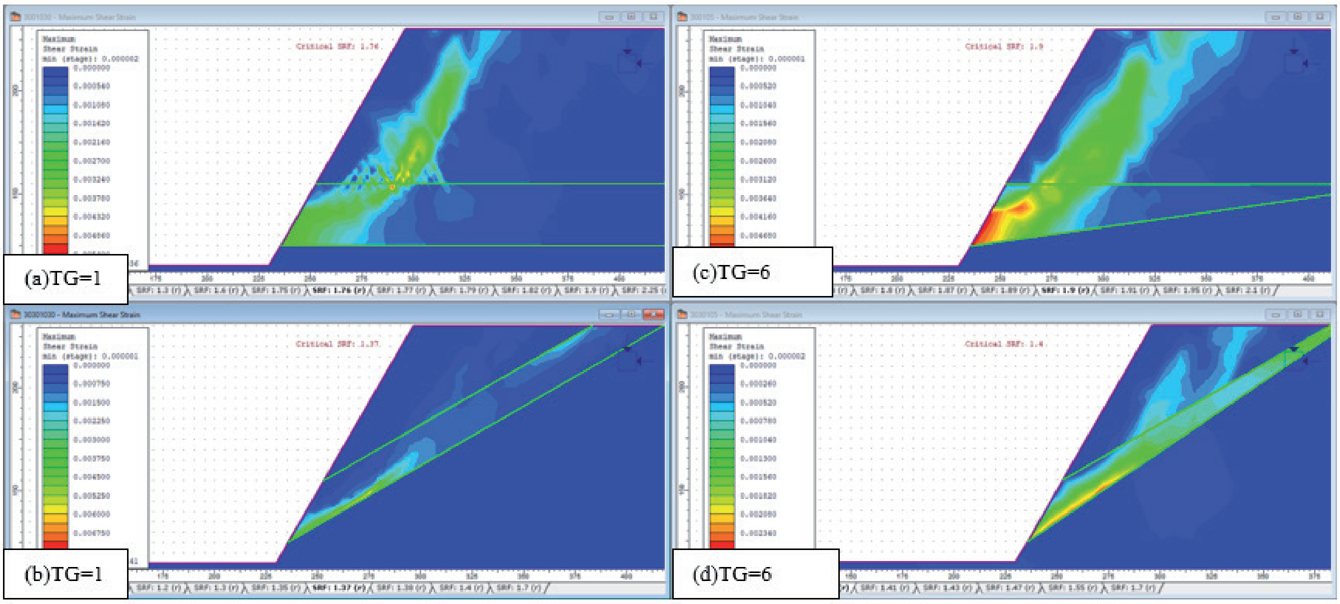

Figure 7. Comparison of shear strain contour between uniform thickness (a-b) and non-uniform thickness (c-d). The TG value obtained indicates the degree of MWL angular wideness towards slope face. Shear-type strain is more pronounced in non-uniform thickness characterized by TG>1.

At the subset with a fixed 25 m WML elevated height, however, TCF 1 Aspect Ratio (ρ = 0.708) emerges as a locally significant stabilizing factor, suggesting that broader tapering reduces stress concentration by distributing shear strain over a larger zone. Yet, this stabilizing effect weakens at higher or lower WML elevations, implying that taper sharpness contributes positively to stability only within an optimal stratigraphic range where lateral continuity is maintained. The Symmetrical Ratio, by contrast, demonstrates weaker and inconsistent correlations, indicating that the lateral asymmetry of the wedge exerts a subordinate influence on the overall stability response. On the other hand, the Wedge area (TCF 5), although shown to have a strong connection to stability indicators, has not established a clear linear correlation in broader geometrical circumstances, and thus cannot be concluded to significantly influence the stability indicators.

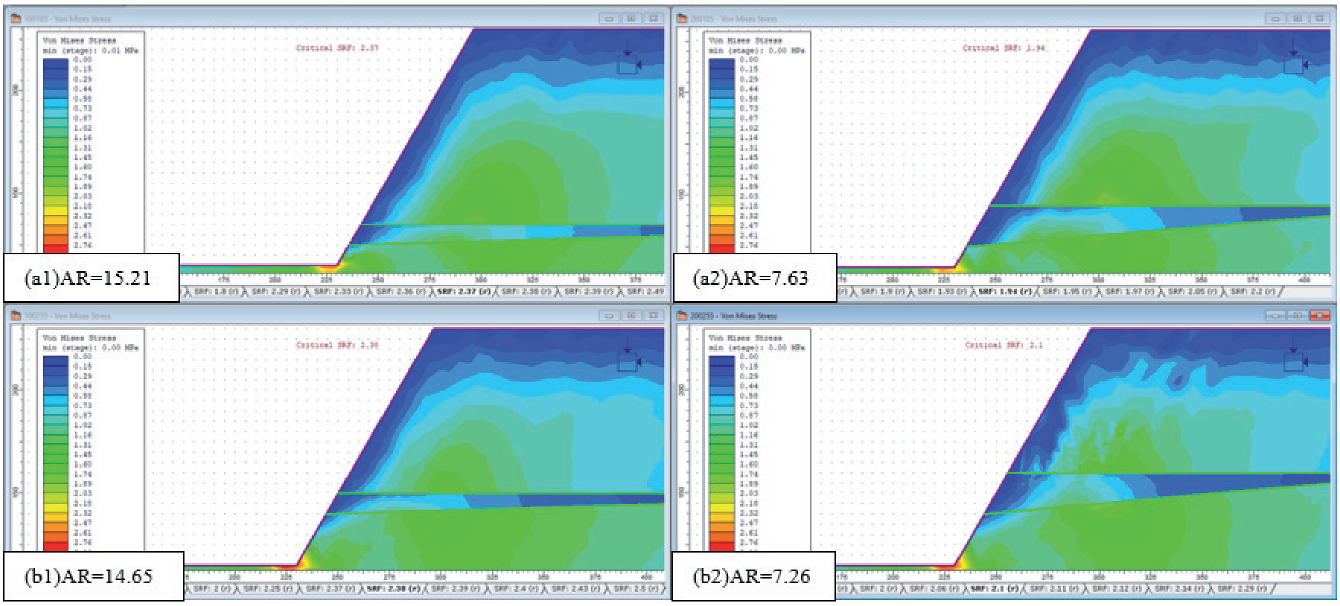

Figure 8. Comparison of Von Misses stress distribution of varying aspect ratio (a-b) at different stratigraphic elevations (1-2). The high AR value obtained indicates the taper sharpness of MWL. A lower aspect ratio dissipates stress concentrations. At certain elevation, broader tapering contributes to stability.

To strengthen the results, a simple validation was performed by counting the number of times the particular TCFs and basic geometrical parameters have both $\alpha = 0$ and $\rho \geq 0.7$ across the full dataset and the subsets generated. This is shown in Tables 6 and 7.

Table 6. Correlation validation scores

	CSRF	Maximum Total Displacement	Slip Surface Radius
WML Exposed Thickness	1	0	3
WML Elevated Height	N/A	N/A	N/A
WML Ave. Dip	3	0	0
TCF 1 Aspect Ratio	1	0	2
TCF 2 Symmetrical Ratio	0	0	0
TCF 3 Tilting Intensity	3	0	0
TCF 4 Thickness Gradient	0	0	3
TCF 5 Wedge Area	0	2	2

Table 7. Significance validation scores

	CSRF	Maximum Total Displacement	Slip Surface Radius
WML Exposed Thickness	4	3	4
WML Elevated Height	0	0	1
WML Ave. Dip	4	3	1
TCF 1 Aspect Ratio	4	3	4
TCF 2 Symmetrical Ratio	1	1	1
TCF 3 Tilting Intensity	3	3	1
TCF 4 Thickness Gradient	1	2	3
TCF 5 Wedge Area	3	4	4

The above findings collectively answer RQ1, establishing that Tilting Intensity and Thickness Gradient are the most reliable TCF predictors of slope instability. At the same time, Aspect Ratio offers conditional stability improvement under moderate elevation conditions.

Persistence of Basic Geometrical Parameters under Non-Uniform Tapering

The fundamental geometrical parameters—WML Average Dip and WML Exposed Thickness—retain their classical inverse relationships with slope stability even under non-uniform tapering. In both the original dataset and all subsets, WML Average Dip ($\rho = -0.734$, $p < 0.01$) shows a strong negative correlation with CSRF, signifying that steeper bedding consistently promotes instability, consistent with established slope mechanics (Wyllie et al., 2004).

However, the subsets reveal that the magnitude of this effect varies slightly with WML elevated height. In the mid-elevation subset (10 m), the dip-angle influence remains significant. In contrast, at higher or lower elevations, it slightly attenuates, likely due to counteracting effects from taper geometry and reduced confinement. Similarly, WML Exposed Thickness as a whole maintains a generally inverse relationship with stability ($\rho = -0.647$, $p < 0.05$), and its effect on Slip Surface Radius is more substantial in subset cases where thickness variation coincides with a strong Thickness Gradient ($\rho = -0.856$).

Thus, while the weak layer's dip and thickness continue to control stability in a fundamental sense, their exact contribution is modulated by taper geometry, confirming that basic geometrical parameters follow their usual trends but are dynamically influenced by non-uniform tapering.

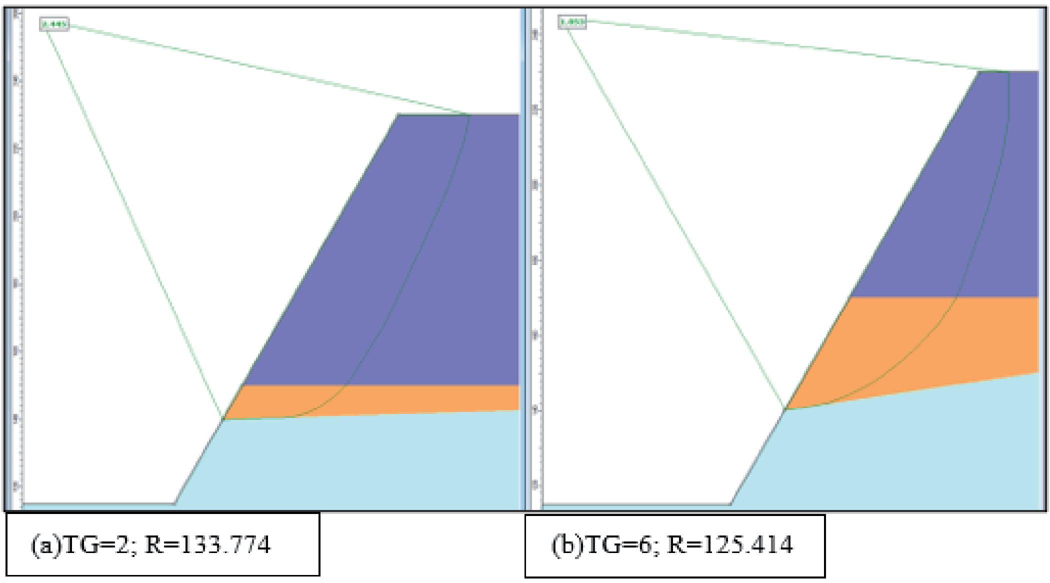

Figure 9. Comparison of the slip surface radius (R) for two different exposed thicknesses (10m and 30m, respectively) with coinciding backend tapered thickness (5m). Two different combinations of exposed and backend thickness still give different thickness gradients (a-b). At a higher thickness gradient (TG=6), the slip surface radius R becomes smaller, indicating a shallower plane failure.

Effect of Stratigraphic Unevenness on Stability Relationships

The WML Elevated Height—a proxy for stratigraphic unevenness—shows the single strongest correlation in the dataset, particularly with Slip Surface Radius ($\rho = -0.880$, $p < 0.01$). This negative relationship indicates that as the stratigraphic elevation difference between the weak and the underlying layers increases, potential failure surfaces become smaller and more localized. This trend holds across all subsets, affirming that stratigraphic unevenness directly alters the mechanical boundary conditions of the slope.

Furthermore, stratigraphic unevenness amplifies the influence of tapering-related parameters, especially Thickness Gradient, by accentuating vertical stress differentials within the weak layer. As elevation differences increase, the stabilizing role of Aspect Ratio diminishes, while the destabilizing effect of Tilting Intensity becomes more pronounced. This interaction indicates that the combined influence of uneven stratigraphy and taper geometry governs the overall slope behavior more strongly than either factor alone.

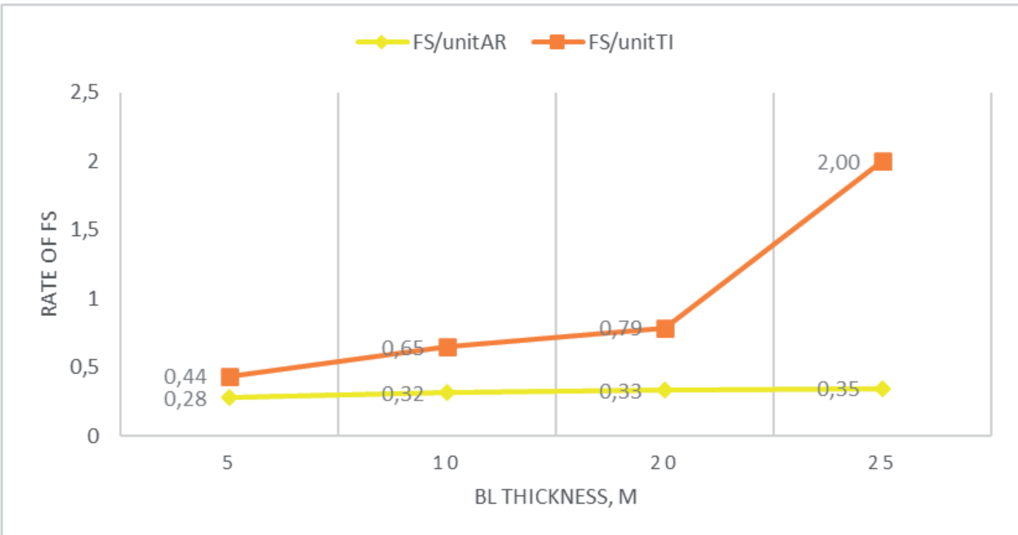

Figure 10. Comparison of factor of safety (FS) rate of change between Aspect Ratio (AR) and Tilting Intensity (TI) at different elevation thicknesses. The unitless FS rate is derived from the resultant FS change per one unit increase in AR or TI (e.g., 0.4375 per unit AR at 5 m elevation, whereas 1 unit TI produces a 0.2804 FS change). In contrast, AR diminishes its effect on the calculated FS as BL thickness changes, while TI shows an exponential influence as elevation increases.

In essence, the research question of how stratigraphic unevenness affects the relationship between TCFs and basic geometrical parameters with stability indicators is addressed by demonstrating that stratigraphic unevenness not only exerts a direct destabilizing influence but also modulates the sensitivity of other geometrical factors, redefining how tapering geometry translates into slope instability across different elevation settings.

Integrating both the original and subset-based analyses reveals a consistent pattern: slope instability is primarily driven by the geometric complexity of the weak interlayer, specifically its inclination, thickness variation, and stratigraphic position. While traditional geometrical parameters such as dip and thickness remain valid predictors, their significance is dynamically modified by tapering configuration and stratigraphic unevenness. The subset analysis confirms that elevation-dependent geometric controls refine and, in some cases, amplify the correlations observed in the global dataset, emphasizing the multi-scale nature of slope stability in stratified and tapered rock masses.

5. Conclusions

This research systematically establishes a geometric correlation framework to understand how tapering configurations in weak middle layers (WMLs) influence slope stability in layered rock masses. Through a combination of overall and subset correlation analyses, several key conclusions can be drawn:

1. Primary Geometrical Controls

   Among all tapering configuration factors, Tilting Intensity and Thickness Gradient consistently exhibited the strongest negative correlation with Critical Strength Reduction Factors (CSRF) and Slip Surface Radius, confirming that taper steepness and vertical irregularity are the dominant geometrical destabilizers in non-uniform weak layers.

2. Conditional Stabilizing Role of Aspect Ratio

   The Aspect Ratio exerts a stabilizing effect only within moderate WML-elevated heights, where lateral continuity and thickness balance limit shear localization. Beyond this range, the stabilizing influence weakens, suggesting the existence of an optimal geometric proportion for maximum slope resilience.

3. Dynamic Behavior of Classical Parameters

   Basic geometrical attributes such as average dip and exposed thickness remain valid indicators of instability; however, their correlation strengths are amplified or dampened by tapering and stratigraphic unevenness, highlighting the nonlinearity of slope response under variable layering conditions.

4. Stratigraphic Unevenness as a Governing Modifier

   Variations in bottom layer thickness profoundly alter both the magnitude and direction of geometric correlations, serving as a mechanical amplifier that intensifies the destabilizing effect of tapering irregularities.

5. Multi-Scale and Interactive Control on Stability

   Overall, the study demonstrates that slope stability in layered rock masses is controlled not by single geometric parameters, but by their interactive and elevation-dependent configuration. This understanding provides a foundation for more realistic geomechanical modeling and for field recognition of critical geometric patterns that predispose slopes to failure.

In summary, this research provides a quantitative, configuration-based interpretation of slope instability mechanisms in tapered and uneven stratigraphic settings, extending classical geometrical models to account for the three-dimensional non-uniformity commonly observed in skarn-hosted and volcanic-interbedded slopes.

6. Implications and Future Work

The findings of this study carry several practical and scientific implications for slope design, geomechanical modeling, and geological interpretation in complex stratified rock masses, as the following.

1. Improved Predictive Criteria for Slope Stability

   By identifying Tilting Intensity and Thickness Gradient as primary geometric destabilizers, this research provides quantifiable indicators that can be integrated into both field reconnaissance and RS2 modeling workflows. These parameters can serve as diagnostic geometry-based stability indices, particularly valuable when full mechanical characterization of the weak layer is limited.

2. Enhanced Model Calibration in RS2 and FEM Analyses

   The recognition that Aspect Ratio exhibits a conditional stabilizing effect under moderate stratigraphic elevation provides a benchmark for calibrating mesh discretization and taper geometry in numerical models. Future RS2 simulations can employ these thresholds to reproduce realistic slope behavior, minimizing artificial confinement effects or unrealistic shear band formation.

3. Guidance for Excavation and Reinforcement Strategies

   The results imply that field engineers should prioritize reinforcement or dewatering along slopes exhibiting high tilting intensity and steep thickness gradients, rather than relying solely on traditional parameters like dip angle. Similarly, bench designs can be adjusted to reduce effective taper inclination in exposed weak zones, thereby improving safety margins.

4. Contribution to Geological Understanding of Skarn Slopes

   From a geological perspective, the correlation between stratigraphic unevenness and failure geometry enhances our understanding of how tectonic deformation, magmatic intrusion, and metamorphic overprinting influence present-day slope instability in iron skarn and volcanic-sedimentary environments.

Ultimately, this study bridges the conceptual gap between geometrical representation and mechanical behaviour in slope stability research. By establishing a structured, correlation-based understanding of tapering configuration effects, it sets the groundwork for a new generation of geometry-aware stability assessments, particularly applicable to tropical island arc mining settings where stratigraphic unevenness and lithologic tapering are the rule rather than the exception.

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