DOI: https://doi.org/10.68732/fa87cde67b765c80

ISBN: 978-9989-2053-7-8

Friction-Angle Sensitivity of Open-Pit Slope Stability and Field Performance

C. O. Aksoy*
Dokuz Eylul University, Mining Engineering Department, Izmir
okay.aksoy@deu.edu.tr
0000-0002-4328-4862

G. G. U. Aksoy & O. Savaş
Hacettepe University, Mining Engineering Department, Ankara

B. Gürel, B. Akyuz, Y. Aydemir & A. B. Aktaş
GOA Mining Company, Ankara
TÜMAD Mine Company

Abstract

This study investigates the sensitivity of slope stability to internal friction angle (φ) in open-pit mining by integrating limit equilibrium analysis with field observations. Two large-scale slopes were analyzed using friction-angle scenarios derived from geotechnical data. For Site 1, φ values of 24°, 28°, and 35° yielded a maximum factor of safety (FoS) of 1.324, while Site 2 with φ values of 25°, 26°, and 33° produced FoS up to 1.421. A normalized sensitivity framework was applied to evaluate the variation of FoS with respect to φ. Results confirm that FoS increases nonlinearly with φ; however, field evidence indicates that analytical stability may not represent actual slope behavior due to geological heterogeneity, structural discontinuities, and weathering effects. The study highlights that φ should not be treated as a fixed parameter but as an uncertainty-driven field-controlled variable. The proposed framework links analytical outputs with real slope performance, improving reliability in slope design.

Keywords

Internal friction angle, Slope stability, Factor of safety, Limit equilibrium method, Open-pit mining, Slope failure.

1 Introduction

Slope stability is a central issue in open-pit mining because slope failure can endanger personnel, interrupt production, damage equipment, and reduce the economic viability of an operation. Modern open-pit mines are commonly designed with steep and high slopes to reduce waste stripping; however, this economic benefit increases the need for reliable geotechnical characterization and stability assessment (Hoek & Bray, 1981; Read & Stacey, 2009). Typical large-scale open-pit slope geometries and failure examples are shown in Fig. 1.

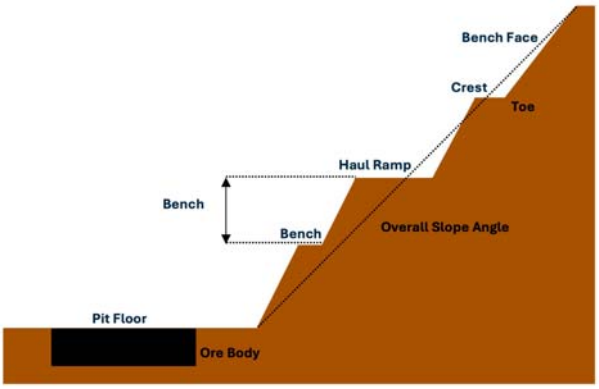


Fig. 1 Typical open-pit slope geometries.

Among the parameters used in slope stability analysis, the internal friction angle (φ) is one of the most influential because it governs the frictional component of shear resistance. According to the Mohr-Coulomb failure criterion, shear strength increases with φ, making it a critical parameter in defining slope stability. In rock slopes and highly weathered rock masses, the mobilized friction angle may be affected by discontinuity roughness, infilling, alteration, weathering, groundwater conditions, blasting-induced damage, and scale effects (Hoek et al., 2002; Barton & Bandis, 1990). Therefore, the friction angle used in design may differ substantially from the friction angle inferred from laboratory or empirical correlations.

Limit equilibrium methods remain widely used in engineering practice because they are transparent, computationally efficient, and compatible with standard geotechnical design workflows. Classical approaches such as the Bishop simplified method (1955) and Spencer method (1967) evaluate global equilibrium along a potential failure surface and express stability through the factor of safety (FoS). Despite their practical value, these methods are strongly dependent on shear-strength inputs and do not explicitly reproduce deformation, progressive failure, or structural control unless these mechanisms are incorporated through the model geometry and strength assumptions (Duncan & Wright, 2005; Griffiths & Lane, 1999).

The relationship between internal friction angle and factor of safety is well established: increasing φ leads to an increase in FoS. However, this relationship is purely analytical and does not necessarily reflect actual slope performance in the field. In many documented cases, slopes with FoS values greater than 1.2–1.5 have still experienced instability or failure due to geological discontinuities, pore pressure effects, or progressive damage mechanisms (Read & Stacey, 2009; Stead & Wolter, 2015). The sensitivity of FoS to φ for the studied cases is presented in Fig. 2. As shown in Fig. 3, the factor of safety increases with increasing internal friction angle for both sites. However, the difference between Site 1 and Site 2 demonstrates that slope stability is not controlled solely by φ, but also by site-specific geological conditions, structural features, and potential scale effects.

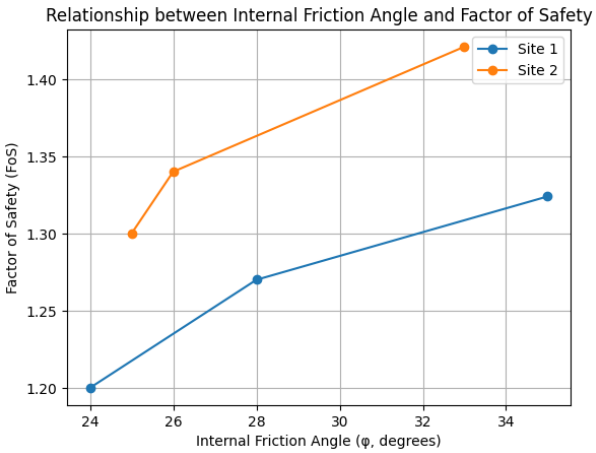


Fig. 2 Relationship between internal friction angle (φ) and factor of safety (FoS) for Site 1 and Site 2.

The problem addressed in this paper is therefore not whether increasing the internal friction angle increases the factor of safety; this is expected from the Mohr-Coulomb strength relationship. The

central engineering question is whether the friction angle values obtained from geotechnical studies and empirical procedures represent the real field condition sufficiently well to support slope design.

Field observations frequently indicate discrepancies between analytically predicted stability and actual slope performance. These discrepancies arise due to: structural control (joints, faults, bedding planes); groundwater pressure variations; time-dependent deformation (creep); and blasting-induced damage and stress redistribution.

Such factors are difficult to incorporate fully into limit equilibrium models and may lead to overestimation of stability when φ is assumed to be high. This study investigates that question by comparing friction-angle scenarios from two open-pit sites with limit-equilibrium safety factors and field observations. The objective is to evaluate whether analytically derived safety factors based on selected φ values are consistent with real slope behavior and to assess the reliability of friction angle estimation in practical slope design. In practical applications, FoS is calculated using slice-based equilibrium methods such as those proposed by Bishop (1955) and Spencer (1967). These methods rely heavily on shear strength parameters and are therefore highly sensitive to variations in φ (Griffiths & Lane, 1999). In the present study, all friction-angle scenarios were evaluated using identical slope geometries, groundwater assumptions, and boundary conditions within each site. Therefore, the observed changes in FoS are solely attributable to variations in shear-strength parameters and not to geometric effects.

2 Materials and methods

2.1 Study sites and input data

Two open-pit mine slopes were selected to investigate the influence of internal friction angle (φ) on slope stability. The selected sites represent large-scale bench configurations with visible geological variability and exposed rock mass conditions.

For Site 1, slope stability was evaluated using internal friction angle scenarios of 24°, 28°, and 35°, with a reported factor of safety of FoS = 1.324 corresponding to the highest friction angle condition. For Site 2, analyses were performed for friction angle values of 25°, 26°, and 33°, with a reported factor of safety of FoS = 1.421 at the highest friction angle.

Field photographs were used as direct visual evidence to support the engineering interpretation of slope conditions, including: bench continuity and geometry; lithological variability and weathering contrasts; rock mass heterogeneity; and potential local instability indicators.

To isolate the influence of internal friction angle on stability response, identical slope geometries, bench configurations, groundwater assumptions, and boundary conditions were maintained within each site during all friction-angle scenarios. Therefore, the observed FoS variations are attributed primarily to changes in shear-strength parameters rather than geometric effects.

Table 1. Summary of analyzed sites and input parameters.

Site	Friction-angle scenarios (°)	Reference FoS	Field evidence
Site 1	24, 28, 35	1.324	Open-pit slope photograph
Site 2	25, 26, 33	1.421	Open-pit slope photograph

3 Field observations

Site 1 exhibits a large-scale open-pit geometry characterized by multiple benches and significant lateral variation in rock color and texture. These variations suggest changes in lithology, alteration, or weathering intensity across the slope.

The observed heterogeneity indicates that: a single friction-angle value may not adequately represent the entire slope; local variations in material strength are likely present; and different slope sectors may behave independently under stress.

These observations highlight the limitations of uniform parameter assignment in limit equilibrium analysis. In Site 1, weathering intensity appears spatially variable, particularly along schistosity-

controlled zones. These weathered sectors likely experience reductions in effective friction angle and localized degradation of shear strength, increasing susceptibility to bench-scale instability despite acceptable global FoS values.

Site 2 presents a deeper open-pit configuration with relatively continuous bench geometry but pronounced lateral variation in rock color and apparent weathering.

These characteristics suggest: the presence of variable strength zones within the slope; possible localized weakening due to weathering or alteration; and potential mismatch between global FoS and local stability conditions.

Even with a relatively higher reported FoS value (1.421), such variability may result in localized instability zones, which are not captured by global limit equilibrium calculations. At Site 2, localized alteration and weathering along structural discontinuities may contribute to strength reduction and differential deformation behavior. Such effects are difficult to capture using deterministic limit-equilibrium approaches.

4 Engineering evaluation

4.1 Factor of safety sensitivity

Normalized FoS values were calculated by scaling each factor-of-safety value relative to the maximum reported FoS for the corresponding site. In this study, the term "normalized FoS" refers to factor-of-safety values scaled relative to the highest reported FoS obtained for each site under the maximum friction-angle scenario. For Site 1, the anchor FoS value was 1.324 at $\varphi = 35°$, while for Site 2 the anchor FoS value was 1.421 at $\varphi = 33°$. Intermediate FoS values were normalized relative to these reference conditions to allow comparative sensitivity interpretation independent of absolute slope scale.

The normalized results demonstrate a systematic increase in the calculated factor of safety (FoS) with increasing internal friction angle (φ). However, the sensitivity analysis reveals that the implications of this increase are not merely numerical but directly influence engineering interpretation. At lower friction angles, the calculated FoS values approach or fall below unity, indicating unstable or marginally stable conditions. In contrast, higher friction-angle scenarios yield FoS values that satisfy conventional stability criteria, despite identical slope geometries and boundary conditions.

The normalized sensitivity results are summarized in Table 2, while the corresponding trends are illustrated in Fig. 3 and Fig. 4.

Table 2. Normalized friction-angle sensitivity results anchored to the reported FoS values.

Site	φ (°)	Normalized FoS	Relative change (%)	Engineering interpretation
Site 1	24	0.842	0.0	Unstable / marginal
Site 1	28	1.005	19.4	Marginal
Site 1	35	1.324	57.2	Acceptable (global FoS)
Site 2	25	1.020	0.0	Marginal
Site 2	26	1.067	4.6	Marginal to acceptable
Site 2	33	1.421	39.3	Acceptable (global FoS)

The results demonstrate that the FoS–φ relationship is inherently deterministic when expressed through the Mohr–Coulomb framework. However, introducing realistic uncertainty in the internal friction angle results in a significant spread of FoS values. This indicates that the primary source of design uncertainty is not the analytical model itself, but the variability and estimation of φ. Even small deviations in φ (±2°) may shift the stability classification from unstable to acceptable conditions, highlighting the critical role of parameter uncertainty in slope design.

The risk-based sensitivity zones were defined qualitatively to provide an engineering interpretation framework for the relative increase in FoS. Low sensitivity corresponds to FoS increases below 10%, moderate sensitivity to 10–30%, and high sensitivity to increases exceeding 30%. The green, yellow, and red bands represent low (0–10%), moderate (10–30%), and high (>30%) sensitivity levels, respectively.

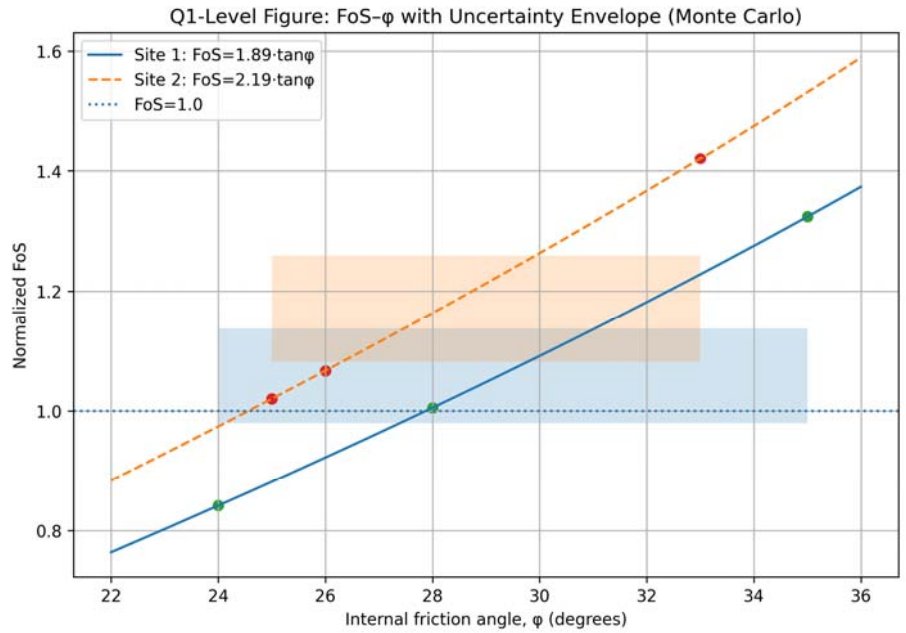


Fig. 3 Sensitivity of factor of safety (FoS) to internal friction angle (φ) for Site 1 and Site 2. Curves are normalized to the reported FoS anchor values.

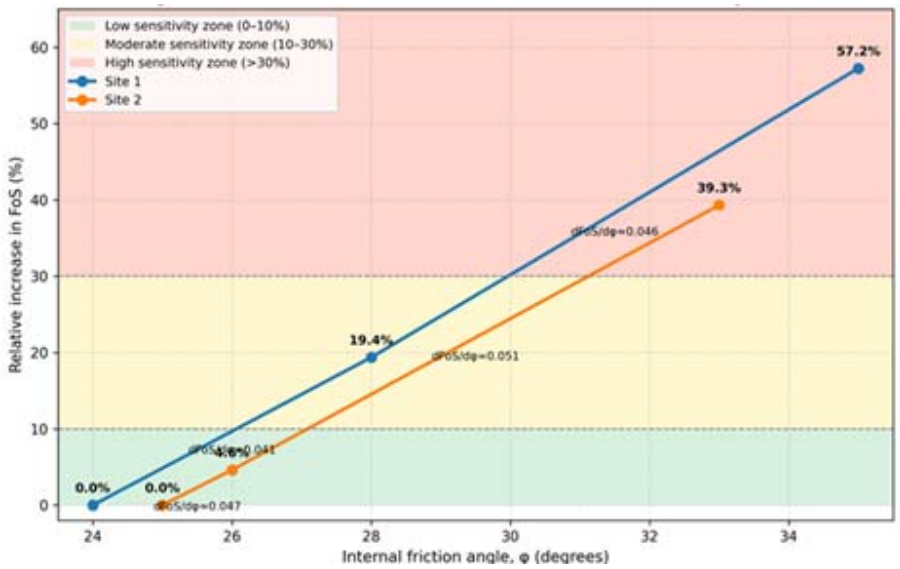


Fig. 4 Relative increase in factor of safety (FoS) compared with the lowest internal friction angle (φ) scenario for each site, presented with distinct risk-based sensitivity zones.

The results clearly demonstrate that the influence of φ on FoS is nonlinear, with increasing sensitivity at higher friction angles. Site 1 exhibits a stronger response, reaching up to 57.2% increase, whereas Site 2 shows a comparatively lower but still significant increase of 39.3%. The annotated gradients (dFoS/dφ) indicate that the rate of change in stability increases with φ, highlighting the risk of overestimating slope stability when higher friction angles are assumed. This figure provides a practical design interpretation framework by linking parameter sensitivity directly to engineering risk levels.

5 Discussion

The results obtained in this study confirm the expected analytical relationship between internal friction angle (φ) and factor of safety (FoS), as defined by the Mohr-Coulomb failure criterion. The normalized sensitivity curves show that FoS increases with increasing φ for both Site 1 and Site 2. This behavior is directly related to the nonlinear dependence of shear strength on the term tan(φ), which governs the frictional component of resistance. However, while this relationship is mathematically consistent, its engineering interpretation requires careful consideration. The field observations from both sites demonstrate that slope stability cannot be reliably assessed using φ as a single governing parameter. The incorporation of uncertainty into the FoS–φ relationship reveals a critical limitation of deterministic slope stability analysis. While classical limit equilibrium methods

produce a single FoS value for a given φ, this study demonstrates that FoS should be interpreted as a probabilistic range rather than a deterministic value. The results indicate that:

– The analytical model itself is not the primary source of uncertainty.

– The dominant uncertainty arises from friction angle estimation.

– Small deviations in φ (±2°) can shift the slope condition from unstable to marginal, or from marginal to acceptable.

This finding has direct implications for engineering design, as it challenges the reliability of single-value FoS criteria commonly used in practice.

6 Conclusions

This study has several limitations that should be considered when interpreting the results. Radar displacement data were not available for quantitative validation, and the FoS values were limited to reported anchor points rather than full numerical datasets. In addition, the normalization approach does not explicitly account for variations in slope geometry or pore pressure conditions, and structural controls were evaluated qualitatively rather than being explicitly modeled. Despite these limitations, the study provides valuable insights into the sensitivity of slope stability to the internal friction angle (φ) and highlights the risks of relying solely on analytical parameters.

References

Barton N, Bandis S (1990) Review of predictive capabilities of JRC-JCS model. Rock Mech Rock Eng.

Bishop AW (1955) The use of the slip circle in the stability analysis of slopes. Geotechnique 5(1):7-17. https://doi.org/10.1680/geot.1955.5.1.7

Duncan JM, Wright SG (2005) Soil strength and slope stability. Wiley.

Griffiths DV, Lane PA (1999) Slope stability analysis by finite elements. Geotechnique 49(3):387-403. https://doi.org/10.1680/geot.1999.49.3.387

Hoek E, Bray JW (1981) Rock slope engineering, 3rd edn. Institution of Mining and Metallurgy, London.

Hoek E, Carranza-Torres C, Corkum B (2002) Hoek-Brown failure criterion – 2002 edition. Proceedings of NARMS-TAC Conference, Toronto, 267-273.

Read J, Stacey P (2009) Guidelines for open pit slope design. CSIRO Publishing.

Spencer E (1967) A method of analysis of the stability of embankments assuming parallel inter-slice forces. Geotechnique 17(1):11-26. https://doi.org/10.1680/geot.1967.17.1.11

Stead D, Wolter A (2015) A critical review of rock slope failure mechanisms. Engineering Geology.