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# Enhanced Rock Slope Stability Analysis: Integrating the Partial Factor Method into the Limit Equilibrium Method

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## Abstract

Rock slope stability is crucial for sustainable design. Especially concerning natural or artificial rock-cut slopes. The stability of these slopes depends largely on features of rock mass, particularly discontinuities. Failure modes are determined by these features and are evaluated using kinematics analysis with stereographic projections. Various methods exist for analyzing rock slopes, including the limit equilibrium method (LEM), which assesses stability based on a factor of safety (FS). Conversely, the partial factor method (PFM), predominantly used in Europe, offers a more reliable and probabilistic approach, incorporating uncertainty factors. Although Eurocode, which employs the PFM, is widely utilized, it faces disputes and undergoes updates based on ISRM recommendations. The partial factor method is considered more conservative than the limit equilibrium method due to its comprehensive probabilistic approach. The choice between methods depends on project requirements, data availability, and expertise. This study compares the limit equilibrium and partial factor methods for rock slope analysis, concluding that the partial factor method is more conservative and sustainable for long-term stability assessment. Whereas, the traditional method is often used for short-term assessments.

*Keywords*: Eurocode; Limit equilibrium; Partial factor method; Rock slope stability

## 1. Introduction

Rock slope stability analysis is vital for calculating the factor of safety (FS), a universally recognized numerical measure. FS is influenced by shear strength and groundwater conditions, indicating the margin of safety against slope failure. Rock mass complexity introduces uncertainty, increasing the risk of failure. The traditional method for slope analysis is the limit equilibrium method [1]. Eurocode recently introduced a reliability-based design approach through Eurocode 7, regularly updated based on research and field experience. This semi-probability method addresses uncertainty in the rock slope analysis, applicable to both soil and rock slopes [2]. This recently introduced Eurocode can address uncertainties in the rock mass. A factor is used which was suggested by Eurocode 7 and was revised in 2021 [3]. In reliability-based design (RBD), the value of the partial factor depends on the number and degree of accuracy during the data collection after investigations. RBD is an important methodology in engineering that focuses on ensuring a specific level of safety and performance by explicitly considering uncertainties in the analysis and design process. It uses probabilistic methods to quantify and manage the risks, providing a more flexible and realistic assessment of any structural performance [4]. The uncertainty in slope stability analysis arises from various factors, including but not limited to the absence of representative data, variations in environmental conditions, and potential human errors in the design and construction process. All these elements collectively contribute to the inherent unpredictability in the stability of structures [5]. In the case of mine development, the acceptance criteria for standard value to qualify the performance of open cut-slope. The performance of slope as the FS or probability of failure (PF) will be as Table 1 [6]. Where RC is the reliability classes for different periods. The partial factors for rock mass strength can be taken using Figure 1 and it is the function of the coefficient of variation (COV), reliability class, and the target reliability index (RI). It has the advantage of replicating the uncertainties in initial input parameters in the target reliability level.

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**Table 1.** Typical FS and PF for acceptance criteria values [6].

| Slope Scale | Consequence of Failure | FS (Min) | PF (%) |
|---|---|---|---|
| Bench | Low-High | 1.1 | 25-50 |
| Inter-ramp | Low | 1.15-1.2 | 25 |
| | Moderate | 1.2 | 20 |
| | High | 1.2-1.3 | 10-20 |
| Overall | Low | 1.2-1.3 | 10-20 |
| | Moderate | 1.3 | 10 |
| | High | 1.3-1.5 | 5 |

## 2. Methods of rock slope analysis

Rock slope analysis examines stability and failure risk in natural or rock-cut slopes. This study comprises the limit equilibrium method and partial factor method for analysis.

### *2.1 Limit Equilibrium Method*

The limit equilibrium method, a traditional approach, assesses slope stability using the Mohr-Coulomb failure criterion. It comprises shear strength to sliding force along the failure plane to determine slope stability. For circular failure, various methods like Bishop and Janbu are employed. These methods provide a realistic and accurate factor of safety calculations, making them widely used worldwide [7, 8].

### *2.2 Partial Factor Method*

The partial factor method employs a probability approach, considering uncertainties in rock mass parameters for slope analysis and determining the FS. Eurocode 7, widely followed in Europe, adopts this method for reliability-based rock slope design. The partial factors reflect the safety, serviceability, and durability of the slope structure, influencing uncertainty and safety levels in both the short and long-terms [9]. Guidelines for assigning partial factors based on parameter uncertainty are outlined. The Norwegian National Group of ISRM recommends specific partial factor values for rock slope design and planning. Generally, cohesion and internal frictional angle are suggested as 1.25, while water and rock mass unit weight are set as one (Figure 1).

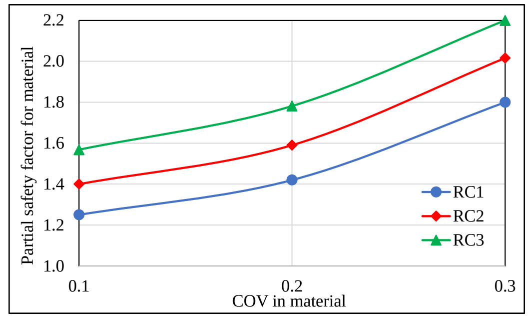


**Figure 1.** The new partial factor for soil strength for different reliability classes and coefficient of variations (COV). For all load factors are equal to 1.0 and the modified chart of [10].

## 3. Case study

One case study was taken and conducted; the geometry of slope height is 35 meters with a face slope angle of $80^0$. The inclination of the potential sliding plane is $40^0$. Given value of specific gravity for rock mass and water are 26 $KN/m^3$ and 10 $KN/m^3$ respectively refer Figure 2.

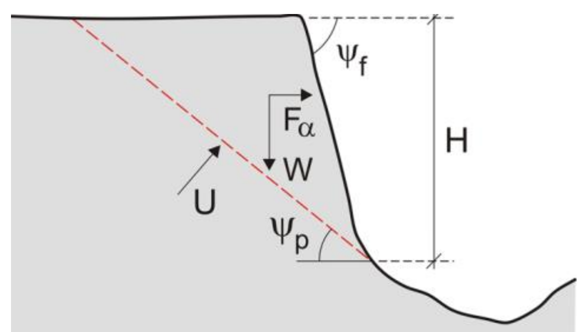


Figure 2. Geometry of slope for case study[11].

$$W = 0.5 * \gamma_r * H^2\left(1/tan\Psi_p - 1/tan\Psi_f\right) \quad (1)$$

$$Fr = \left(W\ cos\Psi_p - U - F_\alpha sin\Psi_p\right)tan\phi_a \quad (2)$$

$$Fs = W\ sin\Psi_p + F_\alpha cos\Psi_p \quad (3)$$

$$F\ S = Fr/Fs \quad (4)$$

$$\sigma_n = \left(W\ cos\Psi_p - U - F_\alpha sin\Psi_p\right)/(H/sin\Psi_p) \quad (5)$$

Where, $\Psi_p$ is the angle of the sliding plane, $\Psi_f$ is the slope, $F_\alpha$ is tectonic force, W is the weight of the sliding block, Fr is resisting force, Fs is sliding force, U is water pressure, and $\phi_a$ is the active frictional angle. The active frictional angle can be calculated based on normal stress ($\sigma_n$) using [12]. For the worst-case scenario value of seismic coefficient $\alpha$ = 0.25 g, which is given by Eurocode as NA (National

Annex). The safety factor can be calculated using the above equations and the final results in tabular form in Table 2. Where α is the seismic coefficient in ground acceleration, Fα is tectonic force. The Value of partial factor is taken as ultimate limit states according to Eurocode 7 (SN/CEN 2008a). The partial factor for weight and water: $\gamma_f$ is 1.0, for Fα: $\gamma_f = 1.3$; and $\gamma_m = 1.25$

$$Rd = \left(W * \gamma_f \cos\Psi_p - U * \gamma_f - F_\alpha * \gamma_f \sin\Psi_p\right) * (\tan\phi_a / \gamma_m) \quad (6)$$

$$Fd = W * \gamma_f \sin\Psi_p + F_\alpha * \gamma_f \cos\Psi_p \quad (7)$$

Where Rd and Fd are resisting and sliding forces in the partial factor approach and further calculations shown in Table 3.

As per Figure **3**, the relative differences in the factor of safety from the traditional method and partial factor method are minor. Initially, a certain factor is already used for the safety approach in the partial factor method. In this way, the partial factor method is more conservative than the traditional method for rock slope analysis.

**Table 2.** The factor of safety (FS) for different scenarios according to the traditional method [11].

| Situation | Worst case | Best Case | Earthquake/no water | Water/no earthquake |
|---|---|---|---|---|
| U (KN/m) | 4766 | 0 | 0 | 4766 |
| α (in g) | 0.25 | 0 | 0.25 | 0 |
| Fα (KN/m) | 4043 | 0 | 4043 | 0 |
| $\sigma_n$ (KN/m$^2$) | 92 | 228 | 180 | 140 |
| $\varphi_a$ ($^0$) | 71 | 56 | 58 | 64 |
| FS | 1.08 | 1.77 | 1.16 | 1.50 |

**Table 3.** The factor of safety (FS) for different scenarios according to the partial factor method [11].

| Situation | Worst case | Best Case | Earthquake/no water | Water/no earthquake |
|---|---|---|---|---|
| U (KN/m) | 4766 | 0 | 0 | 4766 |
| α (in g) | 0.25 | 0 | 0.25 | 0 |
| Fα (KN/m) | 4043 | 0 | 4043 | 0 |
| $\sigma_n$ (KN/m$^2$) | 92 | 228 | 180 | 140 |
| $\varphi_a$ ($^0$) | 71 | 56 | 58 | 64 |
| Rd | 11825 | 14682 | 12995 | 12490 |
| Fd | 14419 | 10392 | 14419 | 10391 |
| FS = Rd/Fd | 0.82 | 1.41 | 0.90 | 1.20 |

*Where, Rd and Fd are in KN/m.*

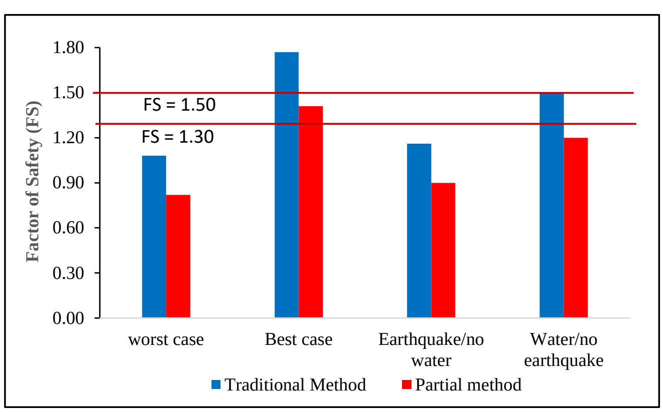


Figure 3. Variation in factor of safety between LEM to PFM [11].

## 4. Results comparison among the approaches

The FS results from both LEM and PFM show a minor difference that is verified by the above case study. The partial factor method employs a probability approach, considering uncertainty in rock mass and loading parameters to provide a relative safety value for specific slopes. Eurocode guidelines the application of factors to address uncertainty, enhancing the realism of slope stability assessments. Detailed sensitivity analysis of input parameters ensures a thorough assessment. Eurocode 7 is widely applied despite some controversies, with updates from the Norwegian National Group of ISRM and further recommended from conferences, with the latest version in 2011.

## 5. Challenges

In the partial factor method, the analysis relies on Eurocode 7, rooted in probability. The subjective nature of assigned factor values can vary among designers, impacting analysis outcomes and interpretations. Originally devised for soil, adopting it to rock slope engineering presents additional challenges, requiring extensive data analysis and potentially inflating project costs. Misinterpretations of partial factors may occur due to practitioners' and engineers' unfamiliarity with Eurocode [5].

Whereas, the traditional method merely identifies slope failure without factoring in uncertainties within the rock mass, making it an inaccurate representation of the slope's specific nature. Assumed failure surfaces may not hold due to the intricate rock mass characteristics. Even slight alternation in input parameters can substantially affect the FS outcome.

## 6. Conclusion

The nature and importance of the project will heavily influence the methods chosen for rock slope analysis. Although the partial factor method is more conservative than the LEM, it factors in the uncertainty within the rock mass. This method relies on reliable analysis for rock slope stability, providing a more realistic FS that accurately reflects the condition of the slope. Given the inherent uncertainty in the rock masses, the partial factor method is a better choice for slope analysis, despite international disputes. Caution is warranted when employing this approach, as it is governed by Eurocode and may be influenced by local regulations during implementation. Method selection is contingent upon the availability of technical resources, project budget constraints, and risk-bearing capacities.

## References

[1] Pereira, R,, Lamas, L., and Muralha, J. and editors. Sliding stability analyses of a rock slope using deterministic, semi-probabilistic, and probabilistic methods. IOP Conference Series: *Earth and Environmental Science*, 2021: IOP Publishing.

[2] Franzén, G., van Seters, A., Athanasopoulou, A., Bogusz, W., Grunicke, U. and Roessler, K. STANDARDISATION OF TUNNEL DESIGN IN EUROPE-APPLICABILITY OF GEOTECHNICAL EUROCODE 7 FOR DESIGN.

[3] Mathe, L., Ferentinou, M. and editors. Rock slope stability analysis adopting Eurocode 7, a limit state design approach for an open pit. IOP Conference Series: *Earth and Environmental Science*, 2021: IOP Publishing.

[4] Knuuti, M., Länsivaara, T. nad editors. Performance of Variable Partial Factor approach in a slope design. *13th International Conference on Applications of Statistics and Probability in Civil Engineering* (ICASP13), Seoul, South Korea; 2019.

[5] El-Ramly, H., Morgenstern, N. and Cruden, D. Probabilistic slope stability analysis for practice. *Canadian Geotechnical Journal,* 39(3) (2002) 665-83.

[6] Read, J. and Stacey, P. Guidelines for open pit slope design. 2009.

[7] Bishop, A.W. The use of the slip circle in the stability analysis of slopes. *Geotechnique*, 5(1) (1955) 7-17.

[8] Wyllie, D.C., Mah, C. Rock slope engineering: CRC Press; 2004.

[9] Länsivaara, T., Poutanen, T., editors. Slope stability with partial safety factor method. Proceedings of the 18th International Conference on Soil Mechanics and Geotechnical Engineering, Challenges and Innovations in Geotechnics, Paris, France; 2013.

[10] Länsivaara, T., and Poutanen. T. Safety concepts for slope stability. Landslides in Sensitive Clays: From Geosciences to Risk Management. 2014:395-407.
[11] Nilsen, B. Rock slope stability analysis according to Eurocode 7, discussion of some dilemmas with particular focus on limit equilibrium analysis. *Bulletin of Engineering Geology and the Environment,* 76 (2017) 1229-36.
[12] Grøneng, G., and Nilsen, B. Procedure for determining input parameters for Barton-Bandis joint shear strength formulation. Department of Geology and Mineral Resources Engineering. 2009.