DOI: https://doi.org/10.68732/6ca29425cf6f78af

ISBN: 978-9989-2053-7-8

Deterministic and Probabilistic Assessment of Rock Slope Stability in Dolomite Quarries in Hungary

F. F. Füzesi & Gy. Bögöly
Department of Engineering Geology and Geotechnics, Faculty of Civil Engineering,
Budapest University of Technology and Economics, Műegyetem rkp. 3., H-1111 Budapest, Hungary
ferencferdinandfuzesi@edu.bme.hu
0009-0004-5554-5021

Abstract

Rock slope stability in dolomite quarries is strongly influenced by the variability of discontinuity geometry and shear strength parameters. This study compares deterministic and probabilistic stability assessments of bench-scale quarry walls affected by discontinuity-controlled failures in four Hungarian open-pit dolomite quarries. The dataset comprises five planar-failure and two wedge-failure cases. Deterministic analyses were carried out using RocPlane and SWedge, whereas probabilistic analyses were performed using Latin Hypercube Sampling.

The results show that deterministic and probabilistic approaches do not yield directly comparable assessments of bench stability. The same deterministic design criterion (FoS = 1.35) corresponded to markedly different probability-of-failure (PoF) levels depending on failure mode, geometry, and the statistical characteristics of the input parameters. For wedge failures, the corresponding PoF values ranged from 0.30% to 14.0%, whereas for planar failures they ranged from 0% to 12.96%.

An extended probabilistic planar-failure analysis was also performed for the Csákvár–3 case by systematically varying slope angle and failure-plane angle. The resulting PoF field showed a strongly non-linear response, confirming that relatively small geometric changes may substantially affect failure probability. Overall, the results indicate that probabilistic analysis provides important complementary information to deterministic design and that FoS-, PoF-, or reliability-based acceptance criteria should be interpreted in a site-specific geological and geometrical context.

Keywords

Rock slope stability, Probabilistic analysis, Probability of Failure (PoF), Dolomite quarries.

1 Introduction

Rock slope stability in open-pit quarries is commonly assessed using deterministic limit equilibrium methods, where stability is expressed by a single factor of safety (FoS). In discontinuity-controlled rock masses, however, both discontinuity geometry and shear-strength properties show considerable natural variability, so deterministic analyses can only represent slope behaviour in a simplified way.

This uncertainty has led to the increasing use of probabilistic approaches, in which the stochastic nature of the governing input parameters is explicitly considered. At the same time, deterministic FoS-

based and probabilistic PoF-based results are not directly equivalent, and previously proposed acceptance criteria are usually site- and condition-specific rather than universally transferable.

This study compares deterministic and probabilistic stability assessments for discontinuity-controlled failures in Hungarian dolomite quarries. The analysed dataset includes five planar-failure and two wedge-failure cases from four open-pit quarries in the Transdanubian Range, together with an extended parametric probabilistic analysis for one planar-failure case. The aim is to show that the same deterministic design criterion may correspond to markedly different PoF levels depending on failure mode, geometry, and the statistical characteristics of the input parameters.

2 Geological Settings and Quarry Context

The study covers four open-pit dolomite quarries in the Transdanubian Range of Hungary: Csákvár, Szentgál, Etyek, and Mány. The analysed quarry walls at Csákvár are developed predominantly in the Sédvölgyi Dolomite (Upper Triassic, Carnian to early Norian), those at Mány and Etyek in the Budaörsi Dolomite (Middle Triassic, Ladinian), and those at Szentgál in the Main Dolomite (Upper Triassic, Norian to Rhaetian) (Budai et al. 2015). Quarry wall heights vary between approximately 44–70 m at Csákvár, 60–100 m at Mány, 30–40 m at Etyek, and 30–35 m at Szentgál. Although the quarry walls are developed as multi-bench excavations, the present study focuses on bench-scale wall sections with typical bench heights of 15–20 m. Despite differences in formation name and local geometry, the investigated dolomites belong to the same regional Triassic carbonate system of the Transdanubian Range and were affected by broadly similar post-depositional tectonic deformation (Haas and Budai 1999; Héja et al. 2022; Haas and Budai2014b; Márton et al.2025), which supports their joint treatment within a unified deterministic and probabilistic stability assessment framework. This common geological history is also reflected in the broadly comparable discontinuity patterns observed in the quarries, which supports their joint treatment within a unified deterministic and probabilistic stability assessment framework. The kinematically possible failure cases and the corresponding deterministic reference configurations considered in this study are described in Sections 3.1–3.3.

3 Methodology

3.1 Geometry and Kinematic Analysis

Discontinuity orientations were measured in the field using a geological compass (approximately 250 measurements) and grouped into characteristic joint sets. Joint-set identification and kinematic feasibility checks were performed in Dips 8.0 using the measured dip directions and dip angles. Only kinematically possible failure mechanisms were considered in the subsequent stability analyses. Accordingly, the analysed dataset comprises five planar-failure cases (Csákvár–3, Csákvár–5, Szentgál–3, Etyek–2, Mány–2) and two wedge-failure cases (Etyek–1, Szentgál–4), where the numeric suffix denotes the quarry wall identifier at the given site.

For the deterministic reference calculations, discontinuity orientations were screened using min–mean–max combinations, whereas in the probabilistic analyses the corresponding geometric inputs were treated as stochastic variables.

3.2 Input Parameters for Discontinuity Shear Strength

Blocks were obtained from the quarries for laboratory testing. A total of 40 uniaxial compressive strength (UCS) tests and 35 indirect tensile strength (Brazilian) tests were carried out in accordance with ISRM suggested methods (Ulusay 2015). Discontinuity shear-strength inputs were further constrained by approximately 70 roughness profiles measured with Barton combs and about 120 Schmidt hammer readings.

3.3 Deterministic Input Selection

Deterministic analyses were performed using case-specific reference input sets to provide a consistent baseline for comparison with the probabilistic results. Geometrical inputs were defined at bench scale (typically 15–20 m), and discontinuity shear-strength inputs (JRC, JCS and residual friction angle, φr) were assigned as fixed characteristic values. For planar failure cases, the failure-plane dip was screened using min–mean–max combinations, whereas for wedge failure cases dip angles were

screened in the same way and dip directions were kept fixed at the characteristic set orientations. The characteristic values used in the deterministic analyses are summarised in Table 1.

Table 1. Characteristic values of input parameters used in deterministic planar (RocPlane) and wedge (SWedge) analyses.

Parameters	Csákvár-3	Csákvár-5	Szentgál-3	Etyek-2	Mány-2	Szentgál-4	Etyek-1
Bench height [m]	15/20	15/20	15/20	15/20	15/20	15/20	15/20
Failure-plane dip [°]	48	51	60	63	60	-	-
Unit weight [kN/m^3]	27.40	27.40	27.40	27.40	27.40	27.40	27.40
Discontinuity waviness [°]	5	5	5	5	5	5	5
Upper face angle [°]	0	0	0	0	0	0	0
JRC [-]	12	12	12	12	12	12	12
JCS [MPa]	30.17	30.17	40.32	60.63	35.57	40.32	60.63
Residual friction angle [°]	22	22	23	21	24	23	21
Joint Set 1 dip/dip dir. [°]	-	-	-	-	-	73/90	63/179
Joint Set 2 dip/dip dir. [°]	-	-	-	-	-	69/13	63/209

Note: Empty cells indicate parameters not applicable to the given failure mode. For wedge cases, dip angles were varied using min–mean–max combinations, while dip directions were kept fixed at the characteristic set orientation. JRC – characteristic value of joint roughness coefficient; JCS – characteristic value of joint compressive strength

3.4 Deterministic Stability Analysis

Deterministic stability analyses were performed using the limit equilibrium method (LEM). RocPlane 4.0 was applied for planar failure analyses, whereas SWedge 7.0 was used for wedge failure analyses. Discontinuity shear behaviour was represented using the Barton–Bandis shear strength model (Barton and Choubey 1977). Stability was evaluated by the factor of safety (FoS), and cases were considered acceptable when FoS ≥ 1.35 in line with Eurocode 7-based geotechnical design practice (EN 1997-1 2004).

3.5 Probabilistic Stability Analysis

In the probabilistic analyses, the same geometric and discontinuity shear-strength input groups were used as in the deterministic calculations, but treated as stochastic variables with case-specific statistical properties. Thus, the deterministic approach yielded a single FoS value for each reference case, whereas the probabilistic approach produced a distribution of FoS values and the corresponding probability of failure (PoF).

Probabilistic simulations were performed for the same planar and wedge failure cases using RocPlane 4.0 and SWedge 7.0 with Latin Hypercube Sampling (LHS). Parameter definition was based on the available field and laboratory datasets, including approximately 250 discontinuity measurements, 40 UCS tests, 35 Brazilian tests, about 70 roughness profiles, and 120 Schmidt hammer readings. In the case of probability calculations, the parameters were considered with a normal distribution.

For planar failure, an additional parametric probabilistic study was carried out by systematically varying slope angle and failure-plane dip. This resulted in 806 geometrically distinct configurations, each evaluated using 10,000 LHS samples, yielding 8.06 million simulations in total. The outputs were post-processed in Python to derive the geometry-dependent PoF field presented in Section 4.3.

4 Deterministic and Probabilistic Stability Results

The results presented below compare the deterministic FoS values obtained for the case-specific reference configurations with the PoF values derived from the corresponding probabilistic simulations using the same input framework.

4.1 Wedge Failure Cases

Fig.1 summarises the wedge failure cases investigated in this study and shows PoF as a function of slope angle for the two wedge failure cases, evaluated for 15 m and 20 m bench heights. Vertical dashed lines indicate the slope angles corresponding to the deterministic design criterion (FoS = 1.35), and triangles mark the associated PoF values.

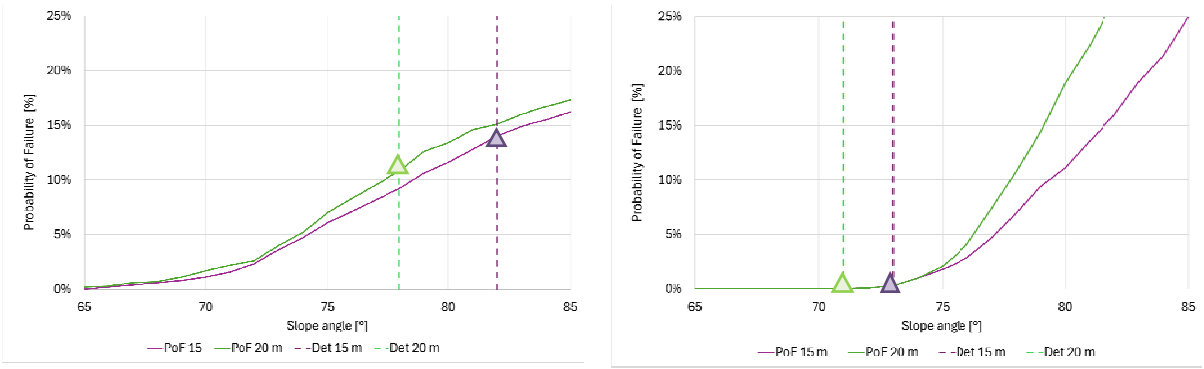


Fig. 1 Probability of failure (PoF) as a function of slope angle for the investigated wedge-failure cases: (a) Etyek–1 and (b) Szentgál–4. Results are shown for 15 m and 20 m bench heights. Vertical dashed lines indicate the slope angles corresponding to the deterministic design criterion (FoS = 1.35) for each bench height, while triangles mark the PoF values at these deterministic design angles.

For Etyek–1 (Fig. 1a), PoF rises gradually between 65° and 85°, reaching values above 10% at steeper angles. The PoF values at the deterministic design angles (marked by triangles) are 14.0% at 82° for the 15 m bench case and 10.8% at 78° for the 20 m bench case.

For Szentgál–4 (Fig. 1b), PoF remains close to zero up to approximately 73–75°, followed by a rapid increase at steeper slope angles, particularly for the 20 m bench case. The PoF values at the deterministic design angles (triangles) are 0.30% at 73° for the 15 m bench case and 0.30% at 71° for the 20 m bench case.

4.2 Planar Failure Cases

Fig.2 presents the planar failure results for the two investigated quarry wall sections at Csákvár: Csákvár–3 (Fig. 2a) and Csákvár–5 (Fig. 2b). In each panel, PoF is shown as a function of slope angle for 15 m and 20 m bench heights. Vertical dashed lines indicate the slope angles corresponding to the deterministic design criterion, and triangles mark the associated PoF values.

For Csákvár–3 (Fig. 2a), PoF increases steadily with slope angle over the analysed range, remaining below ~12% up to 70°. At the deterministic design angles, PoF is 8.71% at 67° for the 15 m bench case and 9.00% at 62° for the 20 m bench case.

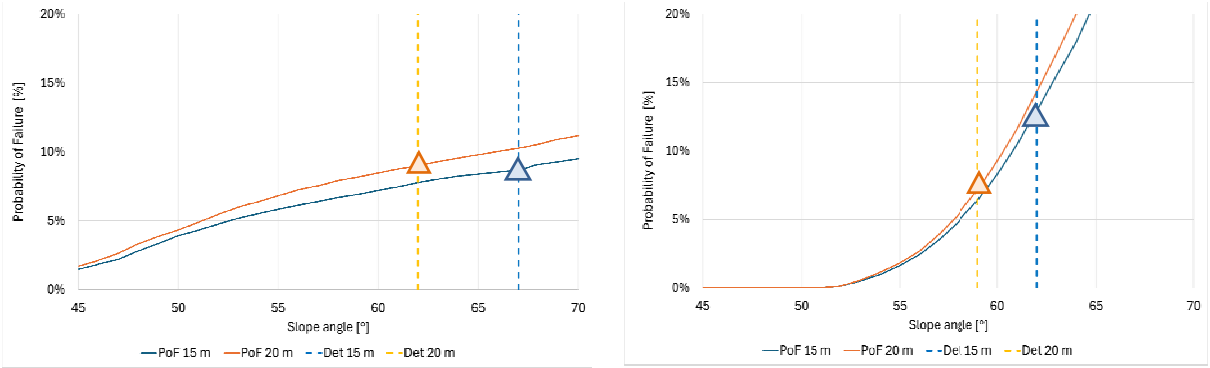


Fig. 2 Probability of failure (PoF) as a function of slope angle for the investigated planar-failure cases at Csákvár: (a) Csákvár–3 and (b) Csákvár–5. Results are shown for 15 m and 20 m bench heights. Vertical dashed lines indicate the slope angles corresponding to the deterministic design criterion (FoS = 1.35) for each bench height, while triangles mark the PoF values at these deterministic design angles.

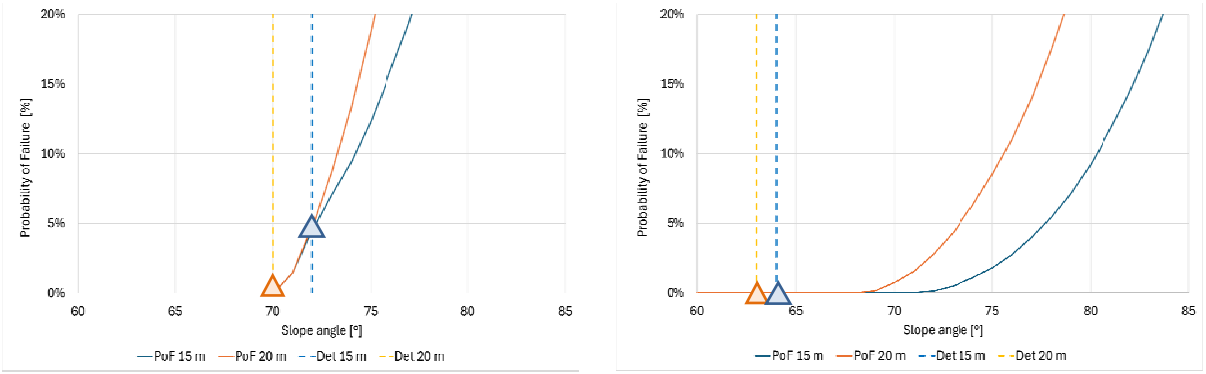


Fig. 3 Probability of failure (PoF) as a function of slope angle for the investigated planar-failure cases: (a) Etyek–2 and (b) Szentgál–3. Results are shown for 15 m and 20 m bench heights. Vertical dashed lines indicate the slope angles corresponding to the deterministic design criterion (FoS = 1.35) for each bench height, while triangles mark the PoF values at these deterministic design angles.

For Csákvár–5 (Fig. 2b), PoF remains near zero up to approximately 55° and then increases rapidly with slope angle. At the deterministic design angles, PoF is 12.96% at 62° for the 15 m bench case and 7.13% at 59° for the 20 m bench case.

For Etyek–2 (Fig. 3a), PoF remains close to zero up to approximately 70° and then increases sharply with slope angle, with the 20 m bench case rising more rapidly than the 15 m case. At the deterministic design angles, PoF is 4.51% at 72° for the 15 m bench case, while the 20 m bench case yields 0% at 70°.

For Szentgál–3 (Fig. 3b), PoF remains 0% at the deterministic design angles for both bench heights, with PoF values of 0% at 64° (15 m) and 0% at 63° (20 m).

For Mány–2, PoF increases gradually with slope angle across the analysed range, with the 20 m bench case consistently yielding higher PoF than the 15 m case. At the deterministic design angles, PoF is 2.17% at 70° for the 15 m bench case and 2.30% at 67° for the 20 m bench case.

4.3 Influence of Slope and Discontinuity Geometry on the Probability of Planar Failure

The extended probabilistic analysis of the Csákvár–3 planar case confirms that PoF is strongly controlled by the geometric relationship between slope angle and failure-plane dip. As shown in Fig. 4, PoF changes markedly across the investigated geometric domain, indicating that even relatively small geometric changes may substantially modify stability conditions.

The PoF field shows a distinctly non-linear, curved pattern. Failure probability generally increases toward steeper slope angles and higher failure-plane dips, while the lower-left part of the diagram remains in a low-PoF domain. Grey cells denote invalid or non-evaluated geometric combinations.

5 Discussion: Relationship Between Deterministic and Probabilistic Stability Results

Uncertainty is inherent to geotechnical engineering because rock-mass properties are often spatially variable and only partially constrained by field and laboratory data (Bardossy and Fodor 2004; Bedi 2013). The present results show that deterministic and probabilistic approaches do not yield directly equivalent evaluations of quarry wall stability. The relationship between FoS and PoF varies with failure mode, geometry, and the statistical characteristics of the input parameters. Accordingly, the same FoS threshold cannot be interpreted as a universal proxy for a single PoF level, although previous acceptance-criteria approaches generally do not distinguish explicitly between different failure modes.

The dominant role of geometry is further confirmed by the extended planar probabilistic analysis (Fig. 4), which shows strong PoF variation across the investigated slope angle–failure-plane angle domain. This pronounced geometry sensitivity is consistent with previous rock slope studies showing that relatively small geometric changes can significantly influence stability and risk estimates (Priest and

Brown 1983; Sjöberg 1999; Wesseloo and Read 2009). Previous studies have proposed various acceptance criteria systems based on FoS, PoF, or reliability measures for open-pit and rock slope design (Priest and Brown 1983; Kirsten 1983; Sjöberg 1999; Schellman et al. 2006; Pothitos and Li 2007; Wesseloo and Read 2009; Adams 2015), typically with PoF thresholds in the range of about 1–15%. The present results further support the view that such criteria should be calibrated on a case-by-case basis. The comparison of the Szentgál and Etyek cases (Fig. 3a–b) illustrates this clearly: the same deterministic design criterion (FoS = 1.35) corresponds to near-zero PoF in one case and clearly non-zero PoF in the other, reflecting differences in geometry and input uncertainty.

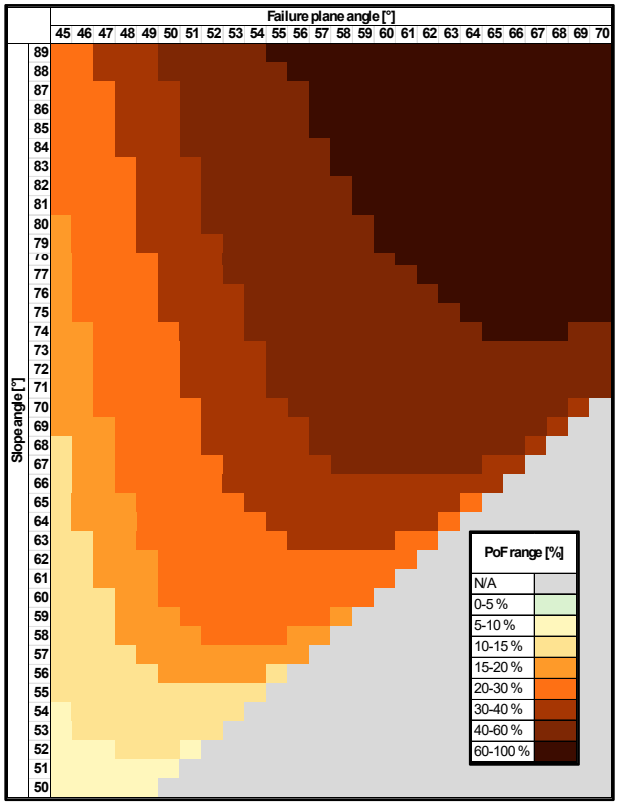


Fig. 4 Geometry-dependent probabilityoffailure (PoF) field for the Csákvár–3 planar-failure case, shown as a function of slope angle and failure-plane angle. Colors indicate PoF ranges derived from the extended probabilistic analysis, while grey cells denote invalid or non-evaluated geometric combinations. In this calculation setup, slope angle and failure-plane angle were treated as swept geometric parameters, whereas uncertainty was represented through stochastic shear-strength inputs.

6 Conclusions

This study compared deterministic and probabilistic bench stability assessments for planar and wedge failures in Hungarian dolomite quarries. The results show that the two approaches do not yield directly equivalent evaluations of quarry wall stability: the same deterministic design criterion may correspond to markedly different PoF levels depending on failure mode, geometry, and the statistical characteristics of the input parameters.

The investigated cases further indicate that the relationship between FoS and PoF may vary not only between different quarry wall sections within the same quarry, but also between planar and wedge failures. These results highlight that the acceptance criteria for PoF values should not be uniform across different failure modes. The extended planar probabilistic analysis confirmed that even small changes in slope angle and failure-plane angle can substantially modify the resulting PoF.

Overall, probabilistic analysis provides important complementary information to deterministic design. The practical application of FoS-, PoF-, or reliability-based criteria should therefore remain calibrated to the specific geological and geometrical conditions of the analysed quarry wall.

Acknowledgements

The financial support of the Hungarian–Croatian bilateral project National Research, Development and Innovation Fund, grant no. 2023-1.2.4.-TéT-2023-00044 is gratefully acknowledged.

References

Adams BM (2015) Slope stability acceptance criteria for opencast mine design. 12th Australia-New Zealand Conference on Geomechanics, Wellington, New Zealand

Bárdossy G, Fodor J (2004) Evaluation of uncertainties and risks in geology: New mathematical approaches for their handling. Springer, Berlin Heidelberg. DOI: 10.1007/978-3-662-07138-0

Barton N, Choubey V (1977) The shear strength of rock joints in theory and practice. Rock Mechanics 10: 1–54. DOI: 10.1007/BF01261801

Bedi A (2013) A proposed framework for characterising uncertainty and variability in rock mechanics and rock engineering. Dissertation at Imperial College London

Budai T, Csillag G, Kercsmár Z, Selmeczi I, Sztanó O (2015) Surface geology of Hungary. Explanatory notes to the Geological map of Hungary (1:500 000). Geological and Geophysical Institute of Hungary, Budapest

Haas J, Budai T (1999) Triassic sequence stratigraphy of the Transdanubian Range (Hungary). GeologicaCarpathica 50(6): 459–475

Haas J, Budai T (2014a) Stratigraphic and facies problems of the Upper Triassic in the Transdanubian Range: Reconsideration of old problems on the basis of new results. FöldtaniKözlöny 144(2): 125–142.

Haas J, Budai T (eds) (2014b) Geology of the pre-Cenozoic basement of Hungary. Explanatory notes for "Pre-Cenozoic geological map of Hungary" (1:500 000). Geological and Geophysical Institute of Hungary, Budapest

Héja G, Fodor L, Csillag G, Ortner H, Kövér Sz (2022) Complex deformation history of the Keszthely Hills, Transdanubian Range, Hungary. Central European Geology 65(1): 77–110. DOI: 10.1556/24.2022.00114

Kirsten HAD (1983) Significance of the probability of failure in slope engineering. The Civil Engineer in South Africa 25(1): 17–23

Márton E, Haas J, Imre G, Velki M, Fodor L (2025) New Mesozoic APWP for Adria aided by data from the Transdanubian Range Unit – Tectonic interpretation in the Europe–Africa geodynamic system. Gondwana Research 137: 274–298. DOI: 10.1016/j.gr.2024.09.006

Pothitos F, Li T (2007) Slope design criteria for large open pits - Case study. Slope Stability 2007: Proceedings of the 2007 International Symposium on Rock Slope Stability in Open Pit Mining and Civil Engineering, Perth, Australia

Priest SD, Brown ET (1983) Probabilistic stability analysis of variable rock slopes. Transactions of the Institution of Mining and Metallurgy, Section A 92: A1–A12

Schellman M, Sepulveda R, Karzulovic A (2006) Slope design for the east wall of Mantoverde Mine, Chañaral, Chile. International Symposium on Stability of Rock Slopes in Open Pit Mining and Civil Engineering, Cape Town, South Africa, pp 451–470

Sjöberg J (1999) Analysis of large scale rock slopes. Doctoral Thesis. Luleå University of Technology, Luleå, Sweden

Ulusay R (ed) (2015) The ISRM suggested methods for rock characterization, testing and monitoring: 2007–2014. Springer, Cham. DOI: 10.1007/978-3-319-07713-0

Wesseloo J, Read J (2009) Acceptance criteria. In: Read J, Stacey P (eds) Guidelines for open pit slope design, pp 221–236. CSIRO Publishing, Collingwood. DOI: 10.1071/9780643101104.ch09