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Probabilistic Stability Analysis of an Open-pit Dolomite Quarry in Hungary

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Abstract

Due to inherent geological uncertainties, slope stability is a critical factor in open-pit mining operations. These uncertainties affect stability assessments, including spatial variability, weathering, and human factors. The quarry in Vilonya, Hungary, excavates dolomite rock, characterized by fragmentation and variable joint conditions. Post-mining, stability is assessed to determine whether slopes can maintain steeper angles than the standard 45°. This study evaluates the stability of slopes in the Vilonya dolomite quarry using probabilistic methods to account for geotechnical variability and to assess the feasibility of steeper slope angles. A combination of field measurements, laboratory tests, and computational analyses were employed. Joint orientations and roughness were determined through photogrammetry and Barton comb measurements. Statistical analysis of rock parameters were done by software like Analytic Solver. Stability was analyzed using Rocscience software (Dips, RocPlane, SWedge, Slide2) for various failure mechanisms, including planar and wedge sliding, as well as global stability. Kinematic analyses identified critical joint sets that may contribute to slope failure. Probabilistic assessments showed that some joint intersections present failure probabilities as high as 67.42% for wedge failure, while planar sliding risks were negligible. Global stability analysis indicated no critical failures, with safety factors consistently above 1.35 across all slopes. Probabilistic methods reveal significant insights into slope stability that deterministic approaches may overlook. The study confirms the feasibility of maintaining steeper slope angles under controlled risk, optimizing extraction while ensuring stability. Incorporating probabilistic analysis is recommended for reliable slope design in similar geological settings.

Keywords

slope stability, open pit, quarry, probabilistic, dolomite

1 Introduction

Slope stability analysis is the area of geotechnics where the most uncertainties are present. Geological anomalies, spatial variability of soil and rock mass parameters, lack of representative data, changes in environmental conditions, unexpected failure mechanisms, simplifications and approximations used in geotechnical models, as well as human errors occurring during planning and construction, all contribute to uncertainty in the calculation [1]. The evaluation of the stability of the rock slope is mostly carried out based on kinematic, analytical, and numerical analyses. In addition, there are many rock mass classification systems, such as rock mass rating (RMR) [2], slope mass rating (SMR) [3] and the Q-slope method [4].

In the probabilistic stability analysis, instead of a factor of safety value, a percentage of probability is assigned to the studied slope to indicate the probability of failure. The application of the probabilistic approach to rock slope stability allows for the consideration of uncertainties and variations in the geotechnical properties of rock masses. Probabilistic analysis can be used for risk assessment of landslide-prone areas, Singh et al. [5], for determining the most economical slope angle to maximize the amount of extractable rock, Obregon and Mitri [6], for considering variations in soil layer thickness and strength parameters as sources of uncertainty, Chaulagai et al. [7] and Abdellah et al. [8], and for analyzing quarries with numerous structural fractures in the rock, Lindsay and Campbell [9].

Neman et al. [10] examine the slope stability occurring during the open pit mining activities of the Batu Hijau gold mine. The research focuses on geological structural factors, as dense structural conditions can contribute to slope failures.

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To analyze the stability of the slope, a kinematic analysis was performed, taking into account the probability and the type of failure. Probability was determined based on structure and mine slope orientation and friction angle using Dips 6 software. The results showed a slip probability between 0% and 2.63%, which is considered safe within a 10% safety margin.

The safety factor of the slope was also calculated manually, with values ranging from 1.04 to 1.905, indicating that the slopes in the study area are stable. Similar to the recent paper, the input parameters were determined from field measurements, investigation of geological structures and orientation of discontinuities and applied kinematic analysis based on geological structures and slope orientation and the data were analyzed with Dips 6.0 software. The distribution of slip surfaces was modeled using stereographic projections, and the probability of failure was determined as a percentage.

Obregon and Mitri [6] also examine the discontinuities of the rock mass during the bench slope design of opencast mines to see if they can cause structurally controlled collapses (e.g. along the plane, wedge, overturning). Using the example of a Peruvian mine, the study performs kinematic and kinetic analyzes using a probabilistic approach. The input parameters were determined from data collected during field measurements and laboratory tests. The dip and dip directions and the shear strength parameters (cohesion, friction angle) of geological discontinuities were modeled with probability distributions. The results were interpreted based on a combination of FoS and PoF. In all design sectors, FoS exceeded the minimum value of 1.1 and overall PoF was less than 12%. This indicates an acceptable level of stability in a mining environment.

A number of other studies examine the stability of quarry boundaries on a probabilistic basis: Kang et al. [11] presents a probabilistic stability analysis based on the Hoek–Brown criterion for an open pit mine, Abdulai and Sharifzadeh [12] provide an overview of probabilistic stability analysis, presenting different methods, Pandit et al. [13] examines the application of an advanced probabilistic method to assess the stability of an Indian gold mine, Sdvyzhkova et al. [14] discusses the probabilistic assessment of the effect of layers in deep mines, Yost [15] performs a probabilistic risk analysis during the reclamation of an abandoned mine, uses the LEM (Limit Equilibrium Method) and examines complex geological structures, Ahangari et al. [16] and Amoushahi et al. [17], Pathan et al. [18] and Du et al. [19] present a practical application.

The host rock of the area of the investigated quarry is dolomite. The rock mass condition is varied: fragmented, weathered, disintegrated in several parts of the quarry, and almost massive in other parts.

According to the rules, after the completion of the mining activity, the remaining slopes of the quarry must be abandoned with an inclination angle of 45°. In the case of the present state, it is investigated whether the planned initially 70° inclination angle would be satisfactory for the stability of the quarry or not.

2 Methodology

In order to analyse the rock slope stability, the first step is to specify the discontinuity characteristics of the rock mass. The direction and the angle of the joint, as well as its strength, spacing, orientation, roughness and weathering, i.e. its condition, are important, because these all influence the properties of the rock mass, and thus its stability as a whole. After the on-site measurements, it is advisable to decide with a stereographic projection whether the direction of the discontinuity is favourable or unfavourable in terms of stability, i.e. whether or not a block of rock can slide down along the discontinuity. It is necessary to examine how well the rock mass can be homogenized, i.e. with which model it is possible to examine the stability.

During the study of the rock material and the joint conditions in the quarry, the direction and angle of joints of hundreds of joints were measured with a geological compass and photogrammetry. Based on this, the joints can be separated into five characteristic sectional groups.

All of the on-site compass and 3D surface model measurements were examined. With 3D digital photogrammetry, similar to laser scanning, high-precision and high-resolution 3D point clouds can be created, and by analyzing these point clouds with target software the discontinuity orientations can be extracted [20].

The JRC (Joint Roughness Coefficient) is a characteristic value of the roughness of the joints. JRC was recorded on site, based on the theory of Barton and Choubey [21] and Barton and Bandis [22] using a Barton comb. The value of JRC can be determined between 0 (completely smooth) and 20 (rough surface).

The hardness of the dolomite surfaces in the quarry was also measured using an N type Schmidt hammer, in order to estimate the difference in strength between weathered and intact surfaces. It is necessary to perform 10 readings with the Schmidt hammer at one measurement location, so that the rebounds are at least 2 cm apart and the average of the 10 rebound values corresponds to one measurement result. During the calculations of the Vilonya quarry, statistical software called Analytic Solver was used for the statistical analysis of the input data.

Analytic Solver is an add-on for MS Excel that performs statistical calculations and analyses. It is a development of Frontline Systems to create and solve Monte-Carlo simulation and optimization models. It can be used on its own, but with the Data Mining add-on, it also offers forecasts and data mining. This software instantly calculates additional statistical parameters for all distributions, such as mean and standard deviation. Fig. 1. shows the workflow process.

In this case study, the relative maximum was always given by the distance between the global maximum and the average value.

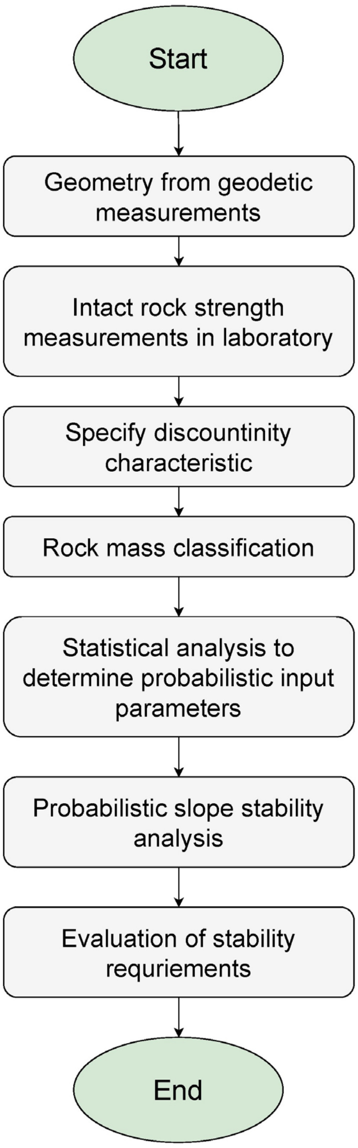

Fig. 1 Flowchart of the methodology

The input data required for the calculation come from on-site (direction of joints and their characteristics) and laboratory tests (uniaxial compressive strength, density). Based on the joint characteristics of the rock mass, the strength values of the rock mass were determined using the Geological Strength Index and the generalized Hoek-Brown failure criterion [23].

The stability analysis examined several types of failure, so the calculation was made with several types of software. All software is part of the Rocscience software pack: Dips, RocPlane, SWedge, Slide2. Dips can be used to display individual subdivision groups on the stereographic grid and to represent the frequency of strike directions on a stereographic plot. In addition, it has several calculation options, such as statistical analysis of dip directions, calculation of mean orientation and reliability, cluster variability, and kinematic analyses: wedge sliding or planar sliding can be calculated with it [24]. RocPlane can be used for a planar failure analysis. Quickly and easily define planar wedge models, visualized in 2D and 3D. A plane sliding stability analysis can be performed using the Limit Equilibrium Method [25]. SWedge is an analysis tool for evaluating the geometry and stability of surface wedges on rock slopes. The wedges are defined by two intersecting joint planes. SWedge provides an integrated graphical environment for fast, easy data entry and 3D model visualization [26]. Slide2 is a dynamic 2D Limit Equilibrium Analysis program designed to overcome your most challenging slope stability problems. It is a powerful 2D slope stability analysis program that uses the limit equilibrium method to evaluate the safety factor of circular and non-circular failure surfaces in soil or rock slopes [27]. All of them are able to run probabilistic analysis using statistical methods.

The RocPlane and the SWedge examine the local failure, while Slide2 is for global examination. The main result of the probabilistic analysis is the Probability of Failure (PoF) besides the Factor of Safety (FoS). The Probability of Failure is then simply the number of analyses which result in a safety factor less than 1, divided by the total Number of Samples. Two Sampling Methods are available – Monte Carlo or Latin Hypercube sampling. The Latin Hypercube sampling technique gives comparable results to the Monte Carlo technique, but with fewer samples. Typically, an analysis using 1000 samples obtained by the Latin Hypercube technique will produce comparable results to an analysis of 5000 samples using the Monte Carlo method.

Finally, the evaluation of the stability should be done according to the resulted probability of failure.

3 Geomorphology and geology of the investigated area

The quarry presented in the study is located in western Hungary the Northeast from the lake Balaton, at the northern part of the village of Vilonya, near the village of Berhida. This area is roughly 1.3 km^2. Based on the geomorphological data, the quarry is located at a high point of the area. From the border of the quarry, the surface level rises slightly in the northern direction, otherwise, it decreases or not changes. The height of the plot boundary varies between 188.2 and 225.0 mBf. The planned elevation of the base is 150.0 mBf. The host rock of the quarry is the Budaörs Dolomite Formation belonging to the Upper Triassic Carnian stage (see Fig. 2) [28].

Field experience has shown that the rock mass is in various conditions, fragmented in some areas of the quarry, cracked, crumbling, and larger in other areas.

Since the quarry is located on one of the highest points in the region, there is no need to count on the presence of groundwater based on previous experiences, since its presence could not be observed during the mining activity so far. The dolomite is karstified, with high infiltration. Based on several years of measurements of the karst water monitoring wells, it can be established that the measured water levels ranged between +135.46 and +143.86 mBf levels, i.e. below the base plate of the quarry.

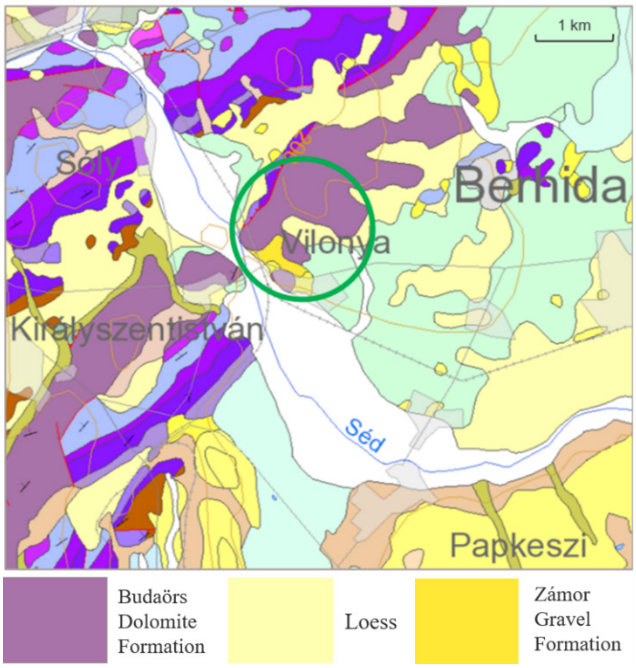

Fig. 2 Geological map of the investigated area [28]

4 Characterisation of rock masses

4.1 Joint properties

In the first step of the analysis is the joint characteristics of the rock mass had to be recorded on site. The dip direction and dip angle of the discontinuities are important, as well as their extent, openness, filling, roughness, weathering, i.e. their condition, as these all influence the properties of the rock mass. The later stereographic examination of the on-site measurements is advisable to decide whether the direction of the discontonuities is favorable or unfavorable from the point of view of stability, i.e. whether a block can slide down along the joint or not.

The measured number of JRC values was 22. An average of 12 values was determined for the JRC measured on-site. However, more Barton comb measurements were made on the Northern and Southern side, so the JRC value can be treated as a random variable on these two sides of the quarry.

The measurements on the Northern side have a normal distribution, while on the Southern side have a lognormal distribution. Table 1 presents the results.

At the site, the dip angles and dip directions characteristic of the discontinuities were determined with a geological compass and photogrammetry. In total, after several visits to the quarry, 368 discontinuities were measured.

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Fig. 3 shows the joints on a stereographic mesh.

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Table 1 Characteristic and statistical parameters of the JRC values

		Northern side	Southern side
Statistical variables	Mean	14	7.66
	Standard deviation	4.05	7
	Absolute maximum	18	16
	Relative maximum	4	8.34
	Absolute minimum	8	2
	Relative minimum	6	5.66
Distribution type	AIC/BIC	normal	exponential
	Khi-square	normal	lognormal
	Kolgomorov-Smirnov	lognormal	lognormal
	Andersen-Darling	normal	lognormal

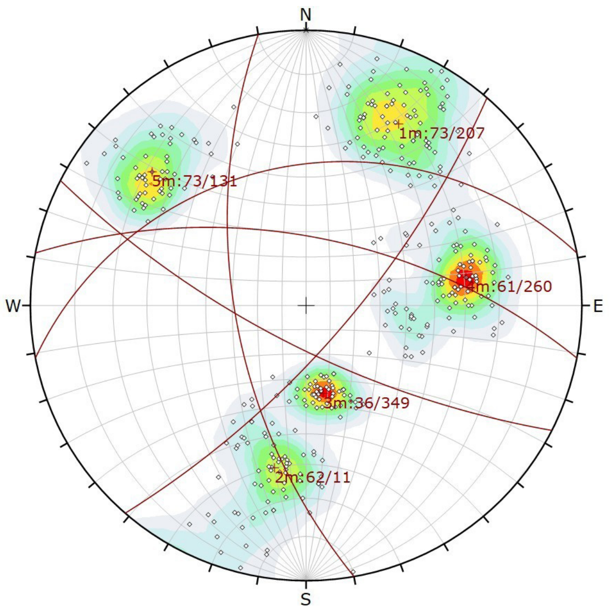

Fig. 3 Representation of joints and sets of joints on a stereographic mesh (According to the measuremets of Németh [20])

from which 5 main sets of joints can be determined. The mean set No. 1 contains 80 dips (1m 73/207), No. 2 had 59 (2m 62/11), No. 3 had 52 joints (3m 36/349), for No. 4 there are 69 joints (4m 61/260), and mean set No. 5 includes 54 joints (5m 73/131). The remaining 54 joints do not belong to any set, they are marked with gray squares scattered on the stereographic plot.

4.2 Properties of dolomite

The surface hardness of the joints, was measured with a Schmidt hammer in such a way that the difference between the strength of the surfaces of intact and weathered rock surfaces can be estimated. Fig. 4 shows the results of the Schmidt hammer test on weathered surfaces, while Fig. 5

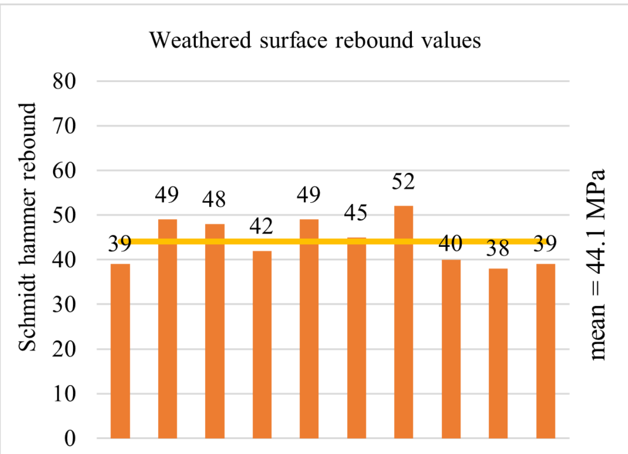

Fig. 4 The results of Schmidt hammer testing for weathered surface

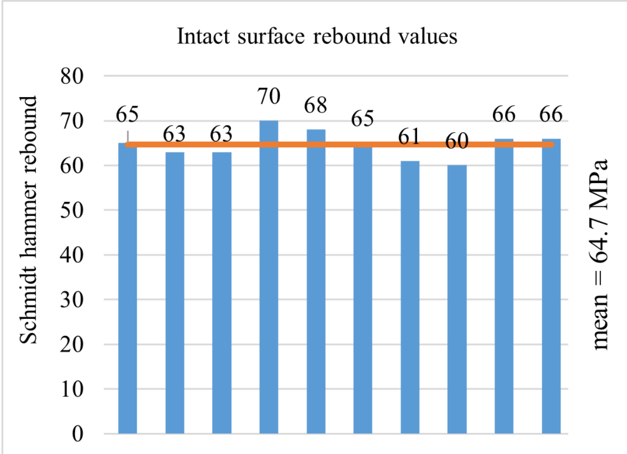

Fig. 5 The results of Schmidt hammer testing for intact surfaces

shows the results on intact surfaces. Compressive strength tests and Brazilian tests were performed on the dolomite specimens to determine the intact rock strength.

Near the uniaxial compressive strength and Brazilian tensile strength values, the Young's modulus, density and ultrasonic propagation velocity were also determined

The joint compressive strength (JCS) was calculated with the UCS and Schmidt-hammer rebound values.

Table 2 shows the mean values of the laboratory test results of dolomite samples.

Table 3 shows the used input data of the calculations, the generalized Hoek-Brown parameters of the dolomite

Table 2 Results of laboratory tests on dolomite samples (mean values)

Properties	Signs	Values	Units
Density	ρ	2,699	[kg/m^3]
Compressive strength	σ_c	50.25	[MPa]
Young-modulus	E	12.34	[GPa]
Tensile strength	σ_t	4.00	[MPa]
JCS (Joint Compressive Strength)	JCS	22.65	[MPa]

Table 3 Input data of stability analysis

	Distribution	Mean	St. Dev.	Rel. Min.	Rel. Max.
Unit Weight [kN/m^3]	normal	26.22	0.81	2.03	0.76
UCS [kPa]	lognormal	50,190	23,977	23,536	39,414
JCS [kPa]	[-]	22,650	-	-	-
f_R [deg]	[-]	27	-	-	-
JRC (Northern)	normal	14	7	8.34	5.66
JRC (Southern)	lognormal	7.66	4.05	4	6
GSI [-]	uniform	35	-	5	5
mi	[-]	12.9	-	-	-
D	[-]	0	-	-	-

rock mass and the Barton-Bandis parameters of the joints. The program considers all input parameters as random variables, for which the distribution type, standard deviation, mean value, and relative minimum and maximum are specified, while all other parameters are treated as fixed values in the calculation.

4.3. Investigated cross sections of the quarry

A total of 70 sections were recorded from the entire area of the quarry, at a distance of a few meters from each other. Slopes usually have 3 benches, and the height between the benches is around 20 m. The bench width is 5 m, and the quarry has seven sides.

Fig. 6 shows the quarry area with the seven sides and the 70 sections.

5. Stability analysis

5.1 Planar sliding analysis

Figs. 7 and 8 show two cases from the discontinuity groups: a non-critical (Fig. 7) and a critical joint (Fig. 8). All results are shown in Table 4. All seven sides were examined, specifying the inclination directions of each section.

The sliding along a planar surface is kinematically possible when the joints are in the pink-shaded area on the stereographic plot.

According to the kinematic analysis, the highest risk of failure is on the sides 13-14 and 14-15, but stability analysis should be done on the sides marked 2vp-1vp, 1vp-12 and 12-13 as well.

Table 4 contains the summarized results of the kinematic analysis. The sides marked 3vp-2vp and 15-3vp are stable according to the analysis of Dips. The stability analysis of

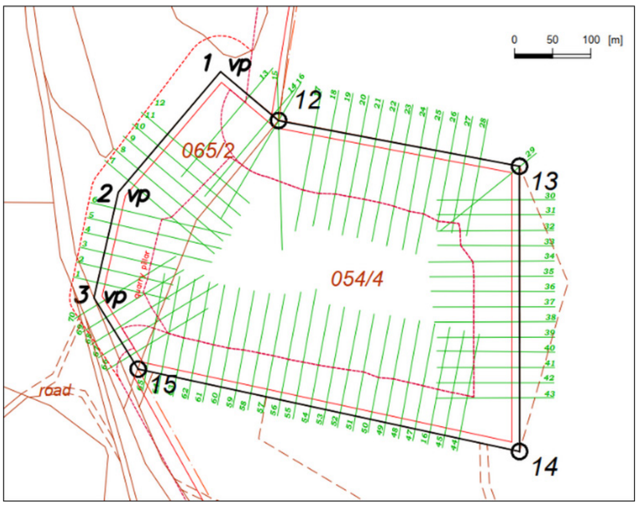

Fig. 6 Vilonya-I. dolomite open-pit mine

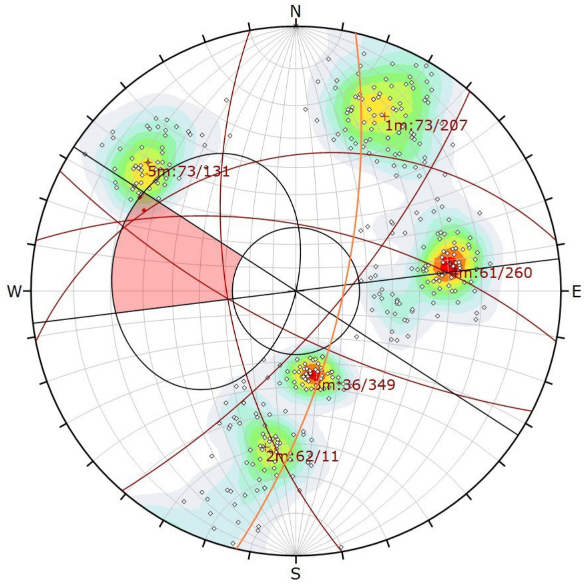

Fig. 7 Planar sliding analysis (3vp–2vp 103°)

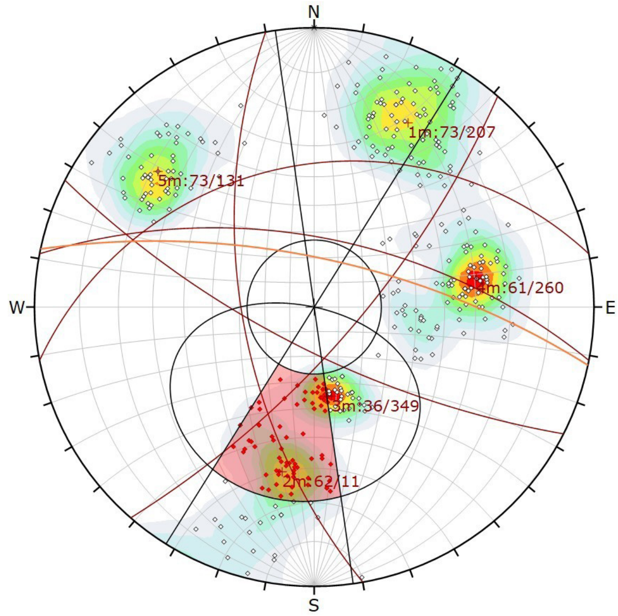

Fig. 8 Planar sliding analysis (14–15 12°)

Table 4 Results of Dips kinematic tests

Sign of the side	Slope direction	Maximum height	Result	Critical mean sets
3vp-2vp	103°	49.7 m	non-critical	-
2vp-1vp	130°	65.0 m	critical	5m
1vp-12	220°	65.0 m	critical	1m
12-13	191°	75.0 m	critical	1m
13-14	270°	75.0 m	critical	4m
14-15	12°	47.5 m	critical	2m; 3m
15-3vp	58°	40.3 m	non-critical	-

planar surfaces marked with red in Table 4 was done. In the RocPlane software, a characteristic value was taken into account for the wedge height of the largest step of the slope (20 m), the width of the bench at the upper face (5 m), and was 0°. The average angle of the slope was determined as 70°, which was taken into account with a uniform distribution of ±3° relative minimum and maximum values.

Fig. 9 shows the 2D view of stability analysis.

One result of the stability analysis is shown, the effect of 3 m joint group for side No. 14-15 in case of planar sliding failure.

Table 5 shows the results of the 3 m joint on the side 14-15. The Probability of Failure is 0.0% and so the Probability of Sliding. The Factor of Safety is 3.88, which is above 1.35, so the slope is stable.

In Table 6 all of the results of a planar sliding analysis can be seen.

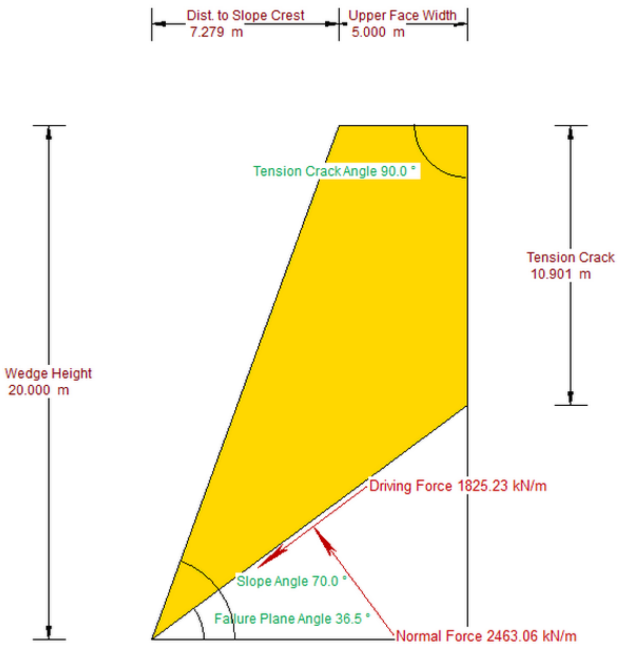

Fig. 9 An example of the 1000 runs of a probabilistic analysis in a 2D view

Table 5 Results of the analysis of 3m side 14-15

Results	Values
Probability of Failure (PF)	0.0 %
Probability of Sliding (PS)	0.0 %
Normal Reliability Index	5,3052
Lognormal Reliability Index	9,6731
Factor of Safety	3.88
Volume of the Mean Wedge	116.92 m^3
Weight of the Mean Wedge	3065.64 kN
Failure Plane Length	15.28 m

Table 6 Results of planar sliding analysis

Sign of the sections	PF (Probability of Failure)	PS (Probability of Sliding)	FS (Factor of Safety)
1m (1vp-12)(12-13)	0.00%	0.00%	2.54
4m (13-14)	0.00%	0.00%	4.16
2m (14-15)	0.00%	0.00%	4.76
3m (14-15)	0.00%	0.00%	3.88
5m (2vp-1vp)	0.00%	0.00%	2.59

5.2 Wedge stability analysis

Similar to the failure examined previously, it is also necessary to check whether two intersecting joints do not form a wedge that can slide. Wedging is also a very common form of failure in rock slopes. The risk of wedging is high in cases of dense articulations such as those found in the present mine. During the on-site investigations of the quarry, a dominant, low-angle, parallel joint system was measured in the entire area of the quarry, which is the bedding plane of the dolomite.

In SWedge software, a characteristic, constant value was given for the height of the slope (20 m), the density (22.62 kN/m^3), the slope of the terrain above the slope (0°), the bench width (5 m), the JCS (22,650 kPa), φ_R (27°). For the probability calculation, statistical variables were specified for the angle of inclination of the section (70°± 3°), the dip angles of the joints and the JRC values measured on the Northen and Southern surfaces.

On the other side of the quarry, the JRC value of 12 was used, which was a characteristic value. Kinematic wedge analysis was performed on all seven sides. The following figures show only two cases: one when there is no intersection (Fig. 10) and another one with more intersections (Fig. 11).

The results show which main joint set intersection can be dangerous for wedge sliding.

Table 7 shows the results of kinematic wedge analysis, and those joint intersections which should be analysed for wedge stability.

According to Table 7, an intersecting wedge can form on all sides except the side marked 2vp-1vp.

Fig. 12 shows the 3D view of the wedge analysis of grop 2m-4m on side No. 14-15.

A total of 11 cases were examined (last column of Table 7), for each calculation, Dip direction of the slope as well as the characteristics of the analysed sections as individual input parameters were given.

Table 8 shows the result of the the analysis of the 2m-4m sectional groups on side 14-15.

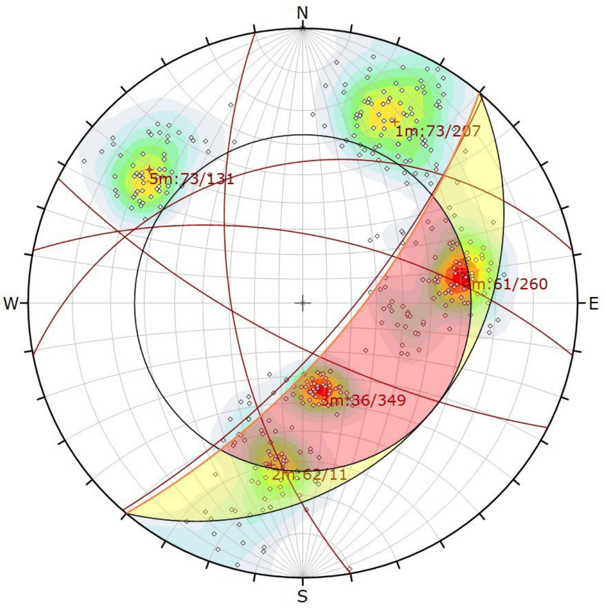

Fig. 10 Wedge stability analysis (2vp-1vp 130°)

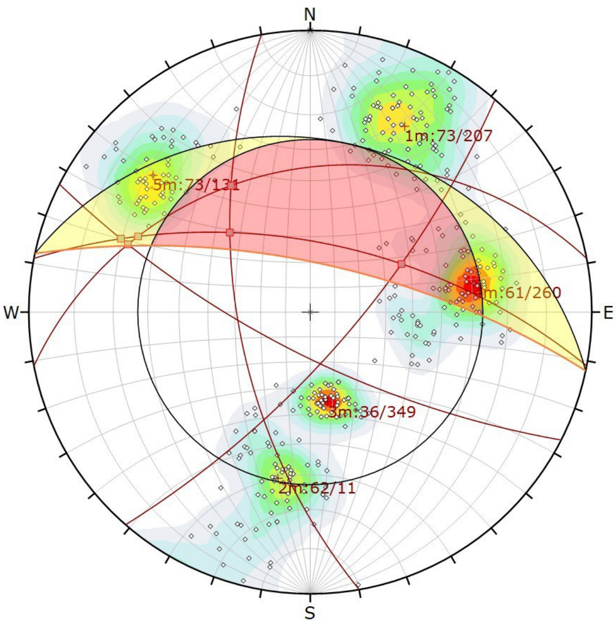

Fig. 11 Wedge stability analysis (14-15 12°)

Table 7 The result of Dips' kinematic analysis of wedge stability

Side sign	Slope directions	Intersecting joints
3vp-2vp	103°	2m-5m
2vp-1vp	130°	no intersecting wedge formed
1vp-12	220°	1m-4m; 4m-5m
12-13	191°	4m-5m
13-14	270°	2m-4m; 3m-4m; 4m-5m
14-15	12°	3m-4m; 2m-4m; 2m-5m
15-3vp	58°	2m-5m

Fig. 12 Analysing the wedge of groups 2m-4m on side No. 14-15

Table 8 The results of the analysis of the 2m-4m sectional groups on side 14-15

Results	Values
Probability of Failure (PF)	67.42 %
Probability of Sliding (PS)	82.28 %
Normal Reliability Index	8,194
Lognormal Reliability Index	7,962
Factor of Safety	0.677
Volume of the Mean Wedge	1,442 m^3
Weight of the Mean Wedge	37,803 kN
Sliding Direction	62.76°/11°

5.3 Global stability analysis, circular slip surface

The global stability analysis focuses on the behaviour of the entire rock mass [26]. The structure of the dolomite rock mass is fragmented, so it can be homogenized, therefore the stability of the rock slope was calculated by taking into account the shear strength characteristics of the rock mass.

For the test, the strength parameters of the rock mass and other input data required for the calculation should be determined first. The strength characteristics of the rock mass were calculated based on the generalized Hoek-Brown failure criterion. The input parameters for the criterion are the GSI value of the rock mass, uniaxial compressive strength, Hoek-Brown constant, and density. The calculation must also take into account the disturbance factor, which models the impact of the excavation method on the rock mass, i.e. how much the blasting destroys the rock mass. This was already taken into account when determining the GSI, so this factor was applied with a value of D = 0. In the case of Slide calcultaion, Global Minimum Method was used. The test was carried out on 70 sections. The results can be seen in Table 9.

Table 9 Slide2 results with the minimum values obtained on each side

Side sign	Sections	Slope direction	Slope angle	FS (det.) minimum	FS (mean) minimum	Difference	Maximum PF
3vp-2vp	1-6	103°	70°	2.48	2.23	−10%	0%
2vp-1vp	7-12	130°	70°	2.47	2.25	−9%	0%
1vp-12	13-16	220°	70°	2.27	2.08	−8%	0%
12-13	17-28	191°	70°	2.09	1.92	−8%	0%
13-14	30-43	270°	70°	2.16	1.98	−8%	0%
14-15	44-65	12°	70°	2.59	2.35	−9%	0%
15-3vp	66-70	58°	70°	2.72	2.46	−9%	0%

In all cases, the safety factor was above 1.35, and the probability of failure was 0% in the entire quarry area. In all cases, the average of FS values calculated during all runs (FS (mean)) was lower than the deterministically calculated FS (FS (deterministic)). FS (deterministic) or Deterministic Safety Factor is the safety factor of the Global Minimum slip surface, from a regular (non-probabilistic) slope stability analysis.

FS (mean) or Mean Safety Factor is the average safety factor of the Global Minimum slip surface obtained from the probabilistic analysis [26].

6 Discussion

The above calculations show that in the case of the dolomite quarry in Vilonya, according to the kinematic analysis using the Dips software, out of the five groups of joints examined on the seven sides of the quarry four groups of joints can indicate a failure to the sides of the quarry. However, when these joint groups were analysed in the RocPlane planar failure analysis software, the result was that the joint groups did not result in planar failure. At the joint group no. 3m, the distribution fitted to the histogram follows the beta distribution, the safety factor varies between 2.6 and 5.9 and the standard deviation is low, s.d. (standard deviation) =0.5438. It is because the sliding wedge at the joint 3m has the largest mass (approx. 3,065 kN/m) compared to the wedge formed by the other joint groups, and in this case there was no case with a high safety factor.

After sliding down the planar slip surface formed on the joints, the stability of the wedge was also examined, i.e. whether a wedge cut out by two exposed joints could be formed, the stability of which is not adequate. The Dips software was also used here, since it is able to calculate – given the angle and direction of inclination of the given section – whether there is an intersecting wedge formed. Except for the 2vp-1vp side, intersecting wedges are formed in all cases. For example, a wedge can occur on the side No. 14-15: the sections marked 2m-5m, and the intersection of the sections marked 2m-4m and 3m-4m can also result in a wedge slide. The 2m-4m joint groups can form 8,194 types of wedges, of which the safety factor was less than 1.0 in 6,742 cases, so the probability of failure is 67.42%. Out of 10,000 wedges, the 3m-4m joint groups caused wedge slippage in 1,835 cases, so the probability of failure here was 18.35%. On the other sides of the quarry, the occurrence of wedge slippage was 0%.

In this case, it is necessary to evaluate whether a wedge large enough to produce the specified probability of failure could form in the mine pit. If this is the case, the slope on the affected side should be redesigned with a lower slope angle.

Although it is not common for quarry sections formed in rocks to fail with a circular failure plane, all 70 sections were also calculated in the Slide2 software. The sections can be analysed globally and modeled as a whole section, while in the RocPlane and SWedge software the calculation is only localized to a specific section of the slope section. No failure probability was higher than 0.00% and the lowest safety factor was 1.918 during the calculations of Slide2.

Similar research was conducted by Afrapoli and Osanloo [29]. The study examines the effect of geomechanical uncertainties on the slope stability of open-pit mines through the examples of iron and copper mines. During the analysis, the probability of failure was compared using deterministic and probabilistic procedures, using the Latin Hypercube Sampling (LHS) technique to reduce variance. The results were interpreted based on the distribution of safety factors (Safety Factor, SF). The defined risk levels were compared with acceptable limits (e.g. maximum permissible error probability of 5%). The results proved that the geomechanical uncertainties have a significant impact on the determination of the angle and stability.

The disadvantage of using PSSA (probabilistic slope stability analysis) is the question of the acceptability of the result. It is important to mention that there is currently no concrete value for the acceptability of the failure probability that can be used everywhere. In such a case, it is advisable for the management of the mine to examine how much risk it is taking for the sake of profitable mining. In the present example, the worst result was 62% when calculating stability. This is not acceptable, as ultimate, long-term stability must be achieved on the present slope.

According to Amoushahi et al. [17] there are no universal criteria for determining the acceptable FoS and (or) PoF in slope design. Different guidelines are proposed by various authors in the literature, depending on the slope scale (bench or overall scale), and (or) slope design life (temporary or permanent), and (or) slope failure consequences (low, medium or high), and (or) uncertainty about the geotechnical data (data quality) and analyses.

Design Acceptance Criteria and Probability of Failure's acceptability are investigated by some researchers. [30–32]. Design guidelines were proposed by Read and Stacey [31] Wesseloo, J. and Read, J. and are actually considered as industry standards for large open pits.

According to these guidelines, overall slopes with high failure consequences can have an acceptable FoS between 1.3 and 1.5, and a PoF of <5%.

According to Macciotta et al. [33] a FoS between 2 and 3 or higher and a PoF <5% should be used to guarantee slope stability for a period of >100 years.

It would be worthwhile to investigate further research that examines how the safety factor and the probability of failure relate to each other, and which is the maximum value of the probability of failure that is acceptable during the design of a quarry section.

7 Conclusions

In slope stability engineering, it is not recommended to ignore the uncertainty. If the distribution of the data series of the material characteristics occurs at a density higher than the low values (such as, for example, the lognormal, gamma, beta, exponential distribution), then the safety factor may differ significantly from the safety factor calculated from the input parameters considered as the mean of the data series. At the dolomite quarry in Vilonya, it can be seen that, although failure cannot be expected on a planar slip surface, wedge may develop and, most likely, slope failure as well.

In the optimal case, when designing the geometry of a section, engineers strive for the safety to be as close as possible to 1.35 from the top due to economic planning and construction, especially in the case of open-pit mines and quarries, when the goal is to be able to extract as much ore as possible. Complete certainty is provided by using a statistical method to support the stability of the slope. That is if it is proven that the probability of failure is minimized during the design of the slope geometry, reaching a value as close as possible to 0%.

Optimally, engineers try to approach the value of 1.35 as closely as possible from above, but it is worthwhile to approach the value of 0.0% as closely as possible.

In addition to a deterministic calculation, it is also worthwhile to support the suitability of the stability of the tested section on a probabilistic basis.

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