

Stability assessment of rock slopes based on Discrete Fracture Networks (DFNs)

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ABSTRACT: The stability of rock slopes is primarily influenced by discontinuities. Since it is difficult to measure 3D systems of natural discontinuities (fracture networks), stochastic approaches have been developed using statistics from limited samples. A widely used method developed in the 1980s is a stochastically generated Discrete Fracture Network (DFN). A general stochastic DFN approach assumes that fractures are planar discs and treats the other geometrical properties (e.g. position, frequency, size, orientation) as independent variables obeying certain probability distributions derived from field measurements of outcrops. A case study demonstrates how DFNs can be used: on the one hand together with numerical calculation approaches such as the Discrete Element Method (DEM) and on the other hand with the Limit Equilibrium Method (LEM). Furthermore, it is discussed whether and how a Eurocode-compliant assessment of the stability of rock slopes can be carried out in these ways.

KEYWORDS: discrete fracture network, stability assessment, rock slopes, probability of failure, discontinuities, fisher distribution.

1 INTRODUCTION

The stability of rock slopes is largely determined by the discontinuities of the rock mass. Numerous authors (Goodman, 1980; Poisel et al., 2017) have shown that the scattering of the discontinuity orientations can have a significant influence on the probability of failure of rock slopes. This is because the dominant failure mechanism (Poisel & Preh, 2004; Hungr et al., 2014; Cruden & Varnes, 1996) of rock slopes is determined by the discontinuities and this can also change within an apparent homogeneous range due to the scattering of orientations. When assessing the stability of rock slopes, both the discontinuity analysis and its consideration in the calculation approaches are therefore of particular importance.

2 RECORDING THE GEOMETRY OF THE SLOPE AND THE DISCONTINUITY SYSTEM (FRACTURE NETWORK)

The rapid development of remote sensing methods – especially photogrammetry with low-cost UAVs – has enabled a technological leap in analyzing discontinuity systems by generating high-resolution terrain models (DTMs). The discontinuity system is extracted from point clouds using analysis tools such as CloudCompare (2020) or the Discontinuity Set Extractor (DSE) (Riquelme et al., 2014), focusing on discontinuity orientation and density. This approach enables a realistic and cost-efficient recording of the discontinuity system, providing a solid basis for reliable stability analysis.

Figure 1 shows an example of a rock face in Tiefenbach, in western Lower Austria, along the Greiner Straße (B 119) state road next to and along the Danube. The geological unit is the so-called Weinsberg granite: coarse-grained biotite granite with porphyritic large potassium feldspar (Mississippian) alongside metablastic to diatectic paragneiss, relics of biotite-rich paragneiss ('pearl gneiss') (Moser & Linner, 2019). Due to vegetation, the structural geological analysis of the rock face was limited to the area marked in red (Figure 1a). The rock face examined is approximately 38 m long, 20-25 m high and has an average angle of inclination of 73°. Figure 1b shows the 3D point cloud model of the selected Tiefenbach rock face, colored according to the dip direction. 100 discontinuities were measured from the point cloud model in CloudCompare. These were divided into two sets: k1 with 43 and k2 with 57 measured

orientations. Figure 2 shows the equal-area lower hemisphere plots (density contours and great circles) of the two sets.

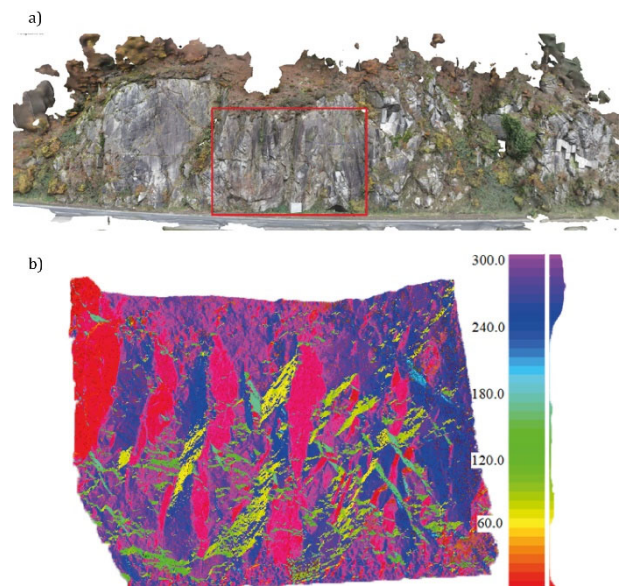


Figure 1. a) Photogrammetry of a rock face in Tiefenbach; b) 3D point cloud model of the rock face, colored according to the dip direction (in degrees): joint set k1 – red/green, joint set k2 – blue/yellow (Illeditsch & Preh, 2024).

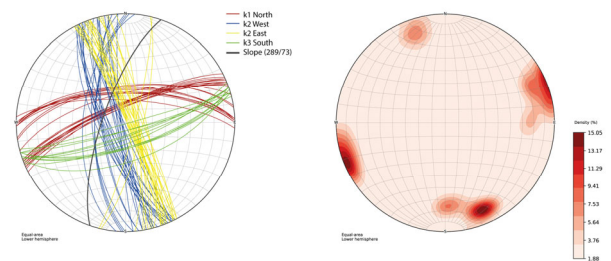


Figure 2. Equal-area stereographic projection of the 100 joint orientations measured at the rock face using OpenStereo (Grohmann & Companhia, 2017): a) great circle representation, slope (289/73); b) density map (Illeditsch & Preh, 2024).

3 DISCRETE FRACTURE NETWORK (DFN)

Due to the difficulty of performing a complete measurement of 3D natural discontinuity systems (fracture networks), stochastic approaches using statistics from limited sampling have been developed. A widely used method developed in the 1980s is a stochastically generated Discrete Fracture Network (DFN). The general stochastic DFN approach assumes fractures to be planar discs, and treats the other geometrical properties (e.g. position, frequency, size, orientation) as independent variables obeying certain probability distributions derived from field measurements of outcrops.

For this purpose, the distributions of the discontinuity orientation, the joint density (e.g. area of joints per m³) and the joint size (persistence) must be considered for each individual set of discontinuities.

Figure 3a shows the density plots of the measured orientations for the fracture systems k1 (left) and k2 (right) in the Tiefenbach case study (compare to Figure 1 and Figure 2). The statistical description of the joint orientation distributions can be performed using the Fisher distribution (Fisher, 1953), for example. The Fisher distribution is the spherical analogue of the normal distribution. It describes the probability density of pole vectors concentrated around a mean orientation on a sphere. The mean vector (plunge/bearing), the concentration parameter and the Fisher angle are listed below the respective density plot (Figure 3a). Using Fisher statistics (mean vector and K-value), a synthetic fracture distribution with 500 joint planes was generated for k1 and k2 (see Figure 3b). This serves as the basis for the investigation using the limit equilibrium method.

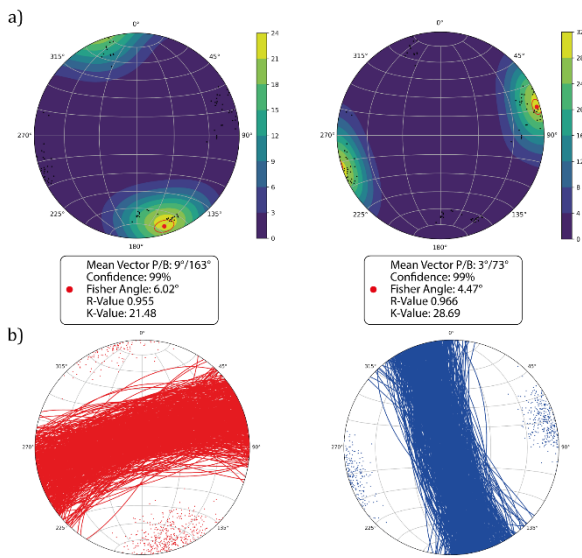


Figure 3. a) Density plots of the joint sets k1 (left) and k2 (right) and associated Fisher statistics (below); b) Synthetic joint sets (k1-red, k2-blue; 500 each) calculated using the derived Fisher statistics.

4 DETERMINISTIC AND SEMI-PROBABILISTIC METHODS

In principle, the Eurocode does not permit the assessment of stability using a global safety factor. However, since the national application document ÖNORM B 1997-1-1:2021 specifies the design approach NV3 for determining overall stability, the additional computational effort is low both when using conventional limit equilibrium methods and when using numerical methods. In accordance with the Eurocode, the strengths are reduced in line with the semi-probabilistic safety concept, i.e. design values are determined and a utilization

factor is calculated instead of the global safety factor, but the general procedure itself remains unchanged.

However, the national application document ÖNORM B 1997-1-1:2021 does not address how to deal with the uncertainties due to the scattering of the discontinuity orientations.

In the classic approach, all discontinuity data (dip directions and dips) are visualized using a stereographic projection and grouped into discontinuity sets according to their type (foliation, bedding planes, joints, fissures, faults and shear planes) as well as their orientation. Representative values for the orientations of the individual sets are determined by calculating average values (average of the dip direction and dip angle).

Another way of obtaining representative values for the orientations is to use pole density plots, which show the concentration of poles in a particular area (see Figure 2 right). In these plots, poles that are closer to each other are weighted more heavily. This is the method recommended by the ISRM.

However, it is also suggested to use probabilistic methods (without specifying which).

Neither approach guarantees that the most unfavorable orientation in situ is considered. Based on two statements in prEN 1997-1:2022, both approaches are not or no longer Eurocode-compliant:

- 1) Geometric properties of discontinuities should normally be nominal values.
- 2) The nominal value of the geometric properties for discontinuities may be determined by sensitivity analysis using a probabilistic approach considering location, orientation, and length of the discontinuities.

It can be concluded from these two statements that a sensitivity analysis using all measured discontinuity orientations must always be carried out when assessing the stability of rock slopes. According to statement 2), a probabilistic approach can be used, but other methods such as the combinatorial approach are also permitted.

In the combinatorial approach, all possible kinematic rock blocks are analyzed using the recorded discontinuity data set. The combinatorial approach is mostly used to analyze block or wedge sliding but can also be used for other interface-dominated failure mechanisms like toppling.

5 PROBABILISTIC METHODS

As an alternative to the semi-probabilistic approach (partial safety concept), a reliability-based design (specification of a probability of failure) may also be carried out in accordance with prEN 1990:2022. This includes purely probabilistic approaches. In purely probabilistic methods, the uncertainties are quantified using probabilistic terms, including structural safety, which is defined by the probability of failure. According to prEN 1990:2021, the time-invariant probability of failure can be calculated as follows in accordance with probability theory:

$$p_f = \int_{G(x) < 0} f(x) dx \cong \frac{1}{m} \cdot \sum_{j=1}^m I(x) \quad (1)$$

where $f(x)$ represents the joint probability density distribution of the random variable x . The right-hand side of the equation approximates the probability of failure using the Monte Carlo method, which consists of performing m limit equilibrium calculations and using a failure indicator function I to count how many failures occur. Finally, the probability of failure is approximated by the failure frequency (Pereira et al., 2023).

The boundary between acceptable and unacceptable structural behavior (limit equilibrium) is defined as the limit state function $G(x)$.

$$G_j(x) = FS(x) - 1 \quad (2)$$

This approach can be used very well when analyzing the failure mechanism of wedge failure. Probability distributions are used for all kinds of calculation parameters such as the spatial orientation of the wedge-forming discontinuities and their strength.

6 LIMIT EQUILIBRIUM METHOD (LEM)

When analysing the stability of rock slopes using limit equilibrium methods, the failure mechanisms of sliding, wedge sliding and toppling are usually investigated. The first step is to identify the dominant failure mechanisms using a kinematic analysis (Markland, 1972).

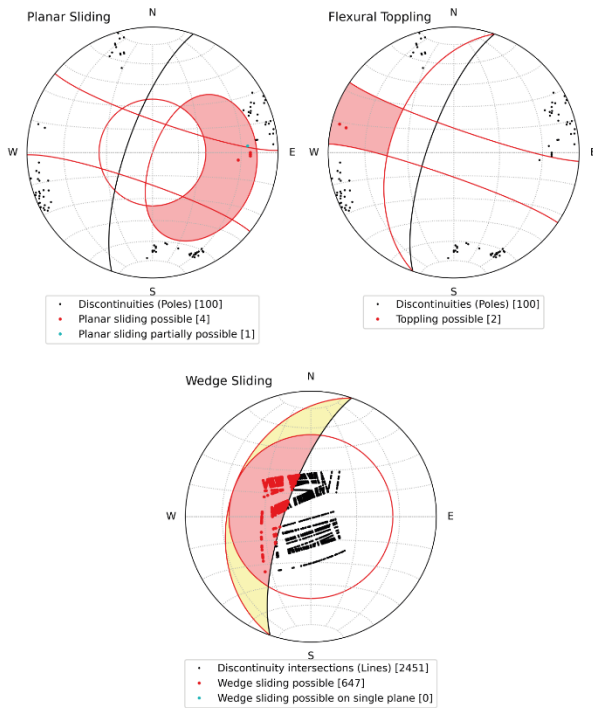


Figure 4. Results of the kinematic analysis for the measured joint sets k1 and k2.

Figure 4 shows the results of the kinematic analysis for the 100 measured orientations of the fracture systems k1 and k2. With the help of kinematic analysis, wedge sliding was identified as the dominant failure mechanism for the Tiefenbach rock slope. The degree of utilization of all 647 kinematic rock wedges determined was then calculated using LEM. This method is referred to as a combinatorial approach.

Furthermore, the stability of the rock face was examined probabilistically, based on the Fisher distributions for the two joint sets k1 and k2 presented in Chapter 3. Figure 5 shows the intersections of the rock wedges examined using the probabilistic approach (black triangles). A total of 10,000 possible intersections (black triangles) were investigated using Monte Carlo simulation. The Monte Carlo sampling technique uses random numbers to draw a sample from the probability distributions of the input data (Fisher distribution for joint orientations and normal distribution for joint strengths).

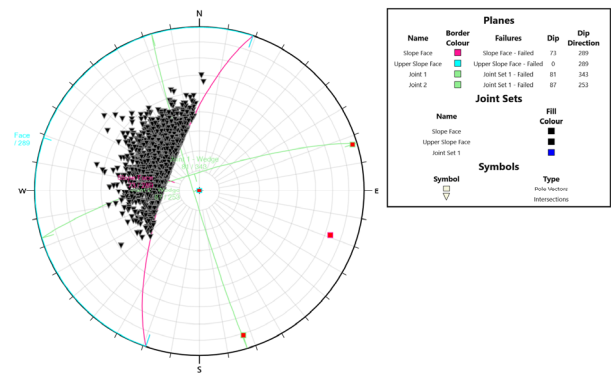


Figure 5. Stability analysis of potential rock wedges using RocSlope2 (Rocscience, 2024); the black triangles represent the intersections of the rock wedges examined.

All calculations were carried out using the Mohr-Coulomb friction model with a characteristic friction angle of $\phi = 35^\circ$ and a characteristic cohesion of $c = 33 \text{ kPa}$.

Applying the partial safety factors according to design situation DS1 and consequence class CC3 (ÖNORM B 1997-1-1:2021), the maximum utilization factor μ according to the combinatorial calculation is 0.85. This corresponds to a converted global factor of safety of $\eta = 1.53$.

The probabilistic calculation results in one unstable wedge ($\eta = 0.99$) of 10,000 examined, which corresponds to a probability of failure $P_{f,50}$ of 1×10^{-4} . According to FprEN 1990:2022, failure consequence class CC2 would therefore be met for a reference period of 50 years, but not CC3.

7 SYNTHETIC ROCK MASS MODELS

In connection with numerical calculation approaches such as the Discrete Element Method (DEM) (Cundall, 1971, Itasca, 2020) synthetic rock mass models are becoming increasingly important. In synthetic rock mass (SRM) models, a Discrete Fracture Network (DFN) is blended with a volume model (Figure 6) to simulate rock mass realistically. The central element here is the DFN, which statistically describes the geometric properties of the discontinuity system. For this purpose, the distributions of the joint orientation, the joint density (e.g. area of joints per m^3) and the joint size (persistence) must be considered for each individual set of discontinuities.

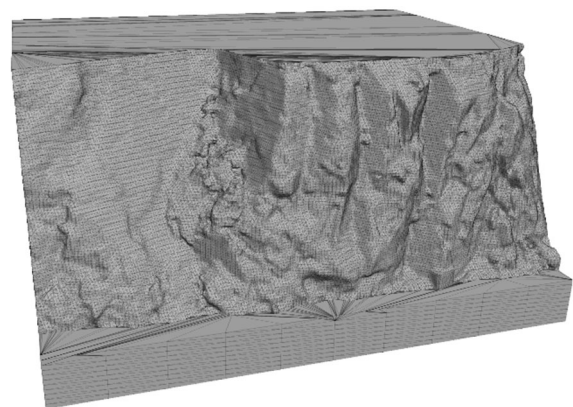


Figure 6. Volume model of the rock face in Tiefenbach (compare to Figure 1) (Froschauer, 2023).

A DFN produces a collection of disc-shaped discontinuities whose geometric properties such as position, orientation, persistence and density/intensity are subject to stochastic probability distributions. The joints mapped in this way therefore do not represent the actual joints in the rock mass.

Nevertheless, this way it is possible to model the discontinuity system very realistically (Figure 7).

Although a discrete fracture network is based on stochastic distribution functions, numerical calculations using synthetic rock mass models cannot be regarded as reliability-based calculations. The main reason is that this approach does not use a Monte Carlo simulation with many random samples ($\geq 10,000$). Instead, a semi-probabilistic calculation is carried out using a realistic discrete fracture network. The safety factor or utilization factor is usually determined using the strength reduction method (Dawson et al., 1999, Zettler et al., 1999).

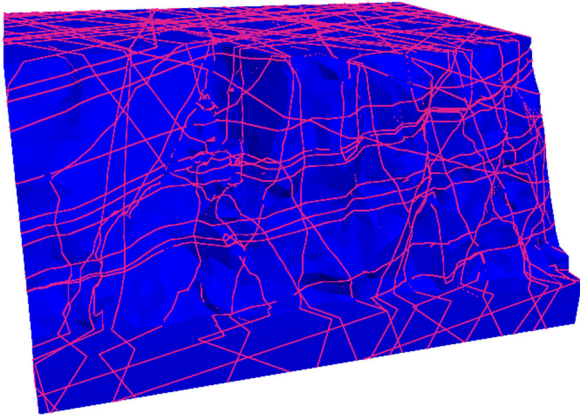


Figure 7. SRM of the in Tiefenbach created using 3DEC (Itasca, 2020) (Froschauer, 2023)

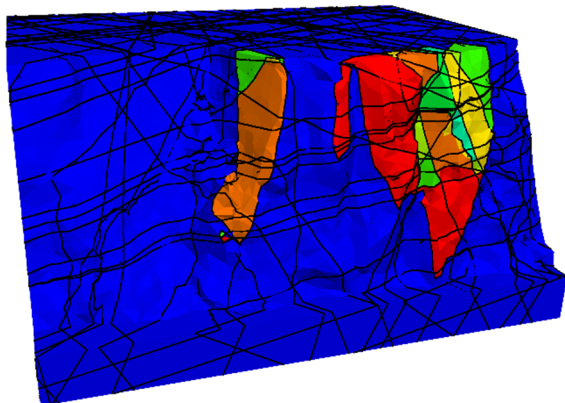


Figure 8. Identification of the unstable rock blocks based on the displacement magnitudes (Froschauer, 2023).

Froschauer (2023) used an SRM model of the Tiefenbach rock face (Figure 7) to identify key blocks according to the definition of Goodman & Shi (1985). These are the kinematic blocks of the rock mass that have the lowest global factor of safety (Figure 8). By knowing these blocks, it is possible to optimize the amount of support required to stabilize the wall (e.g. with rock bolts). The safety factors of the identified key blocks lie above the minimum safety factor ($\eta = 1.53$) determined using the combinatorial approach.

8 CONCLUSIONS

Modern remote sensing methods now enable accurate recording of a rock slope surface and discontinuity system (fracture network). This allows the dominant failure mechanism to be determined and meaningful stability analyses to be carried out. In the case of wedge failure, which is usually the decisive mechanism, comparative calculations have shown that the results of conventional combinatorial calculations are close to the results of the Discrete Element Method (DEM) using a

synthetic rock mass model. Probabilistic approaches generally assign a lower safety level to the rock faces investigated.

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