An algorithmic approach for block analysis supported by 3D imaging

By Markus Pötsch and Andreas Gaich

Introduction

The work of geotechnical engineers includes the establishment of a ground model when performing an analysis of the rock mass. The model bases usually on information of various sources, such as mechanical, topographical, geological, hydrological, or physical-chemical investigations. This involves different kind of information possibly at a large number and inherently showing a significant variation. In the past the assessment of the rock mass behaviour finally relied just on the experience of the acting engineers due to lacking possibilities and time to reasonably combine the various data of the rock mass into a consistent model.

With the introduction of new measurement technologies and methods for data analysis together with increasing computational power also new possibilities for geotechnical analyses emerged. New standards and guidelines calling for consistent design methods as well as the requirement for an objective data basis for project communication and contractual claims triggered the demand for new acquisition and analysis technologies.

Data acquisition and evaluation technologies were improved in several fields, for instance, prediction of tunnel wall displacements (1), advanced geophysical investigations (2), or displacement measurements ahead of the tunnel face (3).

Another concept which is especially addressed in this paper is the recording of rock outcrops from a remote position in order to obtain a geometrically correct model from which measurements can be taken without physical contact. This is performed by generating 3D images showing the condition of the actual rock surface on a dense grid of measurement points.

Especially the determination of the visible discontinuity network gains special importance as it shows, depending on the scale of the considered volume, a major influence on the behaviour of rock masses. Using 3D images, discontinuity properties can be determined without having direct contact, thus a significantly larger number of decisive rock structures can be assessed.

This contribution presents an algorithmic approach for the analysis of the geometry, kinematics and stability of blocks in rock outcrops. The analysis is based on block theory and advanced stereometric vector analysis. It also includes the use of a computer-aided measurement tool for recording the rock surface with 3D images wherefrom the input parameters are obtained. The

Ein algorithmischer Ansatz zur Blockanalyse unter dem Einsatz von 3D Bildern

In den letzten Jahren wurden neue Technologien, welche die Tätigkeit des Geotechnikers unterstützen, verbessern und erweitern, entwickelt. Dieser Artikel stellt eine Methode zur Aufnahme und Analyse von Trennflächen vor, wobei Grundsätze der Felsmechanik, Ingenieurgeologie, Photogrammetrie und maschinellen Sehens verwendet werden. Als Aufnahme- und Auswertungswerkzeug wird das JointMetriX3D System angewendet. Dieses System liefert die Geometrie der Oberfläche und erlaubt die Bestimmung des sichtbaren Trennflächensystems des untersuchten Gebirges. Diese Informationen werden mit Hilfe der Vektorrechnung weiterverarbeitet. Als Ergebnis erhält man die Position und Größe instabiler Blöcken in einem Felsaufschluss (z.B. in einem Felseinschnitt oder der Tunnelleibung).

New technologies have been applied in the field of geotechnical engineering. These technologies support the engineers to improve and extend their analyses. This paper describes a method for data acquisition and analysis of discontinuities using principles from rock mechanics, engineering geology, photogrammetry, and computer vision. The proposed acquisition and evaluation tool is the JointMetriX3D system. This system provides the geometry of the surface and allows to measure the visible discontinuity system of the considered rock mass. The obtained data are processed using vector analysis and lead to the identification of unstable blocks in an outcrop, useful for instance in a rock slope or a tunnel wall.

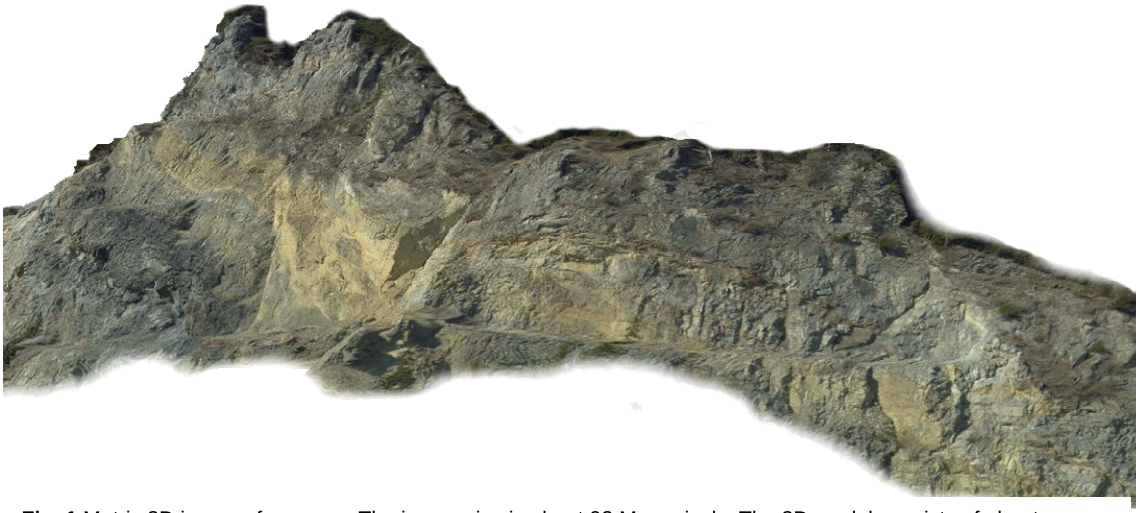

Fig. 1 Metric 3D image of a quarry. The image size is about 92 Megapixels. The 3D model consists of about 1,000,000 points. The image was recorded from a distance of 700 m using the JointMetriX3D panorama scanner.

Bild 1 *Metrisches 3D Bild eines Steinbruchs aufgenommen mit dem JointMetriX3D Panoramascanner aus einer Entfernung von ca. 700 m. Die Bildgröße beträgt ca. 92 Megapixel. Die Oberfläche wird durch ca. 1 000 000 Punkte dargestellt.*

concept and results for block analysis, as well as a brief description of the 3D imaging system are presented.

3D imaging by JointMetriX3D

JointMetriX3D is a high resolution 3D imaging system for the acquisition of rock and terrain surfaces. Two images of a rock outcrop are taken from two different standpoints. This so-called stereoscopic image pair is then processed on a computer using a proprietary software that combines principles from photogrammetry and computer vision (4) which finally leads to a 3D image. A 3D image combines high resolution visual information on the actual conditions of the rock surface and its joint pattern with a dense three-dimensional grid of surface points, or in other words, dense geometric measurements are united with highly detailed visual information (see Figure 2).

The high resolution images are recorded by a calibrated panoramic line scanner. This scanner allows the acquisition of images up to 100 Megapixels. High resolution images are required for large rock structures (quarries, slopes, etc.) or the reconstruction of fine details. For smaller outcrops or less demands on resolution the same principle is also applicable on lower resolution images taken with a calibrated standard digital camera.

Figure 1 shows an example of a 3D image of a quarry captured from a distance of about 700 m. The processing of a stereoscopic image pair of 92 Megapixels each is nowadays possible on a reasonably modern PC, thus allowing new possibilities for data acquisition.

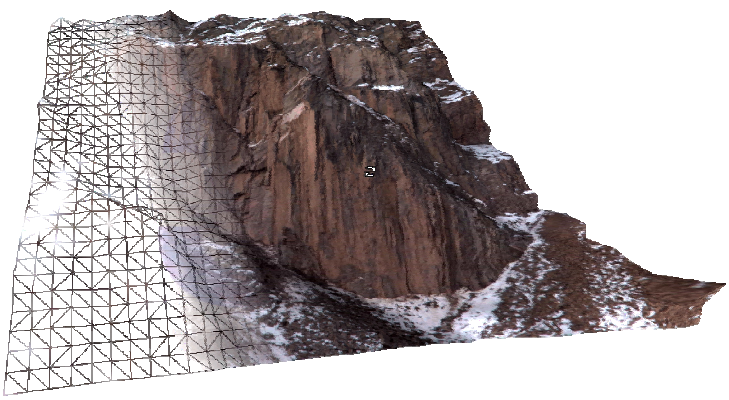

Fig. 2 A 3D image combines three-dimensional surface measurements with high resolution image data.

Bild 2 *Ein 3D Bild kombiniert dreidimensionale Oberflächenmessungen mit hochauflösenden Bildinformationen.*

Evaluation of data

The 3D images are used to take measurements of the rock structures. These measurements are derived from the surface characteristics. In order to ensure accurate measurements the 3D images must conserve fine details.

Rock structures can be discriminated into area elements and linear elements. Usually, area elements are assigned to discontinuities which continue to the surface and appear as an area with limited extent. Linear elements conversely are assigned to discontinuities which appear as a linear trace on the surface. The structures are determined by their spatial properties such as location, extent (length or area), and orientation.

During evaluation the structures are directly marked on the 3D images. The marked structures are analysed by the software and their properties calculated. The location of the area elements is defined by the marked points on the surface, their extension is defined by a closed polygon and expressed as the area enclosed by the polygon. Conversely, the extent of linear elements is defined by an open polygon on the 3D image and expressed as the length. For both, area and linear elements, orientations can be determined. They are represented as the normal vector of the orientation for area elements, and as a spatial triangle

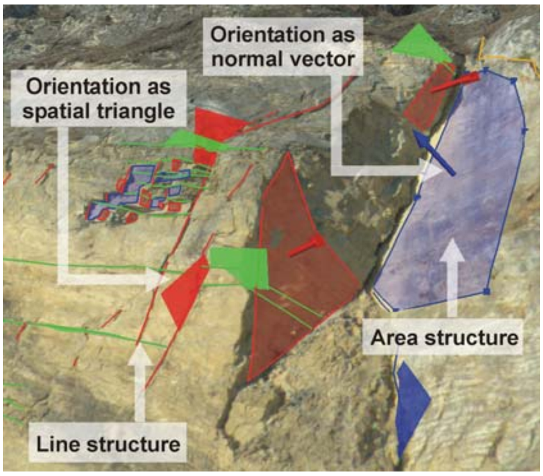

Fig. 3 Line and area elements with corresponding orientations for discontinuity measurements. These measurements serve as input parameters of block analysis using vector methods.

***Bild 3** Linien- und Flächenelemente mit den zugehörigen Orientierungen für die Trennflächenvermessung. Diese Messungen bilden die vektoriellen Eingangsdaten für die Blockanalyse.*

(representing the discontinuity plane) for linear elements (Figure 3).

Using 3D images the user has two kinds of information to judge the evaluation. On the one hand, there is the 3D surface, which describes the shape of the outcrop. On the other hand, the highly detailed image allows for discrimination of natural structures (foliation, joints, faults, etc.), man-made structures (scarps of excavators, etc.), or other geological features such as lithological boundaries. The combination of both sources of information allows the establishment of a consistent discontinuity network and an audit of the evaluation.

Additional properties can be assigned to the identified structures according to their nature and the structures can be grouped into structure sets (discontinuity sets). The sets can be statistically analysed with respect to the variation of the orientations, and the persistence and spacing. At the end of the evaluation the discontinuity system of the rock face has been determined as a trace network with its corresponding spatial properties.

Analysis of data

In a blocky rock mass failure occurs in situations where the resistance of the discontinuities is exceeded. Therefore, a characteristic of a blocky rock mass is the significantly lower discontinuity strength compared to the rock material strength. These failures are defined as discontinuity controlled or structurally controlled failure mechanisms by some authors (5) and consider the stability of blocks.

Several constraints must apply to cause a block failure:

- Discontinuities and surfaces must completely enclose a rock volume in order to form blocks.
- Discontinuities must be arranged in a way allowing the block moving into the free space.
- Active forces must be able to destabilise the block.
- The strength of the discontinuities under the applied loading conditions is exceeded.

Since the location and shape of the failure surface is predefined, limit equilibrium methods have been applied to analyse this problem. Some simple analysis methods exist, dealing with general kinematics of excavations in discontinuous rock which can be easily solved in the stereographic projection (6) (7).

The proposed method for the block analysis favours a discontinuity system determined by metric 3D images. The applied algorithmic steps for the stability analysis include

- the identification of blocks in the rock face on the basis of the trace network,
- the investigation of kinematics of the identified blocks,
- the determination of the mode of failure of blocks which are kinematically free to move,
- and the stability analysis of potentially unstable blocks.

This algorithm supports a hierarchical and consistent procedure.

Identification of blocks

In order to perform an algorithmic analysis, the acquired and evaluated data have to be transformed into a geometrical model. This model relates discontinuity planes to surface planes. It is a simplified model representing a trace network on a complex surface.

The geometrical model is analysed in order to identify regions with the potential of block failure. Blocks form where the traces enclose a spatial polygonal area at the surface (8). Joint planes corresponding to the traces form either finite blocks or infinite blocks. Only finite blocks are selected for kinematical and stability analysis, whereas infinite blocks are not free to move. On the other hand, infinite blocks can change to finite blocks by rock fracture during stress-induced failure and also proceeding excavation.

Kinematics of blocks

The kinematical analysis of blocks is based on the assumptions of rigid body dynamics, i.e. no relative displacements between two points belonging to the same block are allowed. Kinematically admissible displacements of blocks are those which do not produce an interpenetration of the block with the adjacent rock mass. Spending some effort kinematical analysis can be done with stereographic projection methods but in times of increasing computational power vector analysis is suitable to solve the problem.

Block Theory (9) provides the basis for the analysis of translational displacements of convex blocks. Summarising the theorem of

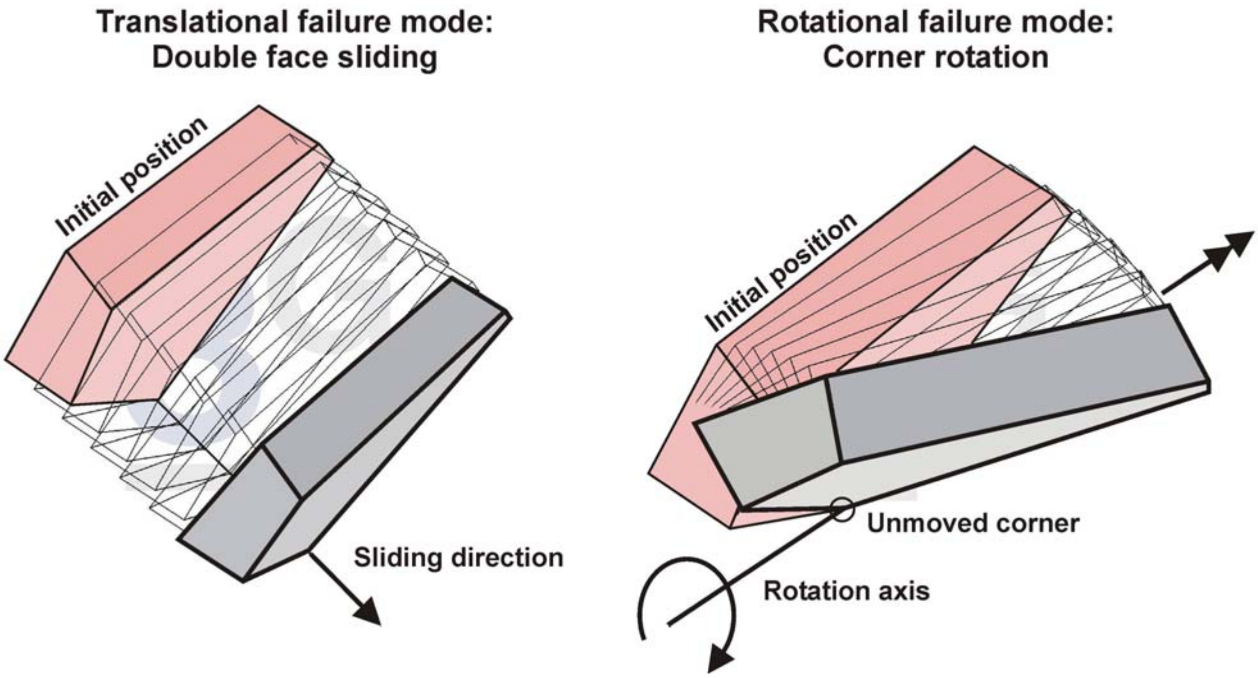

Fig. 4 Failure modes exhibited by an identified block under gravitiy loading (compare Fig. 3).

Bild 4 *Versagensmodi eines identifizierten Blocks unter Gravitation (vgl. Bild 3).*

removablility, a block is kinematically removable if and only if its block pyramid is empty and its joint pyramid is non-empty. Kinematics of non-convex blocks (which have notches and entrants) can be solved by successive decomposition into convex blocks.

Rotational kinematics are not covered by the original Block Theory approach. Mauldon (10) proposed a solution for the analysis of kinematically feasible displacements for rotations of blocks with three joint planes and a concept for blocks with four joint planes. Tonon (11) applied general loading conditions to blocks with three joints. For more complex blocks rotational kinematics become quite extensive.

Rotational displacements are related to a rotation axis which can be either fixed in space or movable with the block displacements. The simplest rotation of a block is the rotation around an edge at a free face. In this case the location and direction of the rotation axis is predetermined. Conversely, rotation around a corner at a free face implies only a point of the rotation axis. For the general case, a block is rotatable around a corner if a bundle of axes which allow for kinematically feasible displacements exists. In other words, a block is rotatable if its rotation space is non-empty.

The third kind of rotation is about a remote axis to the block. It usually can be decomposed into a translation and a rotation. Therefore, the failure mechanism is dominated by an interaction of plane or edge sliding with rotational displacements.

Failure mode

The mode of failure of a block depends on its initial displacements. For translations the initial displacements are dominated by the direction of the resultant of the active forces relative to the joint pyramid, provided that the resultant acts through the block's centroid. For rotations the initial displacements are dominated by the wrench resultant and the mass and moment of inertia of the block. For the determination of the failure mode no joint resistances are considered. Several modes can be distinguished.

- Lifting: The resultant tends to open all joint planes simultaneously.
- Single face sliding: The resultant causes a normal compressive stress on one and only one joint plane while the remaining joint planes tend to open
- Double face sliding: The resultant causes a normal compressive stress on two and only two joint planes while the remaining joint planes tend to open
- Corner rotation mode: The initial displacements of a block cause a reactive force at both joint planes forming the corner while the block tends to separate at the remaining corners.
- Edge rotation mode: The initial displacements at both corners of an edge cause a reactive force on the joint plane belonging to the edge while the block tends to separate at the remaining corners.

A particular case of a corner rotation mode is the torsional sliding (12) where the block remains in contact with one joint plane during rotation about a corner on the plane. Other loading conditions lead to stable conditions (no failure mode).

Vector methods are suitable to determine directions of forces and initial displacements, and to compare these directions with joint systems. This serves for the distinction of different modes of failure for both, translational and rotational failure mechanisms.

Figure 4 shows the possible failure modes of a block identified from the measurements in Figure 3. Gravity is the only active loading. The initial position is indicated by a red shading, whereas several intermediate positions are indicated by grey shading or wire frames, respectively. The translational failure mode is double face sliding in direction of the intersection of two joint planes (indicated by “Sliding direction”). At the same time, the block exhibits a rotational failure mode about the indicated rotation axis which passes through a corner (indicated by “unmoved corner”). In this special case the active resultant pushes the block against one joint plane. Therefore, the failure mode is a torsional sliding mode about the indicated corner. The determination of the dominating failure mode and the corresponding stability level is the task of the subsequent stability analysis.

Stability analysis

Limit equilibrium analysis (LEA) has been used to assess the stability of blocks. Limit equilibrium methods include the assumption of the location and shape of the failure surface, the definition of a relevant force system and the establishment of a failure criterion for discontinuities (usually the Mohr-Coulomb criterion). The principle supposes that the block is at limit equilibrium at the point of consideration, i.e. resistance and forces are fully mobilised simultaneously. In its original approach for block analysis LEA does not consider the moment equilibrium.

Going further into detail, some drawbacks of this approach become obvious. Analysing rotational failure modes the momentum equations have to be included into the analysis.

In contrast to the assumption of LEA the reactive forces are not fully developed simultaneously. Only inertia forces act constantly over time. Other loads vary with time but can be treated as if they were constant in time (e.g. loads from foundations or hydraulic forces). Conversely, others must not be considered as constant (e.g. blasting or seismic induced loads). The development of passive forces (resistance of discontinuities or rock bolts) usually is a function of the displacement. Therefore, the system is highly statically indeterminate. Its solution requires a consideration of the interaction of mobilisation of frictional resistance, mobilisation of support forces, and dilatational behaviour of discontinuities. Approaches for stress-strain relationships for discontinuities or support elements are proposed in the literature but have to be adapted for this application. Due to its complexity an iterative algorithm for solving the stress-stain equations has to be applied which is currently investigated in more detail.

Summary

A concept for data acquisition and analysis using new technologies has been presented. The concept includes data acquisition using a three-dimensional image based documentation and measurement system which provides metric 3D images for the evaluation of rock outcrops. This evaluation results in definition of the discontinuity system of the considered rock mass. Further algorithmic processing of the evaluation allows for the identification and analysis of blocks in a rock face.

Several benefits can be gained from the application of this method:

- Objective documentation of rock mass conditions
- Fast analysis of critical rock slopes
- Assessing the potential volume of rock fall
- Optimising the support measures
- Optimising the shape of the excavation
- Prediction of discontinuity-controlled overbreak in tunnelling

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Authors

Markus Pötsch, Institute for Rock Mechanics and Tunnelling, Graz University of Technology, Rechbauerstraße 12, A-8010 Graz, Austria, email: m.poetsch@tugraz.at; Andreas Gaich, 3G Software & Measurement GmbH., Plüddemanngasse 77, A-8010 Graz, Austria, email: office@3gsm.at