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Computer based stability analysis of rock slopes in a blocky rock mass

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ABSTRACT: Discontinuity network and keyblock analyses are important methods for the determination of rock mass behaviour and stability. Due to high mapping efforts and restricted access only data from selective discontinuities are available for these analyses. This paper presents a method for a complete determination of the discontinuity network of a rock mass and further analyses. The focus is set on rock slope engineering. The data acquisition and evaluation is an image-based process using the *JointMetriX3D* system. The slope analysis focuses on keyblock identification and kinematics including trace network analysis, determination of block loops, and determination of block removablility. An outlook is given on further capabilities of this approach such as analysis of united keyblocks, rotational kinematics, and applications in rock slope engineering and mining.

1 INTRODUCTION

A rock mass containing a considerable number of discontinuities whose strength is low compared to the rock material is referred to as a blocky rock mass. The behaviour of a blocky rock mass is dominated by the properties of the discontinuity system. Despite its importance the determination of the discontinuity properties is subjected to several restrictions. The location of orientation measurements requires a reasonable access within the reach of the geologist and without being threatened by rock falls. This implies that measurements are only taken on selective discontinuities which results in a biased and incomplete data acquisition. Orientations are represented in stereonets including statistical evaluations. Spacing and persistence is less frequently determined; the location of discontinuities cannot be determined with sufficient accuracy. Due to these shortcomings analysis methods treat only general kinematics of rock structures such as stereonet analyses for sliding or toppling failures. Detailed stability analyses of blocks have not been possible.

A new approach to overcome the described problems is currently under development. This paper outlines the general process of the determination of discontinuity properties and the benefit for advanced discontinuity system analysis. A geometrical model has to be established which is based on the acquired and measured data. The model must contain the relevant information and be able to correctly predict the failure modes.

2 ELEMENTS OF DISCONTINUITY NETWORK ANALYSIS

2.1 *Discontinuity data acquisition*

The *JointMetriX3D* documentation and measurement system provides 3D images of exposed rock faces representing the geometry of the surface and its geological assembly. The size of the 3D images captures the entire region of interest, i.e. a complete image of the rock mass structure is obtained.

A digital panoramic camera with a resolution up to 100 Megapixels acquires two images of the considered rock face from which a highly detailed 3D image is computed. The process includes digital image processing, photogrammetry, and computer graphics together with data management skills (Gaich, Fasching & Schubert 2003). The camera positions can be individually selected. Therefore, the system is adaptable to different sizes and geometries of rock faces. Rock faces with a height up to 300 m have already been recorded from distances up to several hundreds of metres.

The computed 3D images are used to determine the discontinuity system of the considered rock mass. Applying the assessment tool *JointMetriX3D Analyst* several measurements can be taken in the 3D images. Discontinuity traces are identified as lineaments and areas. The evaluating geologist marks the identified elements which belong together directly on the 3D image and obtains information about their spatial location, orientation, and length. Evaluating the entire rock face, discontinuity sets can be discriminated and corresponding statistical parameters concerning discontinuity orientation, spacing, and persistence are obtained (Gaich, Schubert & Pötsch 2004).

2.2 *Discontinuity network analysis*

2.2.1 *Establishment of a geometrical model*

For a reasonable analysis a geometrical model has to be abstracted from the evaluated 3D image. The geometrical model contains all relevant information of the geometry of the rock slope and the identified discontinuities. Intersections of planes form the geometry of the slope. Orientation, location and extension of these planes are derived from the 3D image by the use of reference planes. Reference planes approximate the surface of the slope within a defined area. The evaluated discontinuities are intersected with the slope geometry and form the trace network to be analysed. Figure 1a shows a part of a 3D image. The ellipse highlights the rock slope which is going to be considered. After evaluation the resulting discontinuity network is shown in figure 1b. To highlight the discontinuity network the texture and all measurements have been removed from the sketch. Additionally, areas corresponding to reference planes are shown. The evaluated reference planes form the geometry of the geometrical model (Figure 1c). The intersections of the discontinuities with the reference planes represent the trace network.

2.2.2 *Basic keyblock analysis*

Once the geometrical model is established, the trace network is searched for closed polygons (loops) of traces in order to identify the superficial block faces (Lu 2002). The traces are subdivided into stretches between their intersections. Reverse directions are assigned to each trace (directed traces). After randomly selecting the first directed trace, the subsequent traces have to comply with the following two constraints:

- The subsequent directed trace must point away from the endpoint of the current directed trace.
- The subsequent directed trace is the one which forms the maximum right-handed angle with the current directed trace whereby 360° are treated as 0°.

Each loop contains the information about the orientation and halfspaces of both, the discontinuities and free surfaces. Hence, each loop can be analysed to determine the removablilty of the corresponding block. Defining the forces acting on the block it can be analysed with respect to its failure mode (falling, plane and wedge sliding, stable) and stability level (Goodman & Shi 1985).

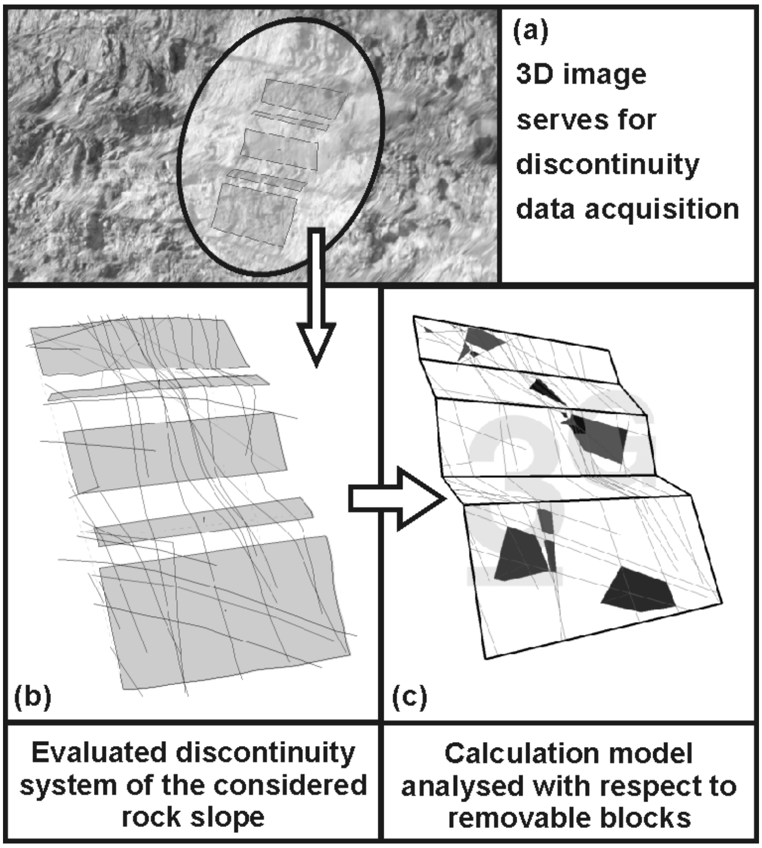

Figure 1. Steps of a slope analysis. (a) Data acquisition by the use of 3D images. (b) Evaluated discontinuity system and areas of reference planes. Texture and measurements are not shown in the sketch. (c) Analysed discontinuity system. The sketch shows the resulting removable blocks with one free surface.

2.2.3 *Advanced analysis features*

Basic keyblock analyses do not cover the entire failure mechanisms which occur in context with rock slopes. Larger unstable areas of rock slopes are identified by analysing the trace network with respect to united keyblocks (Chan 1987). A united keyblock consists of blocks which are not necessarily individually removable. A number of such blocks can form a removable united keyblock (Figure 2). In this way the maximum unstable areas of rock slopes can be determined and support measures designed.

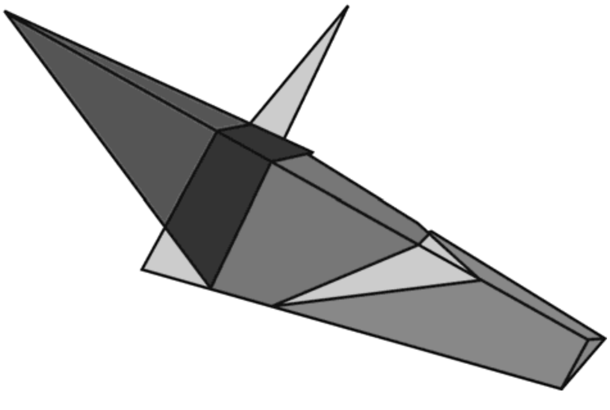

Figure 2. United keyblock formed by several blocks not necessarily individually removable

Basic keyblock analyses treat only translational failure modes. Under certain boundary conditions rotational failure modes dominate the translational boundary conditions. If the kinematical conditions permit rotation, especially blocks with high shearing resistance are prone to rotate. The analysis of the joint pyramids also provides information about the rotatability of keyblocks. Corner rotation, edge rotation and sliding rotation can be distinguished (Mauldon 1992).

3 OUTLOOK

A method has been presented for the determination of discontinuity properties with high quality. The transformation of the information into a geometrical model and the application of kinematical analyses results in a prediction of various failure modes of keyblocks.

Stability analysis can be performed with the predicted keyblocks or united keyblocks. Different load cases such as dead load, water pressure or dynamic loads result in different failure modes and stability levels. The establishment of constitutive laws for rough discontinuities allows determining resisting forces on keyblocks. Since the current geometry of keyblocks can be determined, the requirements on these constitutive laws can be specified. CNL constitutive laws are suitable for keyblocks which are free to dilate. Keyblocks which are restricted in dilation require CNS constitutive laws (Blümel, Button & Pötsch 2002).

With the JointMetriX3D system also the roughness of discontinuities can be recorded. Applying suitable evaluation methods allows a quantitative three-dimensional description of the roughness of the discontinuities (Grasselli, Wirth & Egger 2002). In connection with a constitutive law the resisting forces for stability analyses are accurately determined.

In the design of rock slopes the optimum orientation of the slope can be determined. The design of support measures can be optimised on site. By excavating a slope step by step the discontinuity system becomes visible. The discontinuity network can be frequently determined and analysed as described above. The support is adapted considering the updated model. This results in a safe and economic structure.

The excavation process in quarries can be optimised in terms of stability having a complete image of the discontinuity system by frequent data acquisition. The blasting layout can be optimised when the size and removability of rock blocks is known.

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