From documentation to prediction – a computer-based method for discontinuity analysis and block stability assessment in tunnelling

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ABSTRACT: Tunnel face documentation done by a geologist is a well-established task during tunnel excavation. It mainly serves for the establishment of a geotechnical model and for the "conservation of evidence" for later contractual claims. This contribution describes a method for the documentation of the rock mass conditions, the establishment of a geotechnical model and the prediction of stability of keyblocks. This method is based on a hierarchical procedure which digitally processes discontinuity data from the acquisition to the analysis. The acquisition is performed using a remote sensing system, JointMetriX3D, a three-dimensional imaging system based on photogrammetry. It uses a pair of high-resolution digital panoramic images to establish a metric 3D image of the tunnel face. Geometrical properties are measured from these 3D images serving as the basis for the determination of the discontinuity system of the rock mass. Subsequently a geometrical model is determined which relates the thoroughly determined discontinuity system to the excavation. This geometrical model is analysed with respect to the identification of keyblocks which may result with proceeding excavation. Finally, the stability of keyblocks is calculated. The result serves for decision aids on site and for the final design of excavation and support as well.

1 INTRODUCTION

A rock mass containing a considerable number of discontinuities with low strength 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. In tunnelling the documentation of the faces is performed while construction work proceeds. Due to the pressure of time and the limited access only selected discontinuities are mapped in a manual sketch. Due to the lack of information detailed stability analyses of blocks are not possible to provide an objective basis for the final design of excavation and support. A new approach to overcome the described problems is currently under development. The approach includes the data acquisition process, the establishment of a geotechnical model, and the analysis of keyblocks. The stability analysis of keyblocks in a blocky rock mass is addressed and the important influencing factors such as the keyblock geometry are discussed. This method follows a hierarchical structure which allows for a consistent analysis and objective auditing. An additional benefit of this computer-based method is gained from the high visualisation capability.

2 DISCONTINUITY DATA PROCESSING

2.1 *Discontinuity data acquisition*

The JointMetriX3D documentation and measurement system (Gaich et al. 2004) provides 3D images of the tunnel faces representing the geometry of the surface and its geological assembly. The area 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 tunnel 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 et al. 2003). The camera locations can be individually selected. The typical distance from the tunnel face is around 6 m with a separation of the two locations of around 2 m. From these two images a 3D model is reconstructed using the Shape from Stereo principle. In order to obtain a 3D image the 3D model and one image have to be aligned.

Applying the 3D assessment tool "JMX Analyst" measurements of geometrical properties can be taken directly from the 3D images. Discontinuity traces are identified as lineaments and areas. The length and area, respectively, and the spatial location of the marked elements are instantly available. For identified discontinuity planes the orientations can be determined both from area and linear outcrops. One area element usually covers a number of smaller surface elements from which the mean normal vector is calculated. This magnitude represents the discontinuity orientation which is instantly provided by dip and dip direction and a graphical marker. Having a discontinuity trace with a significant change in depth, i.e. the trace is not observed to be on a planar surface, its dip and dip direction is determined by fitting a plane to the resulting 3D polygonal line. Figure 1 shows an evaluated 3D image of a tunnel face. Discontinuities are represented by linear or area elements. The orientation of traces is represented by an equally oriented spatial triangle. The orientation of the areas is represented by the plane's normal vector.

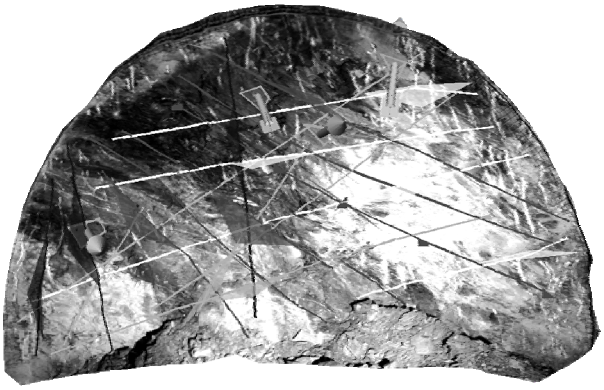

Figure 1: Evaluated 3D image showing discontinuity traces and areas with corresponding orientations.

2.2 *Establishment of a discontinuity network*

In order to establish a discontinuity network accompanying the tunnel excavation, consecutive tunnel faces have to be evaluated. This is done by recording several faces (best every round) using the JointMetriX3D system and generating 3D images. These 3D images are evaluated which allows defining the visible discontinuities. In order to avoid introducing the same discontinuity several times into the network it is necessary to inspect consecutive faces with respect to traces which belong to the same plane.

Face mapping as a data acquisition method (either conventional or by 3D imaging) implies that only discrete sampling locations are available. Depending on the sampling density it is possible that some discontinuities cannot be recorded as they do not appear in the face (especially steeply dipping discontinuities striking normal to the tunnel axis). Therefore, the discontinuity system has to be audited with geological judgement. In order to complete the system discontinuities can be manually introduced.

Figure 2 shows schematically the modelled discontinuity network which has been based on a frequent face documentation and evaluation.

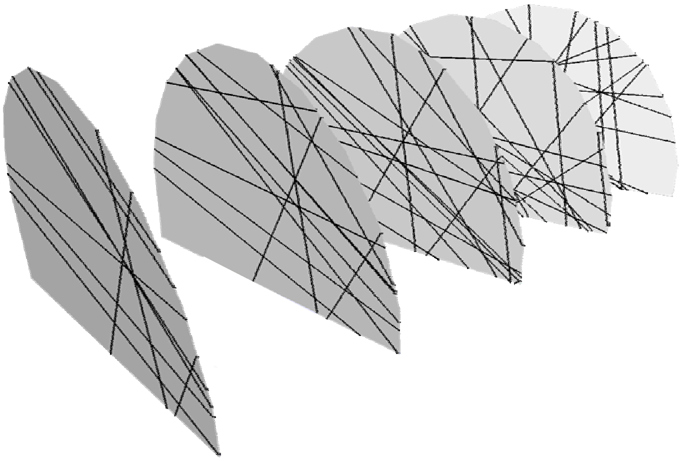

Figure 2: Sketch of tunnel faces at a regular separation of 2.5 m. The traces represent already the modelled discontinuity network.

2.3 *Establishment of a geometrical model*

For the following analysis a geometrical model has to be established which relates the discontinuity network with the excavation geometry. The geometrical model contains all relevant information of the geometry of the excavation and the identified discontinuities. The evaluated discontinuities are intersected with the excavation geometry and analysed from the trace network. Figure 3 shows the geometrical model obtained from acquired discontinuity data.

2.4 *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°.

This trace search criterion is applied to the entire trace map. This results in a subdivision of the tunnel wall into polygons. Each polygon forms part of the free surface of a block.

Since each polygon is formed by discontinuity traces, information about their orientations is assigned. For each polygon the joint and block pyramids are determined. This leads to the analysis of the removablility of the corresponding blocks (Goodman & Shi 1985). Figure 4 shows a removable block in the tunnel face. Compared to commercially available software (for instance Unwedge, PT Workshop) this analysis covers the identification of keyblocks at the tunnel wall, the tunnel face, and the edges of the intersections of wall and face. This is especially important in tunnelling where the rock mass is not supported at the face and the adjacent wall.

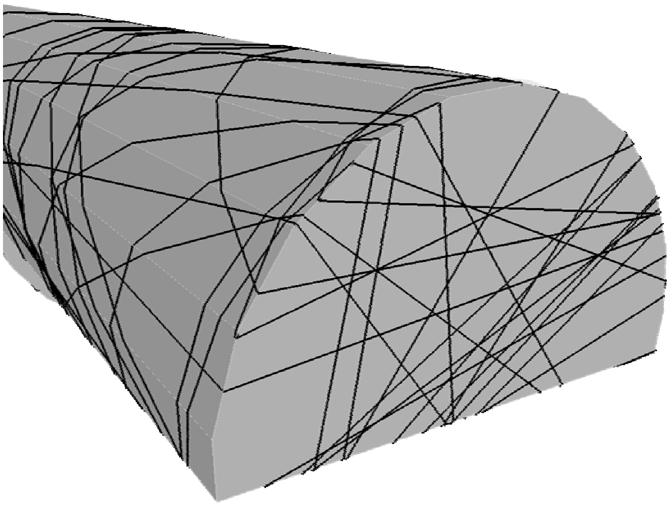

Figure 3: Geometrical model including discontinuity network and excavation

Basic keyblock analyses do not cover the entire block failure mechanisms. A number of blocks which are not necessarily individually removable can form a removable keyblock. These types of blocks are referred to as united keyblocks. Chan (1987) proposes a mathematical formulation for identifying united keyblocks. The drawback of this formulation is that it is applicable only for joint sets containing perfectly parallel discontinuities and one free surface. Its application is therefore restricted to slope analysis problems with a simple geometry of the surface and the discontinuity system. A generalisation for joints sets with non-parallel discontinuities is currently under development.

After determining the kinematically removable blocks they are analysed with respect to their mode of failure. The mode of failure of the block is dominated by the resulting force of the external force system of the block. Block theory provides the analysis of translational failure modes such as falling and lifting, single-face sliding, double face sliding. For instance, the mode of failure of a block whose joint pyramid contains the direction of the resulting force is identified as a falling or lifting block. Criteria for further failure mechanisms are provided by block theory (Goodman & Shi 1985).

Conventional block theory covers the translational failure modes. The force system acting on a block may also result in force couples which induce rotational displacements. Especially under conditions with high frictional resistance rotation is more likely than translation. This fact is relatively simple indicated by the problem of a block on an inclined plane discussed by Goodman & Bray (1976). They proposed criteria for sliding and toppling depending on the (cuboidal) block geometry, the inclination of the base plane, and the frictional resistance. The assumption of an increasing stability level with increasing friction led to a non-conservative design considering only translational failure modes. Mauldon (1992) and Tonon (1998) proposed expressions for the analysis of kinematics, modes and stability of rotations of tetrahedral blocks.

Once the failure modes of the blocks are determined, their stability can be calculated by means of a limit equilibrium analysis. Driving forces can be gravity or inertia forces as well as external water or gas pressure. On the other hand, resisting forces result from friction, clamping or support measures. Traditionally, limit equilibrium calculations provide fast design procedures but are usually conservative. It is inherently assumed that the shear resistance of the joints has fully developed while at the same instance the support provides its maximum bearing capacity.

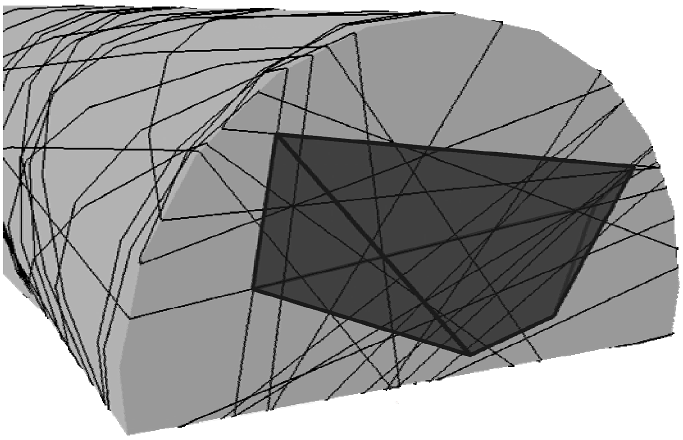

Figure 4: Visualisation of a removable block in the tunnel face

Going further into detail, there is a complex interaction between a block, the surrounding rock mass, and the rock support. If an unstable block displaces along a rough discontinuity, it tends to dilate. If the block is free to dilate, its resistance is increased by the dilation angle of the discontinuity due to the asperities. This fact has been already discussed by Patton (1966). However, if the dilation of the block is restrained, e.g. by the surrounding rock mass, rock support, and as a result of rock mass stress, etc., additional normal stresses can develop and significantly increase the resisting forces (Blümel et al. 2002). On the other hand, forces in rock bolts are mobilised only by displacement of the block. The displacement of the block causes a mobilisation of normal forces in the rock bolts due to dilation of the joints. As a consequence the interaction of driving and resisting forces causes a change of the factor of safety throughout the displacement. This phenomenon predominantly is influenced by the geometry of the discontinuity surface, the strength of the asperities, the geometry of the block, the stress condition and the stiffness of the restraining boundary (support, rock mass, etc.).

Non-linear constitutive models and iterative algorithms have to be applied in order to account for this interaction. Pötsch (2002) proposed an iterative shear model which considers a stiff boundary based on the expression of Barton & Choubey (1977) and Barton & Bandis (1990). Using this model he calculated the factor of safety of pyramidal keyblocks with four discontinuities in the tunnel crown. Figure 5 shows the development of the factor of safety for keyblock displacement under the same initial stress. The different lines refer to different block geometries. This highlights the importance of the accurate determination of the geometry of keyblocks for stability analysis.

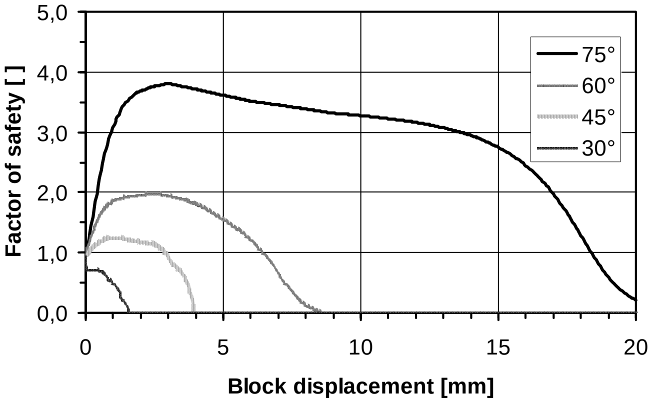

Figure 5: Example for the development of the factor of safety throughout the block displacement. Different lines refer to different dip angles of the planes of pyramidal keyblocks.

3 SUMMARY

A method for discontinuity data analysis for tunnelling has been presented. The method includes the data acquisition process, the establishment of a geotechnical model and the analysis with respect to instabilities of discrete rock blocks. Using the described mapping method by 3D imaging data acquisition is decoupled from the evaluation task – the evaluation can be performed even when actual rock faces do no longer exist. Quantification from 3D images is an indirect measurement principle. Therefore only visually determinable features can be identified in contrast to other parameters, for example discontinuity filling or strength parameters. This results in the measurement of geometrical properties. A 3D image resulting from the JointMetriX3D system represents an objective record of a tunnel face due to its high resolution, true colour, visual information and its three-dimensional information. As presented in this paper information gained from 3D images support and improve rock mass analyses as the data give a realistic impression.

Taking 3D images of a tunnel face in a regular manner leads to a highly detailed and consistent rock mass model. It facilitates the establishment of a discontinuity network. The analysis of this network allows determining the development of the spatial properties along the tunnel alignment and identifying trends. Based on the obtained information the discontinuity system ahead of the face can be predicted. Simulating the excavation process allows determining removable blocks and their stability. This serves as a basis for the final design of the excavation geometry (e.g. round length) and the installed support.

ACKNOWLEGMENT

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