Application of metric 3D images of rock faces for the determination of the response of rock slopes to excavation

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ABSTRACT: Geotechnical analyses in rock engineering practice often rely on simple models. More advanced analysis methods suffer from the lack of information of geotechnical data. Input parameters have to be estimated. If a reasonable estimation is not possible, advanced analysis methods should not be applied. One possibility to improve the geotechnical data acquisition is the application of a remote sensing system and the generation of metric 3D images. Metric 3D images serve as the basis for the assessment of geometrical rock mass properties as well as the size and shape of the outcrop. Evaluations from 3D images facilitate the establishment of a 3D discontinuity network, the determination of discontinuity properties (such as orientation, spacing, trace lengths, etc.) and the geological interpretation. A short review on the development and currently available remote sensing methods is given. The principle of 3D imaging is discussed considering as example the JointMetriX3D system which has been applied in this study. The contribution of data obtained from 3D images to slope analysis methods is described on an advanced block analysis method and the estimation of rock mass properties for numerical analysis.

1 INTRODUCTION

The design of engineering structures related to the excavation and / or support of ground should base on a geological and geotechnical ground model. The final excavation and support is selected according to the response of the ground model to applied excavation geometries and sequences and support measures. Different fields of application will call for different requirements. Permanent civil engineering structures require a more detailed analysis with a higher safety level compared with temporarily existing structures in mining. Nevertheless, the comparison of the response of the ground with the established requirements is common in the design procedures of all fields of application.

The acquisition and evaluation of geological and geotechnical data are integrated parts during the investigation and design stage. This process results in a ground model which contains all relevant information for the design of engineering structures. It serves as input for decision making processes during different phases of projects, ranging from feasibility studies to construction and maintenance.

Traditional methods of geological data acquisition are prone to errors. There are sampling difficulties, human bias, and instrument errors. Time and access restrictions lead to incomplete data sets. As a consequence, the resulting data usually do not allow objectively reproducing the actual rock mass conditions. Especially in mining and underground construction information which has not been recorded, gets lost as the excavation process proceeds.

The presented JointMetriX3D system overcomes those problems and opens new possibilities for optimisations concerning design, safety, and productivity. The core of the JointMetriX3D system is the generation of a high-resolution metric 3D image of a rock surface which is analysed and assessed on a computer. The 3D image is an objective documentation of the rock mass conditions which allows for instantly available geometric measurements at an arbitrary number without access restrictions.

Consistent analysis methods in rock engineering should follow a hierarchical procedure and comply with defined requirements. The contribution of 3D images and corresponding data evaluation to a consistent procedure for rock slopes stability analysis is described, including block and large-scale failure mechanisms.

2 METHODS FOR GEOTECHNICAL DATA ACQUISITION

2.1 *Geotechnical parameters*

Several categories of parameters are applied for describing the properties of a rock mass in situ. These are amongst others mechanical, hydraulic and chemical / mineralogical parameters. Mechanical and hydraulic parameters are particularly influenced by the discontinuity network of the rock mass.

In order to describe the rock mass with its discontinuity network in a comprehensive way, data are collected during a geological / geotechnical survey. Discontinuity-related parameters typically are orientation, spacing, frequency, persistence, aperture / filling width, roughness, waviness, termination index, or the geo-referenced position, as well as the rock surface geometry. These are completed by information concerning distribution of rock types and quality, weathering conditions and specific local phenomena like karstification. All these data can be acquired by visual methods when measuring orientations and distances within a known 3D co-ordinate system (Fasching 2001).

Definitions on certain parameters vary – this contribution follows those given by Priest (1993). A general selection of parameters that is suitable for all possible geological environments is not applicable as it implies that certain features, governing the rock mass behaviour remain unaccounted or features become under- or overestimated (Riedmüller & Schubert 1999). However, several procedures are established in practice and others came up using different kind of technical devices to improve traditional methods which are addressed in the following sections.

2.2 *Traditional methods for geotechnical data acquisition*

Geological documentation can be seen as combination of manual and visual methods. Depending on the type of work, the documented area normally consists of an exposed rock face.

The acquisition process typically results in a freehand sketch of the mapped area representing its main structures. In addition further information is provided by determining the orientation, roughness and rock mass quality. These parameters can be measured only if the considered structures can be accessed, otherwise they have to be estimated. Access can be restricted by various reasons:

- Size is too large.
- Hazardous or dangerous access
- Rock face is subjected to construction work or excavation, e.g. in tunnelling
- Bad weather conditions
- Time

Figure 1 outlines the problem of needed access in surface applications. When mapping has to be done in a larger scale rock mass, e.g. in a quarry, at pit walls, or at slopes it might take considerable efforts to get access, but still there might remain inaccessible areas.

Additional methods for obtaining discontinuity data in the field include the scanline survey and cell mapping which provided statistical measures of the discontinuity network (Priest 1993; Nicholas & Sims 2000).

Figure 1: Mapping in a limestone quarry in Austria. It took the geologist a considerable time to access all areas for getting a significant number of orientation measurements.

2.3 *Advanced methods for geotechnical data acquisition*

There exist several approaches in the past to overcome the problems of needed access and getting a more objective documentation of the rock mass conditions, especially when rock faces are subject to changes when having any outcrop or excavation activity. These methods can be distinguished into image-based approaches and laser scanning. The image-based approaches can be further distinguished by two- and three-dimensional image analyses.

A two-dimensional approach means that just one image of a rock face is used for the analysis. This implies that spatial information such as orientation or referenced co-ordinates cannot be determined. But relative magnitudes such as the delineation of the rock mass can be identified by means of image processing algorithms as well as statistics like relative trace length distributions. A number of authors addressed this topic (Tsoutrelis et al. 1990, Cravero & Iabichino 1993, Crosta 1997, Reid & Harrison 2000, Lemy & Hadjigeorgiou 2003, Franklin et al. 1988).

Three-dimensional imaging means that a surface description in 3D is related to the visual image information. This allows the determination of all visible spatial parameters of the rock mass. If a 3D image is also related to a given co-ordinate system even metric measurements become possible. The principle behind is discussed in 2.4. First approaches used images, taken either by photo-theodolites (Linkwitz 1963) or photogrametric cameras (Rengers 1967, Vieten 1970). The two images with different perspective were realized by means of a rigid setup that carries two cameras and usually a bar that defines the base-length which is defined as the distance between the two cameras. The base-length determines the working distance for such a system ranging from about 5 – 30 times the base-length. The same setup for a close range application was addressed by Hagan (1980) where he performed deep-mine rock structure studies of fracture type, frequency, orientations, infilling, persistence, and surface properties. A more recent application of the principle using digital cameras is described by Roberts & Poropat (2000). It demonstrated that orientation measurements for mapping a high rock wall can be derived from standard digital images.

However, there are some properties that are peculiar for image-based data acquisition:

- Objectivity of the document
- Potential to reduce mapping time
- Data acquisition in inaccessible areas
- Acquisition of a statistically sufficient amount of samples
- Processing and assessment of data in the office without time constraints
- Permanent record for review purposes

Laser scanning allows a quick determination of a probably large number of single 3D point measurements on a rock surface. This “point cloud” has to be processed into a surface description leading to a 3D surface model. From this model orientation measurements can be taken as well as any distances or surface areas as addressed by Feng & Roeshoff (2004) and Lemy & Hadjigeorgiou (2004). A general drawback of this method is the missing image information that would help to identify either interactively or by algorithms, geotechnical relevant locations for measurements.

A combination of a laser scanner and imaging was performed and described by several authors. Feng et al. (2001), Kemeny et al. (2003) or Slob et al. (2004) used a combination of a single digital image and a laser scanner which allowed to measure in 3D and to identify rock structure. Limitations to such systems so far are the limited resolution of the digital image and therefore loss of resolution in the resulting 3D image and bounded operational area for the laser scanner (not suitable for close range and not for longer distances). Besides, current laser systems are expensive.

2.4 *The JointMetriX3D system*

The JointMetriX3D system represents a three-dimensional image-based approach. JointMetriX3D uses high-resolution digital images from which referenced, metric 3D images are computed. It uses a single high-resolution panoramic image scanner that is used to take two images sequentially, and the so-called Shape from Stereo principle to reconstruct the 3D surface of an object. A more detailed description is given in Gaich et al. (2004).

The system includes all advantages of an image-based documentation approach but has additionally a wide operational area, since the base-length between the images can be chosen freely allowing working distances from below one metre up to several hundreds of metres.

The actually used imaging system is a rotating line-scanner. It has three CCD arrays one for each of the colour channels red, green, and blue. Each of the arrays has more than 5300 sensor elements which is a determinant magnitude for the resulting resolution.

The scanner is mounted on a tripod and controlled by a field notebook computer that instantly stores the acquired image data. During imaging, the scanner rotates along a defined axis taking the panoramic image column by column. This principle decouples the vertical field of view (depending on the used lens) from the horizontal one (depending on the rotational motion) which allows capturing rock faces of various shapes and sizes in optimal resolution. Figure 2 outlines the imaging principle when using a panoramic line-scanner.

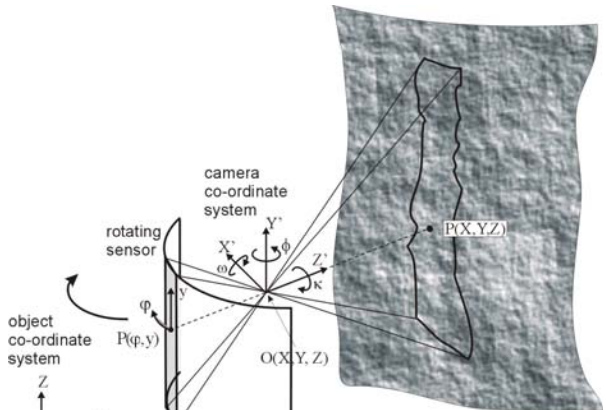


Figure 2: Geometry of panoramic line-scanning.

Panoramas taken with the system have a size of about 100 million picture elements (megapixels). It is crucial for the visual interpretation to have fine details visible in the image. The vertical field of view (typically the object height) in metres is divided by the number of sensor elements (5300). Therefore, the resolution depends on the imaging height, but does not relate to the horizontal extend of the object or the working distance. Resolution therefore ranges from millimetres (one quarry bench) up to several centimetres (high slopes). If resolution is not sufficient yet, it can be increased by dividing the area into several (horizontal) sections which are merged together.

The generation of a 3D image uses principles of classical photogrammetry (Slama 1980) complemented by insights from computer vision where among others the calibration of off-the-shelf cameras was addressed (Faugeras 1993). Having two images of the same region taken from different angles the Shape from Stereo principle is applicable. This principle allows to reconstruct 3D points from their corresponding image points in the stereoscopic image pair that were taken from two different locations.

Several tasks are required before a 3D image is ready (cf. Gaich 2001):

- Calibration of the imaging system
- Determination of reference points
- Identification of corresponding image points (image matching)
- Computation of 3D point cloud (spatial intersection)
- Connection of the 3D points to a surface mesh (triangulation)
- Geometric alignment of image and mesh
- Referencing of the 3D image (to a superior coordinate system)

3 ASSESSMENT OF 3D IMAGES

Once a 3D image is ready, measurements can be taken from it. A purpose-built 3D software is used that allows to inspect a 3D image from any designated side. As the system allows 3D measurements that lead to geometric magnitudes in a given coordinate system, all descriptive rock mass parameters that base on geometric information of a rock face and the discontinuity network can be derived

3.1 *Directly measured properties*

Geometric measurements are taken by placing graphical markers onto the 3D image. These markers denote points or regions of interest, e.g. visible discontinuity traces or discontinuity surfaces. All measurements taken from the 3D image are inherently three-dimensional and digital and in the given coordinate system (Figure 3).

Discontinuity traces as well as lithological borders or geological strata are marked by linear elements providing instantly the true lengths. Any region within a 3D image can be annotated by an arbitrarily defined closed polygonal. The sample points of the polygonal are determined directly from the 3D surface which brings the marked region also into 3D. The area is instantly provided in square metres. 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 3D trace. The plane is visualised as a spatial triangle that intersects the 3D surface as indicated in Figure 3.

An additional tool is the tape measure. By marking two points on the surface it provides the Euclidean distance as well as the distance along the surface and the difference of height.

3.2 *Derived properties*

The measurements taken from the 3D image are grouped to sets by the user. Each set can be visualised in stereograms in order to provide an instant impression of the distribution of the orientations. The stereograms deliver also some statistical figures, such as the spherical aperture or the cone of confidence for each discontinuity set.

For each discontinuity set, the spacing and its statistical properties can be determined. Spacing in this context is referred to as normal spacing, according to definitions given by Priest (1993). A plane of projection perpendicular to the set's mean orientation is automatically determined which ensures that the normal spacing is determined instead of the apparent spacing which would depend on the actual shape of the surface and the observation angle. All discontinuity traces of a set are intersected with this plane of projection. The distance between adjacent discontinuities is measured automatically along scanlines parallel to the mean normal vector.

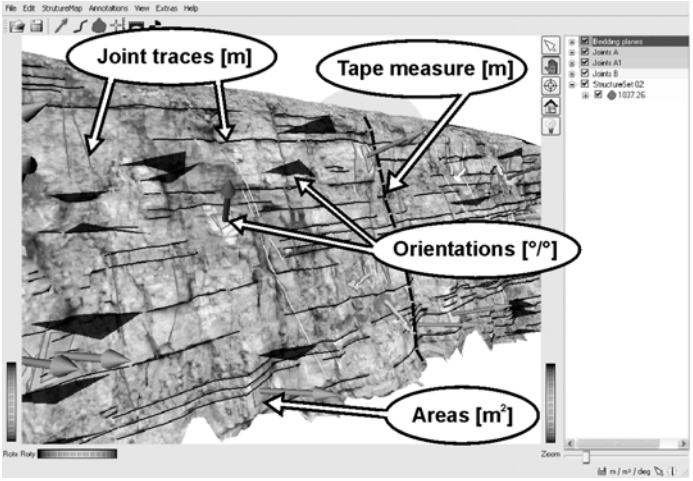


Figure 3: Directly measured rock mass properties in a 3D image including traces, areas, orientations, and the tape measurement

4 ANALYSIS OF THE RESPONSE OF THE ROCK SLOPE

4.1 *Definitions and requirements*

The excavation of rock, e.g. for road cuts or during the mining process causes a change of the boundary conditions of the rock slope. The engineering challenge is the determination of the behaviour of the slope and the prediction of the stability conditions as well.

Goodman (2003) and Goodman & Kieffer (2000) propose a hierarchical procedure for the determination of rock slope failure modes. The hierarchy focuses primarily on the kinematical conditions of the slope and subsequently on stress-related failure modes. It includes the investigation of

a. Weathering and erosion
b. Translational sliding of blocks
    - single face sliding
    - wedge sliding
c. Rotation and rotational sliding of blocks
    - backward rotation (block slumping)
    - forward rotation (toppling)
    - torsional sliding
d. Cracking or deformation to free incomplete blocks
e. Rupture of rock without associated block movements

The points b. and c. are primarily derived from kinematical analyses which are based on the discontinuity system and the slope geometry rather than on the mechanical properties of the rock material. Point d. requires an analysis which deals with the block kinematics and the resistance of rock bridges. Failure modes classified under point e. correspond to stress induced modes and include the development of failure surfaces. These types of failure typically occur in high slopes where the rock mass strength is weak compared to the driving forces. Point a. failure modes imply climatic impacts and physical-chemical resistance of rock. They are not addressed in this paper.

Button & Schubert (2003) discuss the requirements for site investigation, the determination of failure mechanisms and preceding triggering mechanisms, and material parameters. They strongly recommend the establishment of a geological site model as the basis for subsequent analysis and to support communication between the project-oriented staff, such as geologists, geophysicists, geotechnical engineers, and structural engineers.

The application of three-dimensional images allows for determining the geometry of a rock slope as well as the discontinuity system of a rock mass. This facilitates the establishment of a geological model, the discontinuity analysis, and the performance of kinematical and stability analyses.

4.2 *Block failure modes*

In order to perform a consistent analysis a geometrical model is abstracted from the established geological model using a purpose-built software. This software allows constructing complex slope geometries which are common for instance in mining.

The geometrical model contains all relevant information about the slope layout and the discontinuity system (Figure 4). The represented structures are processed from the assessed 3D images. The discontinuity system is represented by its trace network on the slope surface. It provides the location, extension and orientation of all considered discontinuities.

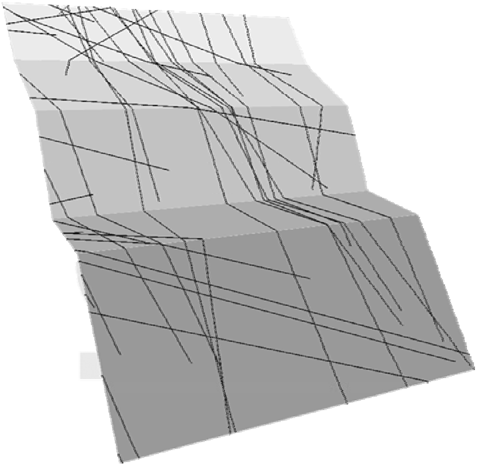


Figure 4: Geometrical model of a slope containing the relevant discontinuity system and the slope geometry

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°.

The trace search criterion is applied to the entire trace map. This results in a subdivision of the slope surface into polygons. Each polygon forms part of the free surface of a block. Figure 5 shows the resulting polygons of the trace map shown in Figure 4.

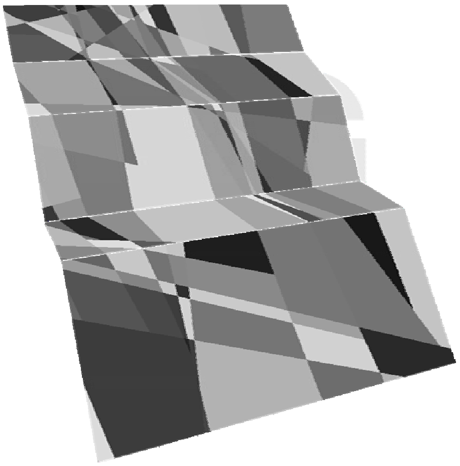


Figure 5: Closed polygons representing the free surface of blocks.

Each polygon contains the information about the orientation and halfspaces of both, the discontinuities and free surfaces. By determining the joint and block pyramids each polygon can be analysed to determine the removablilty of the corresponding block (Goodman & Shi 1985). This is applied for blocks with one free surface as well as for those at edges (two free surfaces), corners (three free surfaces), and more complex slope geometries. Figure 6 shows the kinematically removable blocks with one free surface for the trace map shown in Figure 4.

Basic keyblock analyses do not cover the entire block failure mechanisms which can occur in rock slopes. 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. A generalisation for joints sets with non-parallel discontinuities is currently under development.

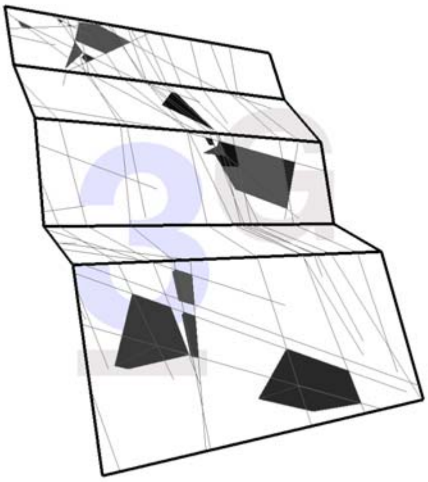


Figure 6: Kinematically removable blocks with one free surface.

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 (cubical) 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.

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 slender block geometries, rock support, or 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, support forces are mobilised only by displacement of the block (provided that the support is not pre-stressed). The displacement causes a mobilisation of normal forces in the support 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, and the stiffness of the restraining boundary (support, rock mass, etc.) as well. 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). This model has several drawbacks with respect of the description of the roughness of a joint. More complex models proposed by Grasselli & Egger (2003) or Lopez et al. (2003) include the real three-dimensional surface of a joint. Grasselli & Egger (2003) used also photogrammetric methods to determine the geometry of the joint surface. Figure 7 shows a 3D image of a rough joint surface reconstructed by the JointMetriX3D system.

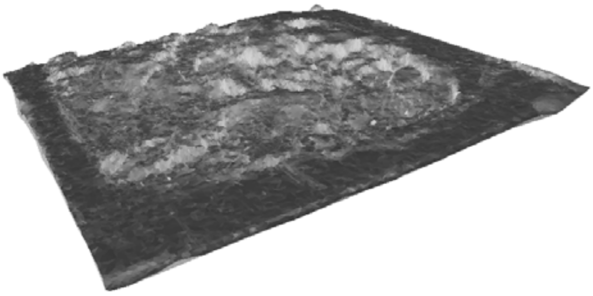


Figure 7: 3D model of a discontinuity at laboratory scale

4.3 *Large scale failure*

Block analyses consider the volume of blocks or united blocks, respectively. They form the basis for the design of road cuts or rock support, the assessment of rock fall hazards, or bench height and orientation in mining pits. At larger scales such as landslides or deep mining pits (Figure 8) the slope can fail due to rupture of the intact rock and the formation of continuous failure surfaces. An influencing factor for the development of this kind of failure is the relation between the height of the slope and the strength of the rock mass. In high slopes the influence of single discontinuities decreases and a jointed rock mass tends to behave as a homogeneous material (but not necessarily isotropic). For that kind of analysis numerical models are convenient, anyhow, the quality of the result strongly depends among others on the quality of the input data. Using continuous numerical models the input parameters usually represent homogenised rock mass properties. One of the most difficult engineering tasks is the proper estimation of the homogenised rock mass strength and deformability. Forward analysis is usually done by rock mass characterisation and classification (Sjöberg 1999).

Figure 8: The footwall of the Aitik copper mine from a depth of around 350 m. The ultimate depth will be at 500 m. In the background several block failures affecting bench stability can be observed. The entire slope has to be designed for large scale failure.

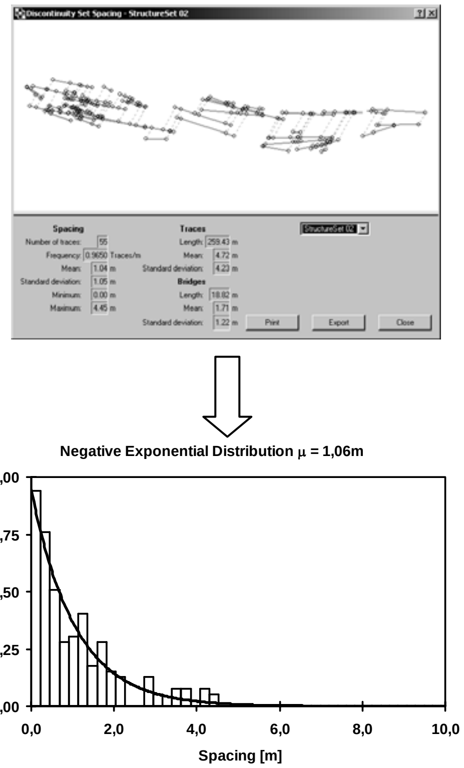
Metric 3D images allow for identifying and mapping of large-scale structures (faults, shear zones, highly persistent discontinuities), joint set properties, and the determination of the location and extent of lithological units (if they can visually distinguished). Therefore, evaluations using JointMetriX3D form the basis for a consistent derivation and estimation of rock mass strength and deformability. Figure 9 shows a statistical analysis of the spacing of one joint set.

A measure for blocks size or fracturing can be derived by determining the spacing for all joint sets. Beside experience and engineering judgment it forms an objective input value for the estimation of, for instance, a GSI value.

In case of discontinuous numerical models the discontinuity network obtained from evaluations of 3D images allows for the establishment of two- or three-dimensional block models (including the orientation, location, frequency, and persistence of discontinuities), as well as estimating the values of the input parameters of the constitutive laws for discontinuities.

5 CONCLUDING REMARKS

The described system allows recording rock faces of various sizes in a reproducible, objective way. Without needing knowledge on photogrammetry but with experience in geotechnical data acquisition one acquires relevant parameters of a rock wall quickly and preserves this way the complete (visual) information of the encountered rock mass conditions.



Discontinuity Set Spacing - StructureSet 02

Spacing
Number of traces: 55
Frequency: 0.9650 Traces/m
Mean: 1.04 m
Standard deviation: 1.05 m
Minimum: 0.00 m
Maximum: 4.45 m

Traces
Length: 259.43 m
Mean: 4.72 m
Standard deviation: 4.23 m

Bridges
Length: 18.82 m
Mean: 1.71 m
Standard deviation: 1.22 m

StructureSet 02

Figure 9: Automatically generated sketch of joint traces and determination of distances leads to a statistical description of the spacing property of one joint set.

Using this approach, the data acquisition task is decoupled from the analysis task – the analysis can be performed even when the actual rock face does no longer exist.

Quantification from 3D images is an indirect measurement principle that allows to quantify visually determinable rock mass structures, in contrast to others, such as discontinuity filling or strength parameters. However, indirect measurements increase safety as measurements can also be taken at inaccessible and possibly hazardous locations. A 3D image resulting from the system represents an objective record of a rock face due to its high resolution, true colour, visual information and its three-dimensionality. It is even possible to support rock mass analyses from a remote location, as the data give a realistic impression to the observer.

Taking 3D images of a rock face in a regular manner, leads to an improved rock mass model that supports the understanding of the observed behaviour and serves as input for decisions on excavation and support on site. This specially bears the potential for saving construction cost since decisions on site are improved if more information on the ground conditions is available. Unbiased and reproducible records of the rock mass conditions can also be a valuable asset in claim support and defence. Taking 3D image in quarries or open pit mines brings more information for the stability assessment and the quality of blasts. Repeated applications allow the determination of the exploited volume.

The JointMetriX3D system can also be applied on larger scale surfaces, such as 300m high walls imaged from a distance of several hundreds of meters which allows an assessment of even hardly accessible slopes.

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