Data acquisition in Engineering Geology

An Improvement of Acquisition Methods for Geotechnical Rock Mass Parameters

By Alfred Fasching, Andreas Gaich and Wulf Schubert

Datenerhebung in der Ingenieurgeologie

Die Beschaffung und Auswertung von geotechnischen Daten wird bei über- und untertägigen Bauprojekten in der Regel systematisch durchgeführt. Die geotechnischen Daten dienen als Grundlagen für Entscheidungen während der gesamten Projektabwicklung – von der Machbarkeitsstudie bis zur Bauausführung und der Erhaltung. Die derzeit routinemäßig durchgeführte Art der Datenerfassung hat eine Reihe von Einschränkungen. Unzulänglichkeiten in der Qualität der Daten werden durch individuelle Fähigkeiten der agierenden Personen, durch Schwierigkeiten in der Erreichbarkeit von Aufschlußflächen sowie durch Zeitknappheit bedingt. Dazu kommt, daß nicht dokumentierte Daten – zum Beispiel durch Ausbruchsarbeiten beziehungsweise durch den Einsatz von Stützmitteln – unwiederbringlich verloren gehen. Die Aufbereitung und Auswertung der Daten ist zeitaufwendig. Dadurch können Daten für numerische Berechnungen nicht laufend zur Verfügung gestellt werden. Zur Verbesserung der geotechnischen Dokumentation und Datenauswertung wurde ein digitales stereoskopisches Aufnahmesystem entwickelt. Dieses System ermöglicht die Erfassung einer Großzahl von geotechnischen Parametern durch interaktive Bildauswertung in 2- und 3 D. Durch dieses System können unter anderem Grundlagen für die Modellierung von Gebirgstypen, die geometrischen Eingabeparameter für numerische Berechnungen auf der Baustelle sowie für eine anschauliche Darstellung komplexer Strukturen erhoben und zur Verfügung gestellt werden. Das System wurde bei unterschiedlichen Bedingungen über- und untertage sowie für die Analyse von unterschiedlichen geologischen Verhältnissen eingesetzt und getestet. Die Ergebnisse zeigen, daß das entwickelte digitale stereoskopische Farbbilderfassungssystem sowie das interaktive Bildanalyseverfahren eine umfassende und reproduzierbare Dokumentation und Auswertung geotechnischer Daten ermöglichten.

Acquisition and evaluation of geotechnical data are integrated parts of subsurface and surface construction works. Geotechnical data serve as input for decision processes during all phases of projects, ranging from feasibility studies to construction and maintenance. The present system of data acquisition, specifically applied during underground construction works, has a number of constraints. Sampling bias may be caused by the "human factor" of individual capabilities, inaccessibility of the rock exposure and time limitations. In most cases data are irrecoverable when excavation proceeds or support has to be applied. Data processing and evaluation is time consuming so that input data for numerical calculations cannot be provided on a daily basis. To overcome the listed shortcomings a digital stereoscopic colour imaging system has been developed which enables the evaluation of a large number of geotechnical data by interactive two and three dimensional image analysis. Among others the data can be utilised for innovative modelling of rock mass structure, for provision of geometrical input data for numerical simulations performed on site as well as for a descriptive visualisation of complex structural conditions. The developed hard and software components have been tested in different environments and on different rock mass types to investigate their general suitability and effectiveness. The achieved results yielded that digital stereoscopic imaging and image evaluation are suitable for an almost complete and reproducible documentation of the structural inventory of rock surfaces, and are most effective for acquisition of geotechnical data.

Acquisition and evaluation of geotechnical data are integrated parts of sub-surface and surface construction works, prior to, as well as during their execution. Decisions about feasibility, design and construction depend to a certain extent on the predictions made on the basis of acquired data. Evidently the quality of data has a direct influence on its interpretation and consequently on predicting engineering consequences. Specifically assessments concerning the distribution of different rock mass types, defined by distinguishable properties like lithology, rock mass structure, tectonic influences, ground water conditions and mechanical and rheological parameters will always be afflicted with uncertainties until construction. These uncertainties within the geological appraisement consequently lead to an increase of uncertainties within the geotechnical design, all the more when numerical modelling is based on those uncertain model parameters (1).

The acquisition of geotechnical data from a rock surface, disregarding if it is a natural or artificial one, is always influenced by three limitations, which are the human factor accessibility and time.

➩ There is no data acquisition system existing which has the versatile capabilities of the human being. The ability to view and move simultaneously to survey a rock mass in three dimensions from a range of distances, locations and angles, to touch and probe the rock exposure, to make comparisons with features observed elsewhere instantaneously,

Fig. 1 Rotating CCD line-scan camera mounted on a tripod for imaging with flexible base width.

Bild 1 *Rotierende CCD Zeilensensorkamera für stereoskopische Aufnahmen mit flexiblem Basisabstand.*

are not achievable by an automatic data collection system. But it has also to be considered that humans are susceptible to subjectivity and personal bias. Humans may have different education, degrees of experience and motivation; they work relatively slowly and can get bored or tired, particularly when working under adverse environmental conditions (2).

- Excluding flat rock surfaces, like foundation areas, accessibility is mainly limited to a strip of some 2 m height as a maximum. This area at the toe of a rock surface, steeply inclined to the vertical, can be covered by the geologist without auxiliary equipment. Within this area, data can be collected which is relevant for the description of the rock mass concerning rock type, rock mass structure, weathering etc. Data from the remaining part of the rock exposure can be collected by visual inspection only.
- With the exception of natural rock surfaces, uninfluenced by or prior to excavation activity, the time available for data acquisition is rather limited. This limitation may be caused by the total available time for data collection within a project or by the working cycle of rock excavation for tunnelling or slope excavation.

The limitations mentioned above, result in the collection of incomplete and highly biased data that influence all further evaluations and conclusions. This can only be overcome by using an alternative data acquisition and evaluation system, which can at least handle the major part of the required data and provide information of much higher quality. An important aspect, which has to be considered when looking for an alternative data acquisition system, is the chance for acceptance and integration into a routine working cycle at a construction site. Any alternative from the "human" data acquisition system is less versatile and disturbs the working process more. Over and above an extra system causes additional cost. Therefore an alternative system has to be quick enough and the resulting data must surpass the expenses.

Parameters for rock mass characterisation and modelling

The purpose of data, collected during the geological/geotechnical survey is to describe the encountered rock mass in a comprehensive way. The data should allow for the classification of the rock mass concerning lithology, structural conditions and rock mass quality, in combination with results of geotechnical monitoring programs. From these data the rock mass behaviour should be derivable, utilising the data in combination with evaluation programs for displacement monitoring data (3) or for prediction of displacements in tunnelling (4). Rock mass modelling and numerical simulation, based on such data, should result in the most realistic results concerning the interaction between rock mass and construction works.

Geotechnically relevant parameters, particularly important for rock mass modelling are discontinuity related data such as orientation, surface geometry, spacing, frequency, size, aperture/filling width, termination index or the geo-referenced position, i.e. in relation to a world coordinate system. The data are completed with information concerning distribution of rock types, weathering conditions and specific local phenomena like karst. All these data can be acquired by visual methods when measuring of orientations and distances within a known 3D coordinate system is provided.

Fig. 2 Proprietary imaging system consisting of two rotating CCD line-scan cameras as mounted on a vehicle for stereoscopic imaging (synchronous operation of both cameras, fixed base width).

Bild 2 *Aufnahmesystem (Eigenentwicklung) bestehend aus zwei rotierenden CCD Zeilensensorkameras für stereoskopische Bilderfassung in einem Arbeitsschritt mit fixem Basisabstand.*

Data acquisition by computer vision

Computer vision can be understood as connecting a computer with (digital) cameras and processing the images on it. Three-dimensional computer vision is inspired by human perception and tries either to reconstruct objects from images or to understand the contents of a scene (5). The image quality is an essential design criterion for a computer vision system. For geotechnical data acquisition the following basic needs are defined:

- Instant image processing directly at the site which brings the need for digital images.

- Image resolution of about 2 to 3 mm on the rock surface (object space) to identify smaller structures which requires image sizes beyond customary digital cameras.
- Colour information to identify lithological boundaries, weathering.
- Stereoscopic camera configuration which is the basis for metrics.
- Metric measurements with an accuracy at least in the cm-range.
- A geo-referencing mechanism, which allows measurements in relation to the surroundings.
- Data acquisition within minutes, important e.g. at tunnel construction sites.

These challenging specifications are not to fulfil using standard off-the-shelf cameras. In order to get a solution at reasonable cost the specifications led to the design and construction of a proprietary imaging system based on panoramic line-scan cameras.

The panoramic imaging system

System description

The imaging system is composed by one or two proprietary panoramic line-scan cameras. The cameras are driven by stepper engines and mounted on a tripod (Figure 1) or on top of a vehicle (Figure 2). By rotation of the line-scan cameras the object space is scanned, thus the scene has to be static. Such panoramic cameras allow to solve a contradiction: they combine a high resolution in the object space which is achieved by using lenses with longer focal lengths with a large field of view which normally requires shorter focal lengths. The cameras can take panoramic images up to 360° field of view. Such images have a size up to 27 000 x 6 000 pixel at full resolution, which means a raw image size of 460 MB for one single colour image. The system was already applied to record rock mass exposures in subsurface environments and in quarries delivering high-resolution stereoscopic images where measurements can be taken from.

Measurement from images

In order to measure from the images the perspective geometry of the cameras, the so-called internal orientation must be known. The internal orientation includes the focal length, the geometric distortion of the used lens, and the position of the principal point (6). Once these parameters are known metric measurements can be taken within the scope of two different co-ordinate systems:

- Camera co-ordinate system (no geo-reference): The imaging system itself defines the coordinates, i.e. measurements do not relate to the surroundings. But relative measurements within a single image pair are valid and have physical reality. This is the simpler configuration, which

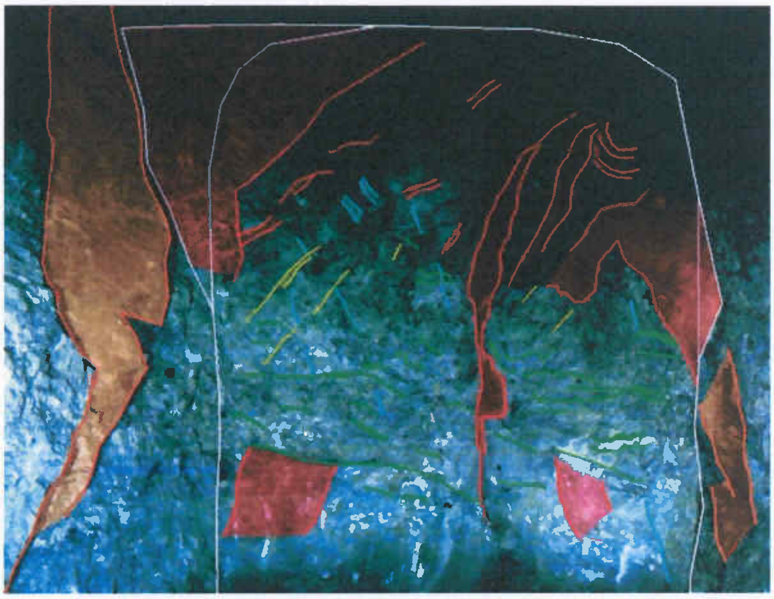


Fig. 3 Image taken in a drift tunnel in the RHI mine in Breitenau, Austria (red: fault planes, green: foliation planes, blue and yellow: joint planes, orange: fault planes in the sidewall areas, white: cross section with over break areas).

Bild 3 *Aufnahme einer Tunnelortsbrust im RHI Bergbau Breitenau, Österreich (rot: Störungsflächen, grün: Schieferungsflächen, blau und gelb: Kluftflächen, orange: Störungsflächen im Bereich der Ulmen, weiß: Tunnelquerschnitt mit Überprofilen).*

requires no other positioning system. But it is sufficient for many geotechnical analyses, like the evaluation of a single rock wall that uses measurements of structures only in relation to each other. Since the measurements base on panoramic images the field of view might be 120° without any problems, thus long drawn-out rock walls can be acquired.

➪ Object co-ordinate system (geo-referenced): Structures are measured in relation to a given (external) object co-ordinate system. To achieve this, the so-called exterior orientations of the cameras within the object space must be determined. The exterior orientation of a camera is defined by the location of the centre of projection and the pose of the optical axis. By observing at least three non co-planar control points (points with known co-ordinates in the object space) the exterior orientation can be determined (6). This process was adapted for panoramic line-scan cameras (7,8). In the case of tunnel construction sites, control points already exist. Since commonly applied reflection targets are used for displacement monitoring it is quite natural to use them to determine the camera orientation.

Using the parameters of the interior and exterior camera orientation the three-dimensional reconstruction of surface points becomes possible. The points are connected to a surface description and combined with geometrical structures originating from rock mass discontinuities, which finally leads to three-dimensionally defined geotechnical parameters.

Image analysis

Interactive structural analysis

A single rock mass image from a stereoscopic pair is used to interactively annotate geotechnically relevant structures identified within the rock mass. This approach was plurally used in the past in order to digitise structural (2D) information from conventional photographs (9, 10, 11, 12).

The major problem in automatic identification of discontinuities originates from changing rock mass conditions and the task to determine the geotechnically relevant (or significant) structures. Fully automatic approaches do not deliver satisfactory results at present (13, 14). Too many parameters in a chain of processing steps influence the final results and have to be set individually. Current analysis tools are not robust to be adaptive to varying rock mass conditions. Therefore an interactive analysis performed by an experienced geologist is proposed. Using software that allows the handling of the images, traces of discontinuities can be marked. These structures are displayed as graphical overlays on the original images. Internally they are grouped to manage discontinuity sets and are stored in a hierarchical manner, which simplifies the computation of statistical values. Figure 3 shows a tunnel face and the 2D structural map of the main joints grouped into four discontinuity sets. It took an experienced geologist about five minutes to come to this result, which is now metrically correct and based on a reproducible 3D model.

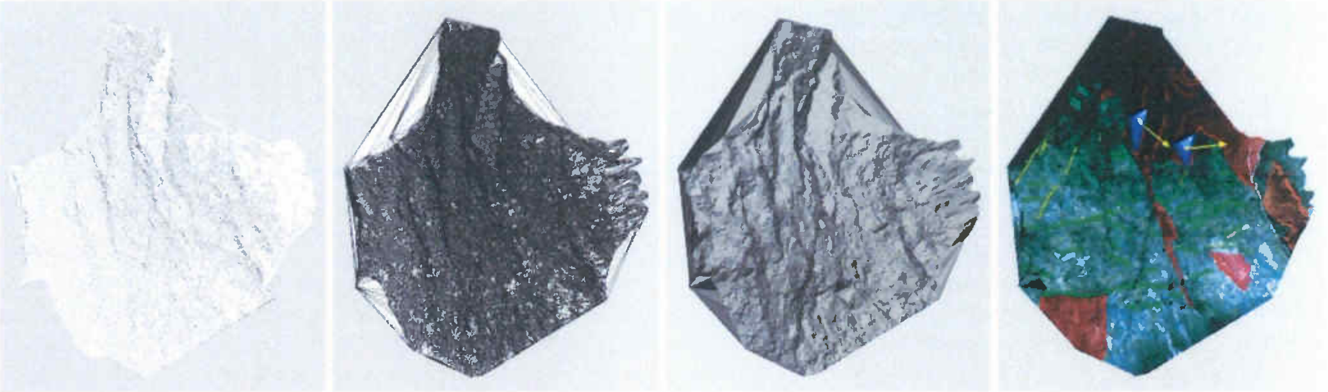


Fig. 4 Surface reconstruction and display of results: a) 3D point cloud, b) triangulated surface model, c) shaded surface model, d) textured surface reconstruction with discontinuity orientations.

Bild 4 *Oberflächenrekonstruktion und Ergebnisdarstellung: a) 3D Punktwolke, b) triangulierte Oberflächenrekonstruktion, c) schattiertes Oberflächenmodell, d) texturiertes Oberflächenmodell mit Trennflächenorientierungen.*

Stereoscopic vision

A major support for the interactive analysis is the use of stereoscopic vision that allows to inspect the images three-dimensionally on the computer.

The two images of the rock mass exposure are simultaneously displayed and separated for each eye by means of graphic's hardware (e.g. synchronised shutter glasses) which enables three-dimensional perception (15). This allows a better assessment of ambiguous regions. In the working process the mode is switched between two-dimensional annotation and three-dimensional vision.

Automatic surface reconstruction

Surface reconstruction allows recovering the three-dimensional shape of the rock mass exposure. Starting from the stereoscopic image pair, three steps are performed:

- Matching is the process of identifying corresponding points within the image pair. This task is an important basis for the quality of the reconstructed surface: the denser – and more accurate the point correspondences – are detected, the more reliable are measurements derived from the surface model.
- Three-dimensional point reconstruction refers to the computation of the three-dimensional object co-ordinates of a surface point based on the corresponding image points and the orientation of the cameras. The results is an unorganised set of 3D surface points (point cloud).
- Mesh generation ensures a connection between the single points of a point cloud. Often used are triangulated irregular networks (TIN) like the Delaunay Triangulation (16), which results in a surface description exclusively composed by triangles.

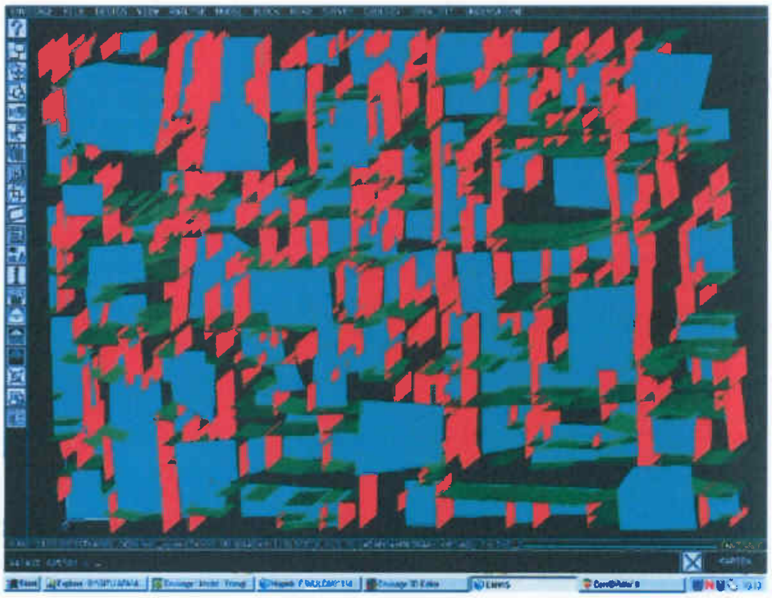


Fig. 5 Artificial discontinuity system (green: bedding planes, red and blue: joint sets), modelled on the basis of rock mass image evaluation (Figure 6) using the software VULCAN.

Bild 5 *Künstliches Trennflächensystem (grün: Schichtflächen, rot und blau: Kluftflächen), basierend auf einer Bildanalyse (Bild 6), modelliert mit dem Programm VULCAN.*

Fusion of results

The resulting structural maps from the interactive analysis can be geometrically aligned with the automatically computed surface reconstructions if both results base on the very same images. With that 2D structural maps become 3D existence and therefore enable the derivation of 3D magnitudes of the structures, like the true length of discontinuities or distances between them.

The resulting geotechnical surface models consist of 3D points, their connection among each other and the 3D structural data. The models are handled in a standard graphics file format called virtual reality modelling language (VRML), which is virtually supported by any Internet browser. This allows easily interchanging such models using the World Wide Web. In Figure 4 the steps of surface reconstruction from

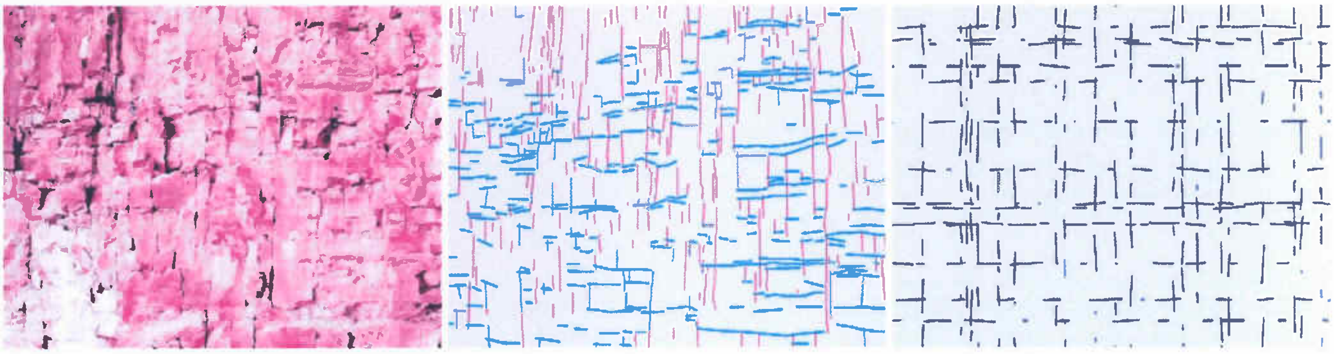


Fig. 6 UDEC-model, generated on the basis of a detailed image analysis of discontinuity parameters (discontinuity trace length, spacing, gap length); a) original image, b) result of detailed interactive image mapping, c) UDEC mesh based on statistical evaluation of discontinuity data showing joints for block generation.

Bild 6 *UDEC-Modell, basierend auf einer Detailauswertung von Trennflächenparametern (Trennflächenlänge. Trennflächennormalabstand, Kluftbrükkenlänge): a) Aufschlussbild, b) Ergebnis der Bildschirmauswertung, c) UDEC Block-Modell entsprechend der statistischen Auswertung der Trennflächen Daten.*

the 3D point cloud to the textured surface model are displayed.

Discontinuity orientations

The results so far enable 3D point measurements either in relation to the camera- or to an external object co-ordinate system. The measurement of spatial orientation information can be derived from single 3D point measurements where a spatial triangle is determined by three surface points. If the surface points are chosen to lie on a discontinuity then the normal vector to this surface triangle represents the orientation of this discontinuity. This principle was already used in geotechnical analyses based on conventional photographs (17,18).

Another way is to use the stereoscopic vision system. A virtual triangle can be navigated through three-dimensionally perceived rock mass by means of a 3D input device, like a space ball. This triangle is positioned until it matches the discontinuity and the (also displayed) normal vector represents the discontinuity orientation (Figure 4d).

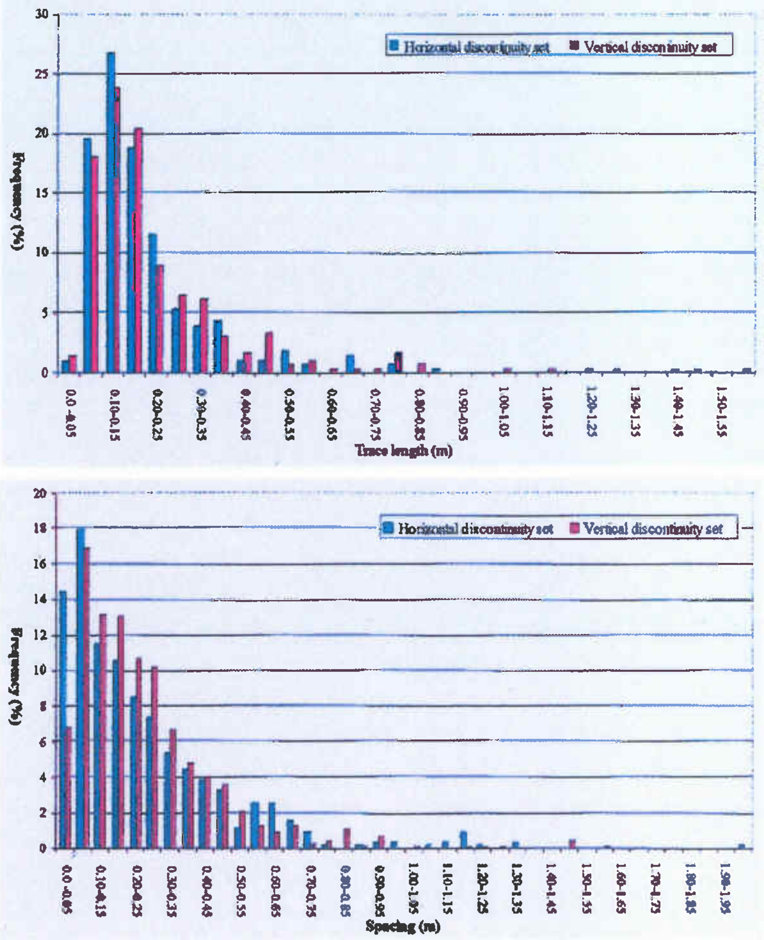


Fig. 7 a) Discontinuity trace length histograms, b) Discontinuity spacing histograms.

Bild 7 *a) Histogramme der Trennflächenlängen, b) Histogramme der Trennflächennormalabstände.*

Examples of data utilisation

General modelling of jointed rock mass

Stereoscopic rock mass images contain high quality information on the discontinuity systems. Therefore the elaboration of discontinuity models based on these images and data is a proximate field of application.

The complexity of jointed rock mass is a field of worldwide research activities. It is still very difficult or even impossible to model discontinuity networks as encountered in nature. Therefore software for generating three-dimensional artificial discontinuity systems, based on investigation data, has been developed (19). Modules for modelling discontinuity networks are integrated parts in software for numerical calculations of jointed rock mass as well (20). Collecting and evaluating data of discontinuities from stereoscopic images provides two major advantages. First, it can improve the input data for geometrical modelling of discontinuity systems. Second, by routine application of stereoscopic imaging, e.g. during tunnel excavation, a high density of in-situ geometric data can be acquired. Based on these data the modelling of actual discontinuity networks, closer to their natural properties as well as the evaluation of the influence of discontinuities on the excavation geometry (overbreak) is possible. The acquired models can be utilised directly for preparation of numerical models as well as for the verification of artificially generated discontinuity models (21). An example of a discontinuity model, based on rock mass images, is shown in Figure 5.

Utilisation of data for numerical modelling

An evaluation of selected discontinuity parameter (trace length, normal spacing, gap length) has been performed with discontinuity traces shown in Figure 6b (2). The traces result from an interactive image mapping of a limestone cliff (Figure 6a). The data were used for generating a UDEC-model (Figure 6c).

The selected window has a size of about 17.5 m². Traces of bedding planes are marked with green colour (276 samples), traces of a joint set are marked with red colour (289 samples). Both discontinuity sets are oriented normal to the image plane. The results of parameter evaluation for discontinuity trace length and normal spacing are displayed in Figure 7a and 7b as well as in Table 1 and Table 2.

The acquired input parameters for the automated generation of the discontinuity mesh of UDEC result in a discontinuity pattern which reflects the general layout of the two discontinuity systems satisfactorily, displaying the local concentration of parallel traces as well as the open joint pattern.

Table 1 Results of discontinuity trace length analysis.
Tabelle 1 *Resultate der Trennflächenlängenauswertung.*

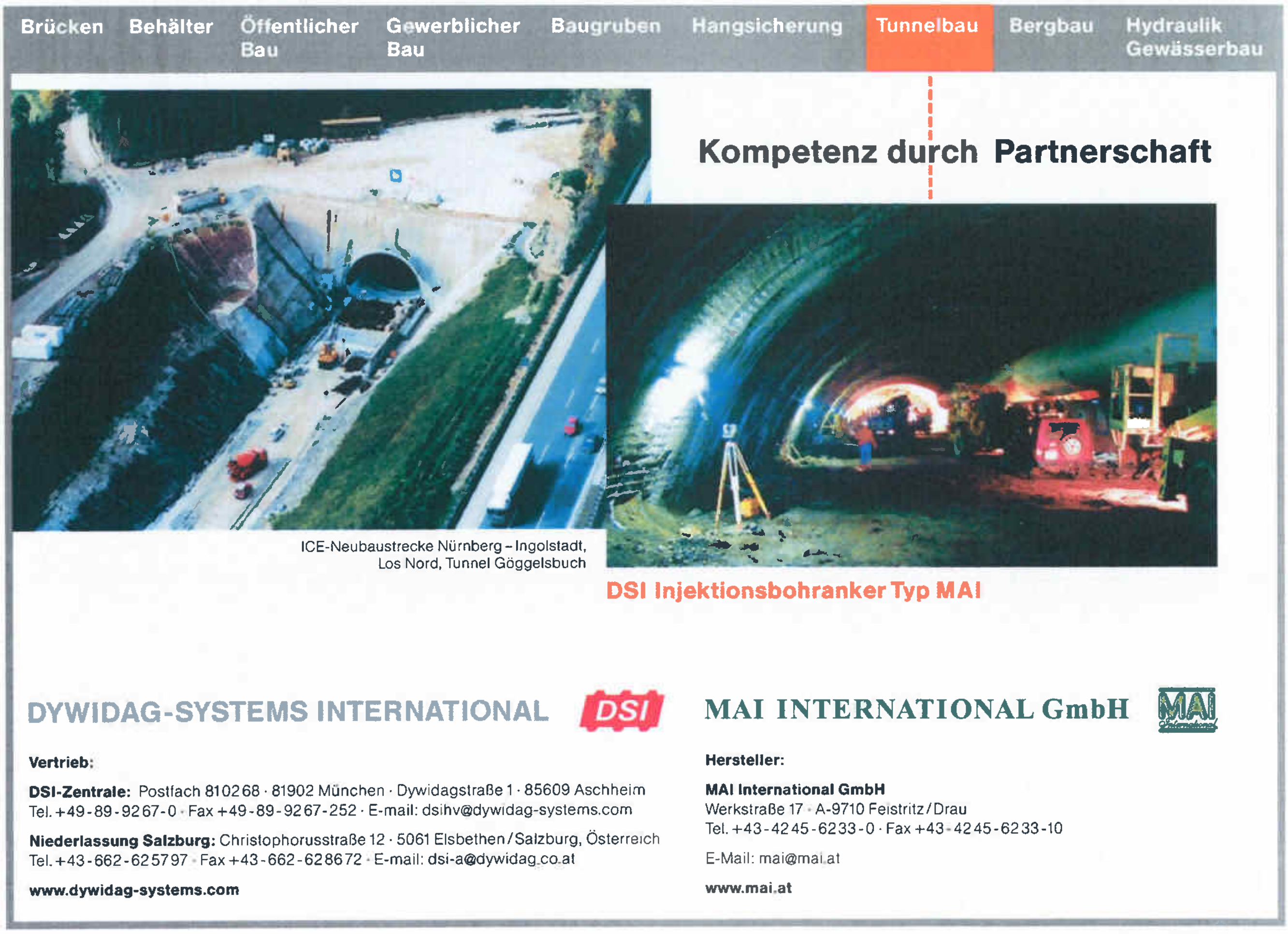
	Horizontal discontinuity set	Vertical discontinuity set
Mean value	0.21 m	0.23 m
Standard deviation ..	0.18 m	0.20 m
Minimum value	0.03 m	0.03 m
Maximum value	1.48 m	1.58 m
Number of samples .	276	289

Table 2 Results of discontinuity spacing analysis.
Tabelle 2 *Resultate der Auswertung der Trennflächennormalabstände.*

	Horizontal discontinuity set	Vertical discontinuity set
Mean value	0.25 m	0.26 m
Standard deviation ..	0.24 m	0.22 m
Minimum value	0.01 m	0.03 m
Maximum value	1.97 m	1.59 m
Number of samples .	538	614
Number of sampling lines	50	35
Total length of sampling lines	134 m	157 m

Discussion

For rock mass modelling high-resolution stereoscopic images as well as data derived from their evaluation are enormous improvements



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as the accuracy of evaluation as well as of interpretation increases.

The recoverable objective documentation of the majority of essential structural rock mass parameters allows for a flexible use of the data. In dependency from the question formulation and urgency the exactness of evaluation can be selected, always with the option to go back to the initial data. Rock mass modelling in combination with image information increases the content of information to the viewer as major features of a jointed rock mass are easy to recognise visually. The transportation of information between different parties involved is improved as the professional filter, implied by the mapping person, can be moved to the background when required. Imaging provides the possibility to trace structures by successive documentation of rock faces, as excavation works proceeds, independent if this concerns tunnels or slopes.

With the accuracy, contained in scaled and oriented images, it provides information for a better understanding of the observed rock mass portion. Therefore the quality of interpretation as well as extrapolation can be increased. Critical scrutinising of numerical models can only be performed when a realistic data source is available. Parameter modifications are justifiable only when the raw data are of high quality and when they can serve as starting point for simplifications required by the modelling software as well as for checking the plausibility of results. In order to have at least a better control on geometrical parameter, data acquisition based on stereoscopic imaging may reduce the total amount of uncertainties, still caused by material properties, material laws, failure modes as well as by the concepts of numerical models on their own. As demonstrated the possibility of a detailed evaluation of discontinuity parameters improves the accuracy of statistically generated geometrical models for numerical simulations.

The general subjective impression of rock mass quality, supplemented by a few measurements cannot guarantee the correctness of input data for any further evaluation. Therefore the provision of detailed data should be possible as a routine on a daily basis, and should not be restricted to exceptional situations or projects.

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