sary, to create a mesh, which is then available for the visualization. Making stereoscopic pictures of the tunnel face, which is needed to identify geological structures, brings the possibility, to give the model a realistic appearance, by using these photos as texture.

With the Tunnelling Visualization System it would be possible to provide the client and other interested parties with a guided tour of tunnels in planning and may be used to alleviate concerns by environmentalists. Another application of TVS is the planning of rescue operations after tunnel or mine collapses.

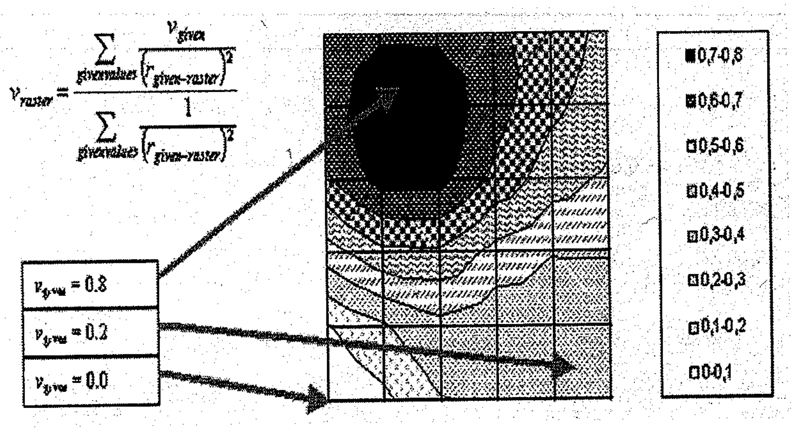

Fig. 5 Algorithm to find values on fixed raster-points.
Bild 5 *Verfahren, um Werte an Rasterpunkten zu ermitteln.*

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Stereoscopic Imaging and Geological Evaluation for Geotechnical Modelling at the Tunnel Site

By Andreas Gaich, Alfred Fasching and Michael Gruber

During the design phase of a subsurface excavation project knowledge about geological, hydrogeological and geotechnical conditions is rather limited. Depending on the amount of performed investigations a detailed prediction of geological conditions as well as rock mass behaviour during excavation is impossible or possible only up to a certain extent. To optimize this process and to provide data for numerical simulations to be performed within the shortest time possible on site, a more objective acquisition and evaluation of geological data, preferably semiautomatic, is needed.

Presently the geological survey at the tunnel face consists of sketches of the rock mass structure, compass readings of joint orientation, and other relevant observations like qualitative assumptions of shape and size of rock blocks, rock type, rock mass integrity, degree of weathering, and water ingress. This documentation is occasionally supplemented by conventional images of the tunnel face to support the graphical sketches. In general, time available to perform the survey by the geologist is extremely short. In addition the work in unsupported area bears considerable risk for the geologist. These circumstances lead to incomplete and inconsistent data.

An improvement towards an objective tunnel face documentation is the generation of high resolution digital stereo-images. For this purpose calibrated rotating colour line-cameras and photogrammetric orientation principles are used to

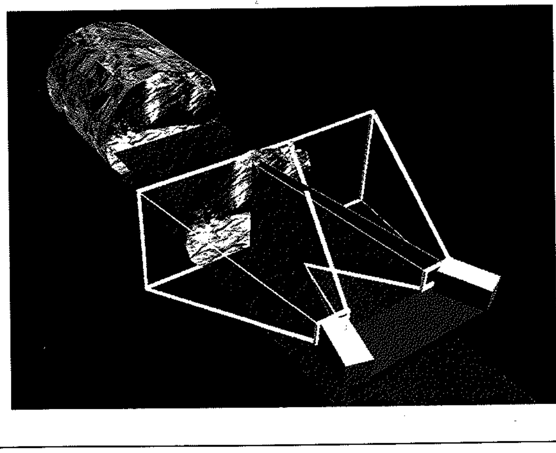

Fig. 1 Configuration of the stereo imaging system. The rotating line cameras scan the tunnel face.
Bild 1 *Konfiguration des Stereo-Bilddatenerfassungs-Systems. Mittels rotierender Zeilenkameras wird die Ortsbrust aufgenommen.*

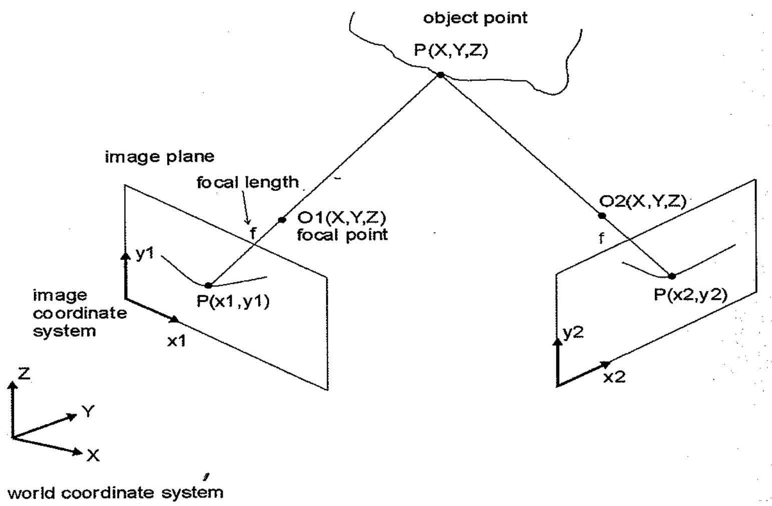

Fig. 2 Principle of 3D-reconstruction from stereo images by forward intersection.
Bild 2 *Prinzip der 3D-Rekonstruktion aus Stereobildern durch räumliches Vorwärtseinschneiden.*

provide facilities for three-dimensional measurements and documentation. An experienced geologist selects geotechnical relevant structures using a mid-level graphics workstation and software tools currently developed. This stereoscopic inspection is the basis for the precise three-dimensional reconstruction of geological conditions. In order to support the interactive evaluation an image processing component for automated structural analysis of the tunnel face images as well as the automatic establishment of a digital elevation map of the tunnel face may be used.

By interactive interpolation between subsequently documented tunnel faces the modelling of the rock mass surrounding the excavated tunnel will be possible. The models derived shall be used for comparisons between predicted rock mass model and actually encountered conditions, for interpretation of geotechnical measurements, for input into numerical simulations, and for short term prediction of rock mass structure ahead of the tunnel face.

Electronic imaging system

Essential requirements

For choosing the proper components for the electronic imaging system the physical requirements to the images together with availability of sensors and the financial potential are of prime importance in the considerations. These are:

- evaluation of the images on site => simple data generation and transfer,
- captured area of about 10 m width and 8 m height,
- geotechnical structures in the range of a few centimetres distinguishable => images of about 4 000 x 3 000 pixel needed,
- structural and colour information used for geological classification => colour images needed,
- image acquisition within minutes,
- semiautomatic determination of camera orientation within the tunnel.

Selection of the Imaging System

The electronic imaging system consists of two digital CCD-line sensor cameras with 6 000 ele-

Stereoskopische Bilddatenerfassung und geologische Auswertung für geotechnische Modellierung auf der Tunnelbaustelle

Im Rahmen des Forschungsschwerpunkts SITU – Numerische Simulation im Tunnelbau, finanziert durch den FWF (Fonds zur Förderung der Wissenschaftlichen Forschung), werden in einem interdisziplinären Projekt (Telematik, Ingenieurgeologie) Arbeitsroutinen zur Erstellung von 2D- und 3D-Modellen für numerische Simulationen auf der Baustelle entwickelt. Durch die Benutzung eines Aufnahmesystems zur Erzeugung hochauflösender digitaler stereoskopischer Bilder wird eine objektive geologische Auswertung anhand der Ortsbrustaufnahmen ermöglicht. Die Aufnahmen, die in einem Tunnelkoordinatensystem absolut orientiert werden, erlauben die Ermittlung von Trennflächenparametern wie Orientierung, Abstand und Durchtrennungsgrad.

Die zweidimensionale Bildauswertung mittels eines eigens dafür entwickelten Editors soll durch Strukturerkennungsprogramme unterstützt werden, die im Rahmen des Forschungsprojekts entwickelt beziehungsweise angepaßt werden sollen. Erhobene Daten können zur statistischen Auswertung und Speicherung in die Geo-Datenbank DEST „Datenevaluierungssystem für den Tunnelbau" (13) übernommen werden. Das Verbinden von aufeinanderfolgenden Stereo-Bildpaaren wird eine rasche Modellbildung der Gebirgsstruktur um den ausgebrochenen Hohlraum auf der Baustelle ermöglichen. Die so entwickelten Modelle sollen als Basis für numerische Simulationen auf der Baustelle sowie für den Vergleich zwischen den prognostizierten und tatsächlich angetroffenen geologischen Verhältnissen und für die Interpretation der geotechnischen Meßergebnisse dienen.

Within the research initiative SITU – Numerical Simulation in Tunnelling, financed by the FWF (Scientific Research Funds of Austria), an interdisciplinary project (telematics, engineering geology) deals with the development of working routines for preparing two- and three-dimensional geotechnical models for numerical simulations on site. Using a high resolution stereoscopic imaging system an unbiased geological data acquisition can be performed. The images oriented within a given tunnel coordinate system are brought into a stereoscopic vision system enabling three-dimensional inspection and evaluation. Data like discontinuity orientation, spacing and persistence as well as an automatic reconstruction of the tunnel face shall be obtained.

The two-dimensional image evaluation using an editor developed for this purposes shall be assisted by a semiautomatic structure identification based on image processing tools, to be developed or adapted within this research project. The gathered data can be transferred to the Geo-Database DEST "Data Evaluation System for Tunnelling" (13) for statistical evaluation and storage. Interpolating structures between subsequent stereo images will enable to model the rock mass surrounding the opening within a short time at site. The models shall be used as input to numerical simulations on site, comparison of expected and encountered geological conditions and for the interpretation of geotechnical monitoring results.

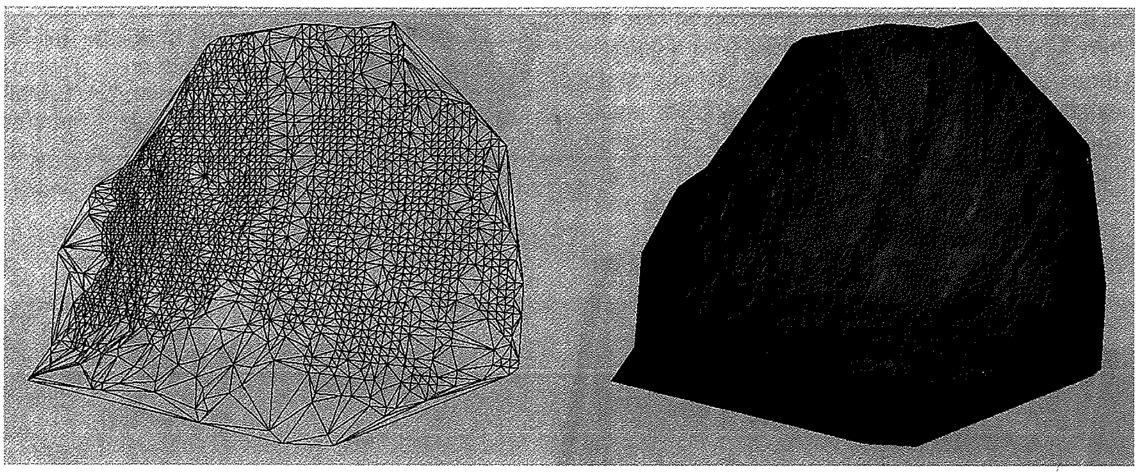

Fig. 3 3D-Reconstruction of a tunnel face. A triangulated irregular network (TIN) of the three-dimensional reconstructed object points defines a surface in 3D space (a). A shaded surface with overlaid image is depicted in (b).

Bild 3 *3D-Rekonstruktion einer Ortsbrust. Ein „triangulated irregular network" (TIN) der dreidimensional rekonstruierten Objektpunkte definiert eine Oberfläche im Raum (a). Eine schattierte Oberflächendarstellung mit überlagertem Ausgangsbild ist in (b) dargestellt.*

ments mounted on stepper motor driven rotation units. These are fixed with a rigid frame on a vehicle (figure 1). Rotation of the cameras delivers panoramic images on a cylindrical surface. These imaging technique and the correct seaming of single image parts is used within different applications (7, 10).

Using an imaging strategy called "binning" the effective number of elements per camera is reduced to 3 000 resulting in a bisection of the exposure time needed at the same lighting conditions.

Measurement from stereo images

Together with the interior orientation of the cameras, the geometry of the imaging set-up which is calibrated in the laboratory, and the determination of position and direction at the imaging moment (exterior orientation (5, 9)), a rigid transformation between cameras and a world respective tunnel coordinate system can be found (1, 11, 12). This defines an injective coherence between images and captured object and allows measurement from the images.

Due to the special sensor no standard routines for camera calibration are existing. Therefore procedures for the determination of interior and exterior camera parameters have to be adapted (3, 4, 6).

The principle of three-dimensional measurement and reconstruction is shown in figure 2. From the known interior and exterior orientation of the cameras and the calculation of corresponding image (image matching) the according object point is reconstructed, i.e. the spatial rays are rebuilt at the time of capture. The intersection in space corresponds to the object point P(X,Y,Z).

An automatic analysis of test images taken with a standard CCD-camera at the Semmering pilot tunnel is performed. Classical image processing procedures with enhancements (8) are used for three-dimensional point reconstruction (figure 3). The resulting points are guided to a surface description using a Delaunay triangulation delivering a triangulated irregular network (TIN), a special case of a polygonal mesh (2).

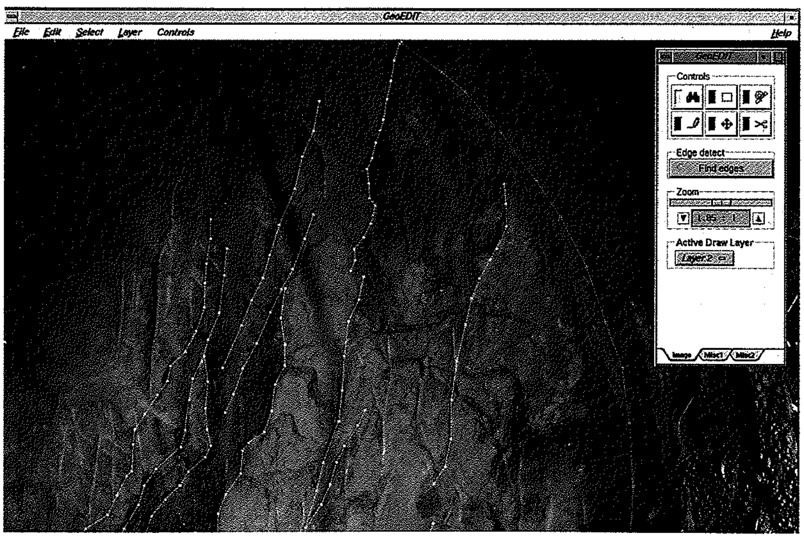

Fig. 4 GeoEdit – an editor for interactive determination and evaluation of essential geological structures of the rock mass.

Bild 4 *GeoEdit – ein Programm zur interaktiven Bestimmung und Auswertung von Trennflächenparametern.*

Accuracy of the 3D-reconstruction

An estimation of the achievable accuracy of the three-dimensional reconstruction which is the basis for processing the data and the generation of a rock mass model depends on the quality of following parameters:

- laboratory calibration of cameras and imaging set-up,
- coordinates of the geotechnical convergence marks used for computing the exterior camera orientation,
- resolution of the generated images,
- image quality concerning noise, radiometric correction,
- localization of corresponding points in the stereo images (automatic and interactive)

Interactive evaluation of tunnel face images

For enhanced geological modelling an interactive program called GeoEdit has been developed within the research project. It allows the geologist to evaluate structural features of tunnel face images. Traces of discontinuities, boundaries between different lithologies etc. can be identified with this tool. To distinguish between different structures in an image, grouping by a layer concept is considered and displayed in different colours (figure 4).

A novel approach in geological analysis on site is the stereoscopic inspection of the tunnel face images. Using graphics hardware and software tools already implemented three-dimensional perception is possible. This brings crucial advantages because certain structures cannot be identified only from a single image.

To provide this we use a graphics workstation capable to display two images at the same time with a resolution of 1 024 x 768 pixel and 96 Hz refresh rate. The user wears so-called shutter glasses which enable alternately one image for each eye. The parallaxes or disparities in the geometrically co-oriented images are processed from the brain to depth information resulting in three-dimensional perception.

Methods for geological and geotechnical data evaluation have been studied and a selection of suitable evaluation routines has been made for further testing and adaptation. This includes evaluation routines for parameters such as discontinuity size, persistence, spacing, and frequency (figure 5).

As the intended method of stereo-image documentation during tunnel excavation will provide a new type of sampling, the methods used so far will have to be tested for their suitability. First tests with the software developed have been made on images from surface outcrops (Dennig limestone quarry north of Graz) as well as on images taken during tunnel excavation (Semmering Pilot Tunnel of the S6 – Semmering Freeway, Pilot Gallery at the Tunnelkette Klaus of the A9 – Pyhrn Motorway).

Concept for geodata acquisition

A concept for acquisition of data has been made. Two main purposes have to be achieved:

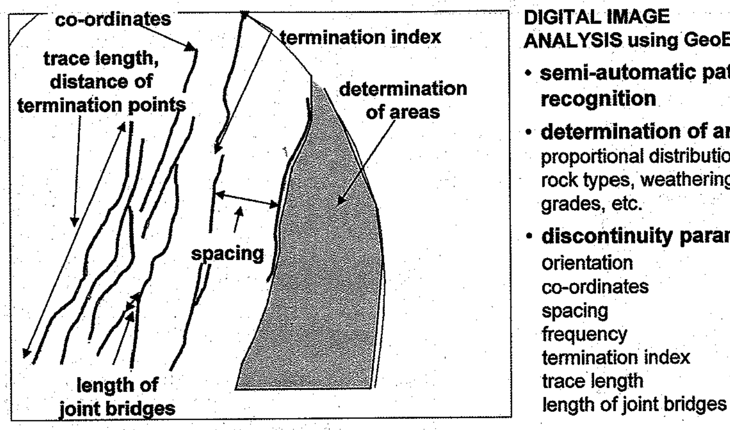

Fig. 5 Parameters determined and evaluated using GeoEdit.

Bild 5 *Auswertung von Bilddaten mit dem Programm GeoEdit.*

- ⇨ general geological – geotechnical documentation: all data and parameters, observable by the new data acquisition method and deemed relevant for the characterisation of the encountered geological and geotechnical conditions, shall be transferred to the geo-database for further evaluation (DEST – Data Evaluation System for Tunnelling, developed at the Institute of Engineering Geology and Applied Mineralogy, Technical University Graz).
- ⇨ preparation of models for numerical simulation on site: For numerical simulation different input parameters for the generation of model geometry and definition of material properties have to be provided depending on the software intended to use, e.g. 2D- and 3D-Distinct Element, Boundary Element or Finite Element Codes. Data required for the generation of geometrical models (mesh generation) shall be obtained by the evaluation of stereoscopic images in 2D- and 3D-mode. Material properties, required for numerical simulation, are acquired during tunnel excavation only to a minor extend by additional laboratory analysis. In general values obtained during the planning stage, empirical values or values from the literature are used as input parameters. Table 1 shows a comparison between selected information and parameters of a state of the art tunnel documentation, and docu-

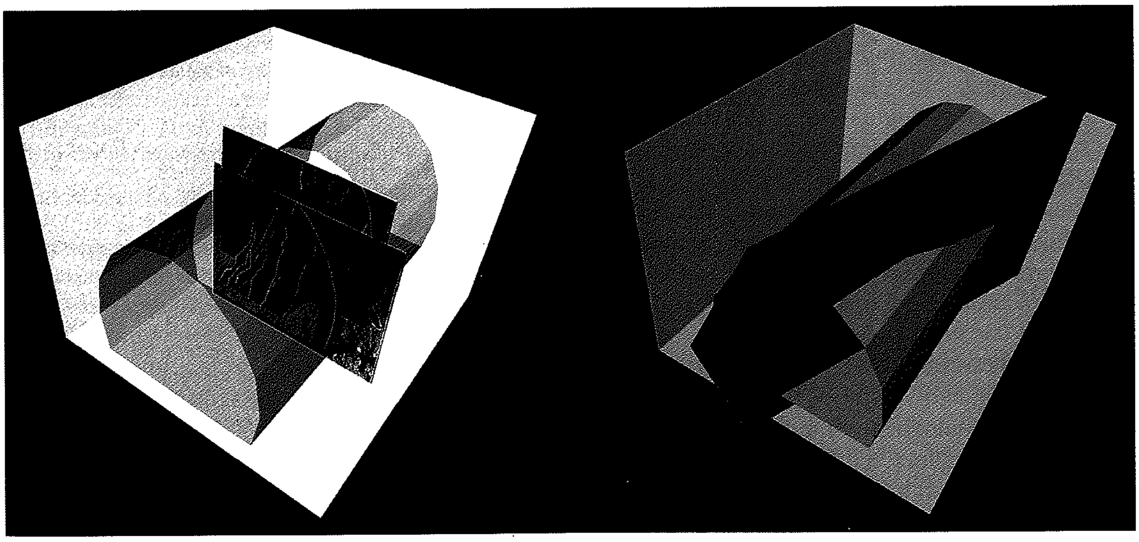

Fig. 6 Reconstruction of a fault zone between two subsequent digital stereoscopic images of tunnel faces and extrapolation of the fault zone, Semmering Pilot Tunnel – S6 Semmering Freeway.

Bild 6 *Rekonstruktion einer Störungszone zwischen zwei aufeinanderfolgenden digitalen Ortsbrustaufnahmen und Extrapolation der Störungszone, Semmering Pilotstollen – S6 Semmering Schnellstraße.*

Table 1 Comparison between state of the art documentation and improved system.
Tabelle 1 *Vergleich zwischen aktuellem und verbessertem Dokumentationssystem.*

Parameter	State of the Art Documentation	Documentation by Stereoscopic Imaging	Preliminary Classification
Rock type	Identification at the face	Identification through colour information	Supplementary classification at the face required for method B, at least at the beginning of the works
Proportional distribution of rock types	Rough estimation, additional evaluation of standard images required for sufficient quality of data	Automated evaluation at the screen	Results are quickly available by method B
Type and properties of discontinuities (e.g. location, length, spacing, termination index)	Classification at the face, very limited due to problems with accessibility and shortage of time; improved evaluation requires additional documentation tools (photos) and additional evaluation work	Classification of the whole area of tunnel face at the same accessibility at the computer; automated evaluation	High resolution digital images of method B enable almost all required classifications with exception of small scale structures (e.g. surface roughness)
Discontinuity orientation	Only very limited number of compass readings at the face possible	Possibility of taking readings at the whole face area	Improved data quality of method B by reduced sampling bias

mentation based on digital stereoscopic image documentation together with a preliminary classification.

The evaluation of parameters like discontinuity spacing, discontinuity size, and trace length as well as the discontinuity frequency follows well established methods (14).

Example UDEC-model

For the generation of a UDEC model the following input parameters for modelling discontinuities and sets of discontinuities are required, including information about mean value/centre of gravity and maximum deviation:

- orientation of discontinuities in relation to orientation of model cross section,
- length of discontinuity segments (trace length),
- length of gaps between discontinuity segments,
- normal spacing of discontinuities.

For modelling structural singularities like fault zones the required coordinates and trace lines of the fault boundaries as well as thickness of fault zones can be directly evaluated from the digital images in 2D- and 3D- mode.

Additional input parameters of rock mass properties (e.g. bulk modulus, shear modulus, density, cohesion, angle of internal friction, tensile strength) as well as properties of discontinuities (joint stiffness, tensile strength, angle of friction, cohesion) are determined during the planning stage of a project in general and should be available from relevant reports or from literature.

Visualization and modelling

To illustrate geological conditions for preparation of three-dimensional models for numerical simulations as well as for interpretation of geotechnical measurements the geotechnical evaluation results, together with the images of subsequent stations, can be used to connect corresponding structures. To demonstrate this we used a commercially available program (15) which can handle three-dimensional boundary representations and user interaction. An exemplary result is given in figure 6 (top).

The derived model can be extrapolated to the volume outside of the excavated tunnel (figure 6, bottom). This evaluation tool will be further developed to provide a tool for a automated modelling of a rock mass volume around and ahead of a tunnel.

The generation of sections at chainages in orientations to be selected freely will be developed in co-operation with research project 1b – Visualization of the SITU Joint Research Initiative.

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Application of Numerical Simulation Methods on Site

By Harald Golser

For an economical and safe construction of tunnels, a continuous adaptation to the actual ground conditions of the excavation method and the quality and quantity of support is required. Up to now, this optimization process has been based on experience, on data from geological documentation and on displacement monitoring. To arrive at more objective decisions it is desirable to supplement this empirical approach by numerical simulations.

The acceptance of numerical simulations on site will be increased only, if results of such simulations are realistic and available in time for the day to day decisions. For that purpose, a pre-fabricated "model library" of typical geotechnical conditions is established. Two- and three-dimensional simulations with finite element, boundary element and distinct element methods are performed on site directly. The results of various simulations are compared to the actual behav-

Die Anwendung von numerischen Simulationsmethoden auf der Baustelle

Im Rahmen des Forschungsschwerpunkts SITU – Numerische Simulation im Tunnelbau – wird im Teilprojekt „Baustelleneinsatz" die Anwendbarkeit numerischer Methoden auf der Baustelle untersucht. Weiters wird der Zugang zu Baustellendaten und -information für die übrigen Mitglieder des Forschungsschwerpunkts sichergestellt. Es gibt eine Vielzahl an mathematischen Modellen und numerischen Methoden, aber nicht alle sind für eine Simulation unter speziellen geotechnischen Bedingungen gleich geeignet. In Vergleichsrechnungen wird die Anwendbarkeit numerischer Methoden wie die der finiten Elemente, Randelemente und diskreten Elemente und die Grenzen notwendiger beziehungsweise zulässiger Vereinfachungen untersucht.

Mit handelsüblichen Programmen werden auf der Baustelle numerische Analysen und Rückrechnungen durchgeführt und deren Ergebnisse mit den geotechnischen Messungen verglichen. Diese Simulationen liefern Hinweise für Verbesserungsmöglichkeiten der Programme und Anforderungen an die Hardware für den Baustelleneinsatz. Die ersten Ergebnisse aus numerischen Simulationen auf der Baustelle (Siebergtunnel) bewiesen die grundsätzliche Eignung von Vorausberechnungen und Rückrechnungen als integrierte Bestandteile des Tunnelbaus, sie haben aber auch kleinere Mängel der Modelle deutlich aufgezeigt.

Within the joint research initiative SITU – Numerical Simulation in Tunnelling – the project "Site Application" deals with the application of tools for numerical simulations on site. In addition, the site data and information required by other participants of the JRI is collected and provided. A considerable number of mathematical models and simulation methods exist, but they are not equally suitable for different geotechnical conditions. In comparative calculations, the suitability of different numerical methods such as finite element method (FEM), boundary element method (BEM) and distinct element method (DEM) and limits of acceptable simplifications are investigated. With commercial numerical analysis codes, forward and back analyses are calculated on site and compared with results from geotechnical measurements. These simulations provide indications for improvements of the software and hardware required for site application. The first results of numerical calculations on-site (Siebergtunnel construction site in Austria) have proved the general applicability of forward analysis as well as back analysis as an integrated part of tunnel construction, but also showed certain shortcomings.