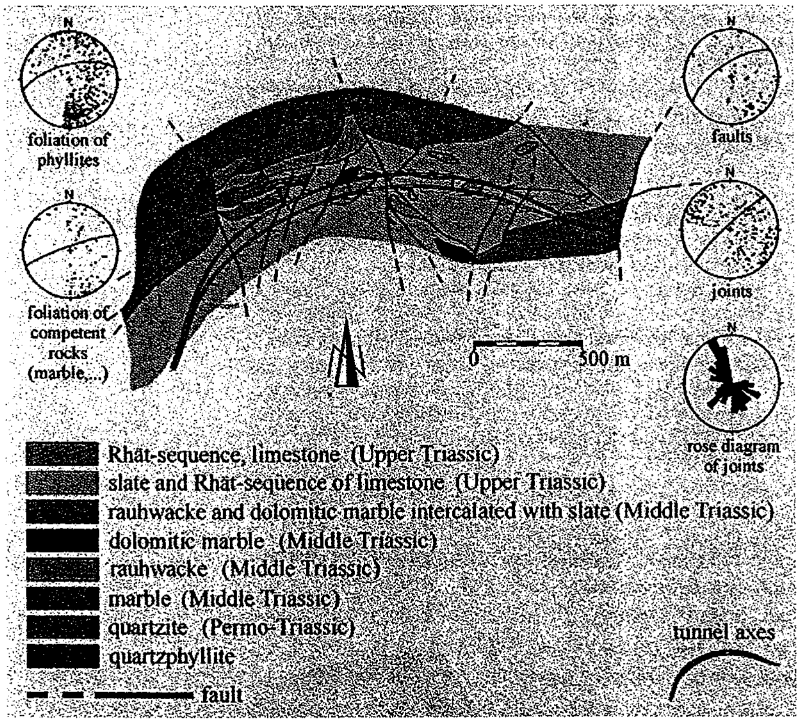
Tunnelling in a Tectonic Melange of High Structural Complexity

By Helge Püstow, Gunter Riedmüller and Wulf Schubert

The evaluation of interactions between the rock mass behaviour, excavation methods and installed support, which is of paramount importance for the design and construction of tunnels, requires a comprehensive study of the geometrical and geomechanical ground characteristics. This task is extremely difficult in tectonic melanges due to the enormously heterogeneous nature of the rock masses internal structure (1, 2). The characterisation of melanges is fundamentally complex (3). Any attempt to homogenise the rock mass to a pseudo-isotropic media will result in errors predicting the excavation behaviour. When evaluating the melange rock mass system behaviour, as well as adequate excavation methods and support, an accurate geotechnical relevant characterisation of the tectonic melange is necessary. Conventional classification methods do not assess suitable classification parameters. If the melange specific rock mass parameters are insufficiently evaluated, the rock mass behaviour cannot be predicted reliably.

Fig. 1 Geological map of the tunnel alignment corridor.
Bild 1 *Geologische Karte des Tunnelkorridors.*



During both the site investigation and the construction phases, limitations result in particular from the significant lack of spatial information related to the ground conditions. Recent research revealed the importance of assessing strength contrasts between the matrix and blocks, as well as block characteristics such as block sizes and block volumetric proportions (11, 12, 13). Information on these parameters is typically derived from surface mapping, one-dimensional spot coring, or from the results of a pilot tunnel. Geophysical methods such as reflection seismic only give a rough estimate of large blocks near to the surface. A more accurate image of block sizes and locations can be obtained by cross-hole seismic tomography. The exploration methods have to be properly designed to acquire enough information to estimate the block volumetric proportion at the engineering scale of interest (13). Misinterpretations of borehole logs may lead to expressions such as an "interbedded" or "interlayered" rock mass or "soil with boulders" causing improper designs. When extrapolating block sizes derived from investiga-

Tunnelbau in einer tektonischen Melange von großer struktureller Komplexität

Der Schnellstraßentunnel „Spital" (Semmeringgebiet, Steiermark, Österreich) dient als Fallstudie für einen Tunnelbau in einem äußerst schwierigen Baugrund. Eine tektonische Melange von großer struktureller Komplexität beeinflußt den gesamten bergmännischen Vortrieb. Die vorliegende Arbeit stellt einige neue Ansätze vor, mit dem Ziel der Minimierung von Unsicherheiten und der Realisierung eines ökonomischeren und sicheren Tunnelbaus. Schwerpunkte werden hierbei in der Verbesserung des geometrischen und geomechanischen Verständnisses eines Block-in-Matrix Gebirges („bimrock") gesetzt. Neue Methoden zur Verbesserung der geologischen Erkundung vor und während des Tunnelbaus werden vorgestellt. Ein Verfahren wurde entwickelt, das eine Bestimmung von Vortriebsstrecken mit dem Potential einer Ausbaureduktion und damit eine Kostenoptimierung ermöglicht.

Serving as a case study for tunnelling in extremely heterogeneous ground conditions, the whole alignment of the express way tunnel "Spital" (Semmering area, Styria, Austria) is affected by a highly internally differentiated tectonic melange. To reduce uncertainties and to realise a more economic and safe construction, this paper promotes the geometrical and geomechanical comprehension of block-in-matrix-rocks "bimrocks". New methods for optimising the investigation prior to and during the tunnel construction in tectonic melanges are introduced. A procedure for determining tunnel sections with the potential for support reduction is developed. It facilitates a cost optimisation of the tunnel construction.

tion results, all available information should be integrated within a framework to allow for most accurate ground predictions.

Results from geotechnical research on "bimrocks" have already been successfully applied for the safety evaluation of a dam and the construction of a tunnel (3, 4). In this paper a new method is developed to apply geotechnical significant "bimrock" parameters for the optimisation of tunnel design and construction of a traffic tunnel in the Austrian Alps.

Geotechnical problems related to tunnelling in tectonic melanges

Abrupt rock type changes are typical when tunnelling in tectonic melanges, which are characterised by significant spatial variations in stiffness between blocks and matrix.

Presently no standard methods exist to classify this type of rock mass. The quantitative classification methods in tunnelling, such as the RMR system (5) or the Q-system (6) are not suitable for the support determination in tectonic melanges. In these quantitative systems, no adequate classification parameters exist for sufficiently characterising the rock mass behaviour (7). Recently, Hoek et al. (8) extended the GSI concept to include materials such as melange rock masses. Their recommendations are a direct extension of the Hoek-Brown Failure Criteria (9). While the recent extension of the GSI classification by Hoek et al. (8) recognises the materials anisotropy, the system behaviour is still treated as an isotropic continuum. Habimana et al. (10) recognised the influence of the tectonisation degree on the Hoek-Brown Failure Criteria and proposed a new formulation relating the material type (structure) to observed laboratory test results. In our point of view more supporting data derived from case histories is necessary for the application of these failure criteria in a tectonic melange rock mass.

Medley (11) and Medley & Goodman (12) defined geotechnical significant features of a melange as follows: *"At the particular scale of engineering interest, a melange is a chaotic rock mass composed of strong blocks of rock of various sizes and lithologies, embedded within a weaker, usually argillaceous or soil-like matrix."* The simple and non-genetic term "bimrock" (block-in-matrix-rocks) was introduced by Medley (13). Results from Medley's as well as Lindquist's (14) and Lindquist's & Goodman's research (15), and more recently Goodman & Algren (4) point to the importance to improve geotechnical characterisation of tectonical melanges by considering "bimrock" definitions.

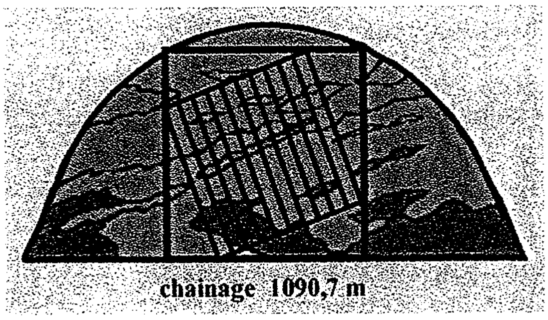


Fig. 2 2D-determination of block/matrix ratios at the tunnel face by window mapping of a representative area (quadratic region of interest (ROI)).

Bild 2 *2D-Bestimmung des Block/Matrix-Verhältnisses an repräsentativen Bereichen der Ortsbrust unter Verwendung der Auswertung von Meßstreifen.*

In our point of view this state of the art characterisation of tectonic melanges can be applied to improve tunnel constructions. The following study is a comprehensive application of a geotechnical relevant bimrock characterisation in tunnelling. To predict sufficiently the rock mass behaviour in tectonic melanges and to optimise site investigation and tunnel construction the geologic structure, volumetric block proportions, strength properties as well as observed displacements are evaluated.

Application of block-in-matrix characterization for the tunnel Spital

Project Overview

The tunnel Spital is a bypass of the town of Spital am Semmering. It is one of three tunnels necessary for upgrading the Semmering expressway (S6). It consists of twin 10 m diameter tunnels separated by approximately 50 m over most of the length. The maximum overburden reaches 89 m, with an average of 30 m. The tunnels have a total

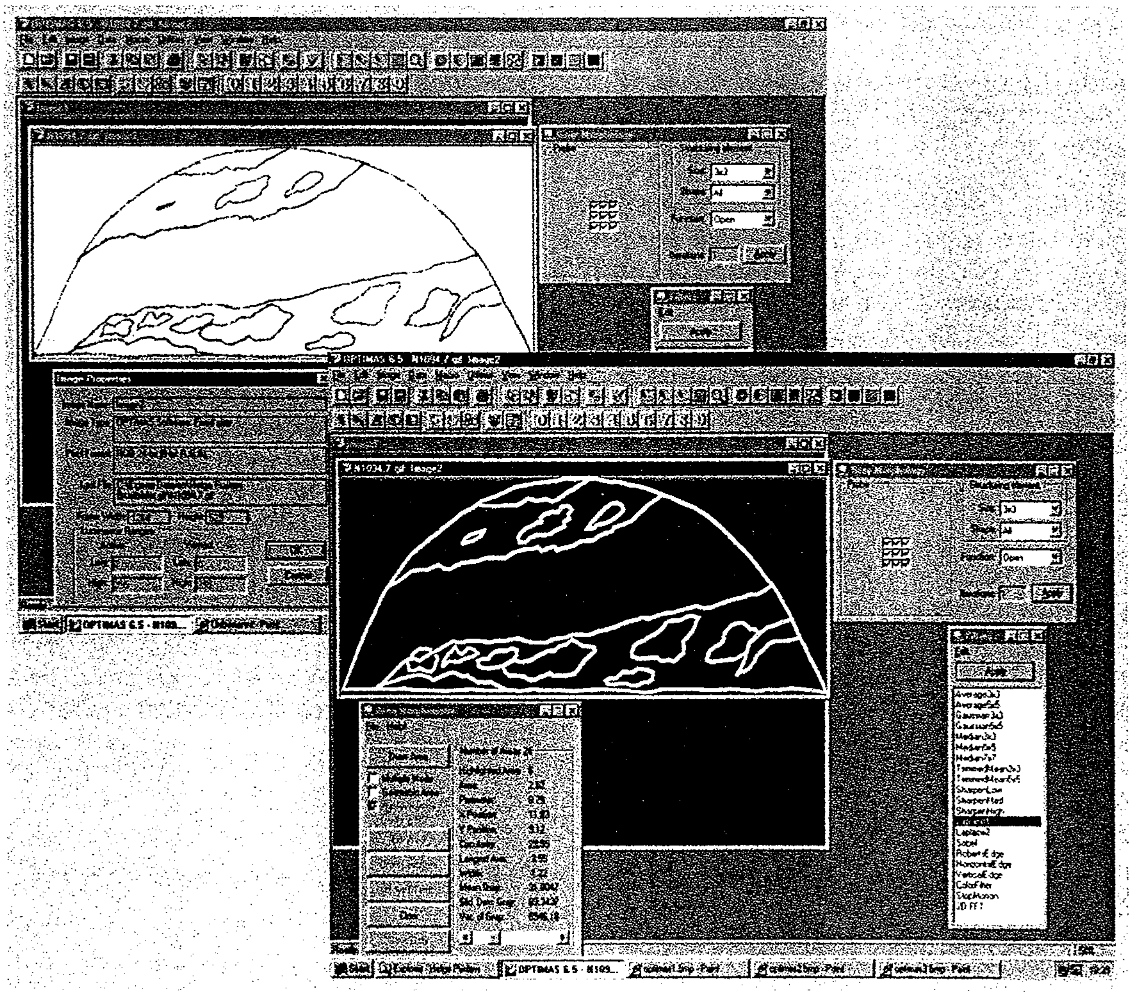


Fig. 3 2D-morphometry at the tunnel face by means of photogrammetric methods. Melange-specific features such as block/matrix areas, lengths of fault traces, numbers of blocks and faults, perimeters of blocks, block positions and lengths of block axes are evaluated.

Bild 3 *2D-Morphometrie der Ortsbrust mit Hilfe photogrammetrischer Methoden. Melange-spezifische Merkmale wie Block/Matrix-Flächen, Störungslängen, Anzahl von Blöcken und Störungen, Umfang von Blöcken, Blockpositionen und Achslängen von Blöcken werden ausgewertet.*

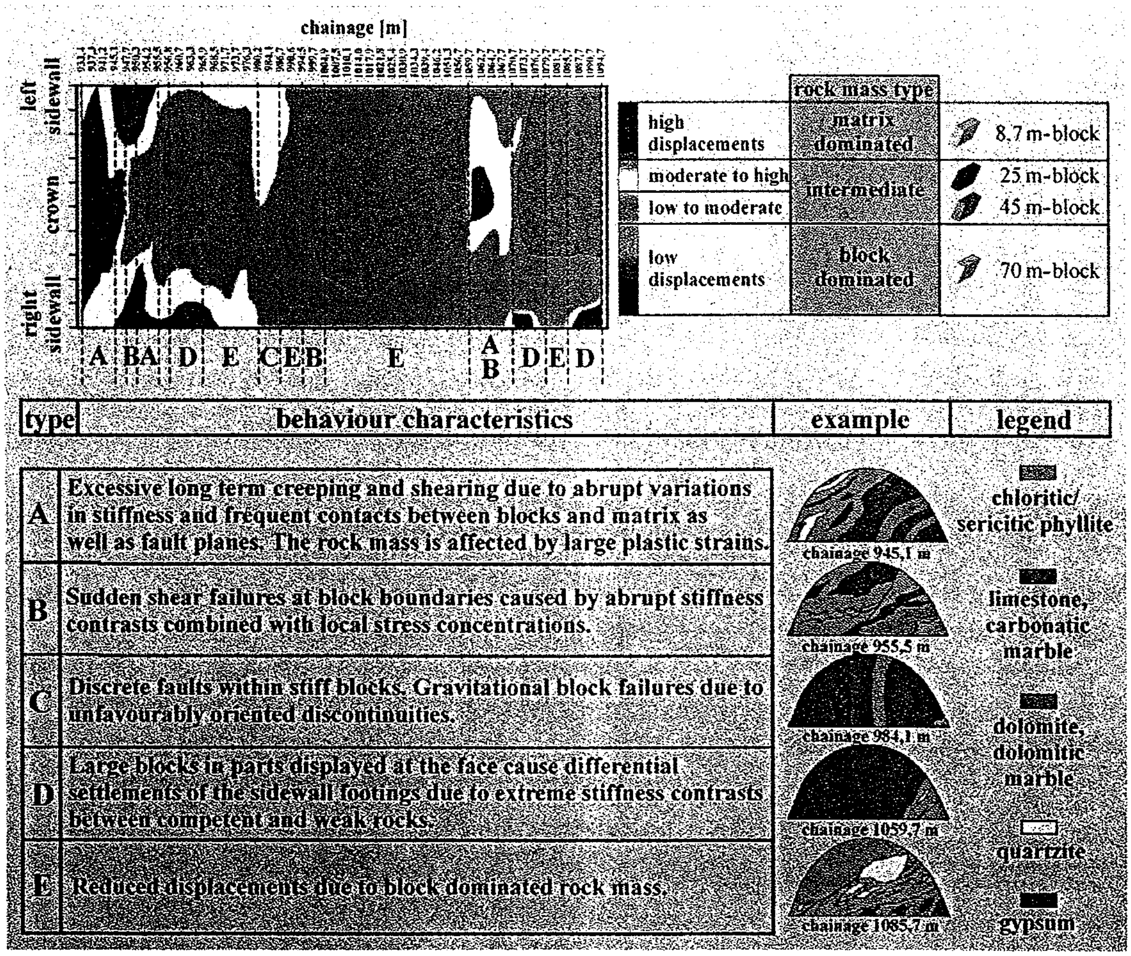


Fig. 4 Definition of rock mass types (tunnel Spital, north tube, chainage 933.4 m to 1094.7 m).

Bild 4 *Definition von Gebirgstypen (Tunnel Spital, Nordröhre, Station 933,3 m bis 1094,7 m).*

length of 2 500 m. The mined tunnels, each with a length of 2 044 m, were conventionally excavated. The remaining sections, each with a length of 454 m, were constructed by cut and cover techniques. The mined excavation started in January 1999. The break-through was in summer of 2001. Completion is scheduled for August 2002. Due to the difficult ground conditions the construction has been delayed and costs have increased.

Geologic setting

The tunnel alignment is located within the "Semmering-Unterostalpine" tectonic unit. It consists of a nappe-system, which includes a polymetamorphic crystalline basement and a low grade metamorphic Mesozoic sedimentary sequence. Within a ductile crustal environment a tectonic melange was generated between two nappe-structures (16, 17). Thrusting generated stiff blocks ("horses") which are surrounded by a foliated weak matrix of intensely sheared phyllite. The lenticular-shaped competent blocks are strongly aligned with the undulating phyllite foliation that generally dips towards NNW reflecting the thrusting direction of the plunging nappe system. Most block and matrix contacts are either composed of brecciated material or highly sheared fine-grained clayey coatings.

During a later tectonic event, brittle faults developed which belong to the Mur-Mürztal-Graben system. These faults displace the pre-existing tectonic melange resulting in a highly differentiated block fault architecture. The associated steeply dipping brittle faults strike roughly parallel and perpendicular to the tunnel axis forming dense intersecting fault assemblies.

Figure 1 illustrates the heterogeneous geological surface conditions. Eight different rock types exist. Several competent blocks (e.g. limestone) are visible with sizes ranging from tens of meters up to 400 m.

Bimrock definition

The nature of bimrock systems is that blocks exist at all scales (3). Therefore, bimrocks require a characteristic engineering dimension, adjusted to a particular scale of engineering interest (18). With respect to the dimension of the tunnel Spital, a lower and an upper bound of block sizes are defined (19). The lower block size is 8.7 m and the upper block size is 70 m. The input data for calculating geotechnical relevant block sizes is deduced from the results of geological face mapping during the tunnel construction and the tunnel geometry. A statistical evaluation of block shapes reveals an average block axes ratio of S : I : L = 1 : 3.6 : 3.6. Using this representative block shape the lower block bound was calculated by equalizing the area of the tunnel face with the elliptic area of the axial plane S : L. This results in a lower block bound size of 8.7 m. The upper block size was determined by considering the tunnel diameter and the radius of the plastic zone related to the average block shape. The calculations resulted in a block size of 70 m. Between the block sizes ranging from 8.7 to 70 m the rock mass is geotechnically defined as a bimrock. Blocks smaller than the lower bound are assigned to the matrix and blocks larger than the upper bound are termed blocky rock.

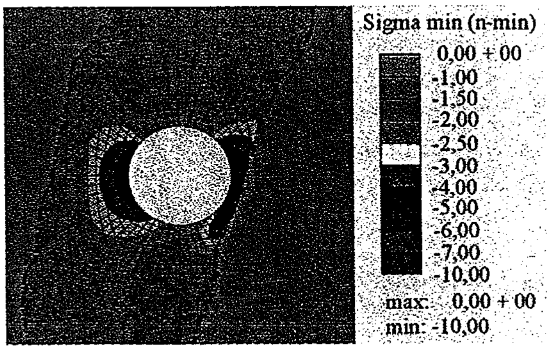


Fig. 5 Numerical analysis of type E rock mass. The geometric situation generates stress concentration at the sidewalls with the potential of sudden shear failures.

Bild 5 *Numerische Analyse des Gebirgstyps E. Die geometrische Situation verursacht Spannungskonzentrationen in den Ulmen mit dem Potential plötzlichen Scherversagens.*

Determination of block sizes and block volumetric proportions

Block sizes and block volumetric proportion influence the rock mass strength significantly. Its determination can be done during site investigations by drilling and during construction by face mapping.

Data acquisition

The data acquisition requires scan line techniques along drill cores or window mapping at

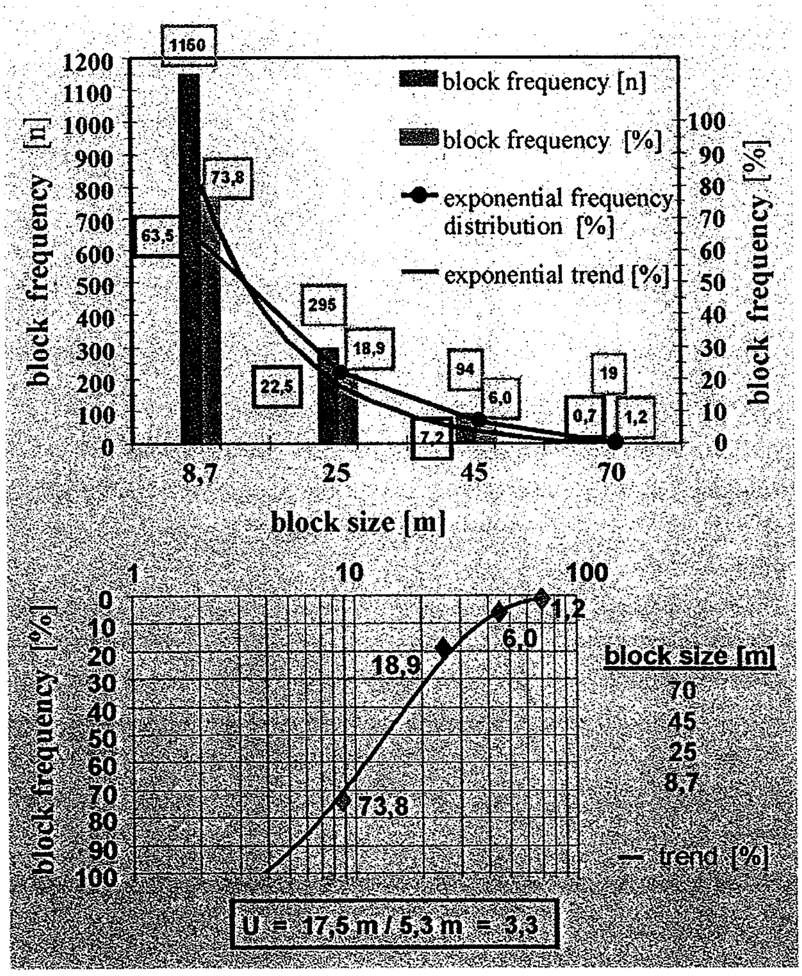


Fig. 6 Assessment of block size distributions (exponential function) being the basis for the 3D-modelling of the tectonic melange.

Bild 6 *Ermittlung der Verteilung von Blockgrößen (Exponentialverteilung) als Grundlage für die 3D-Modellierung der tektonischen Melange.*

TUNNELLING

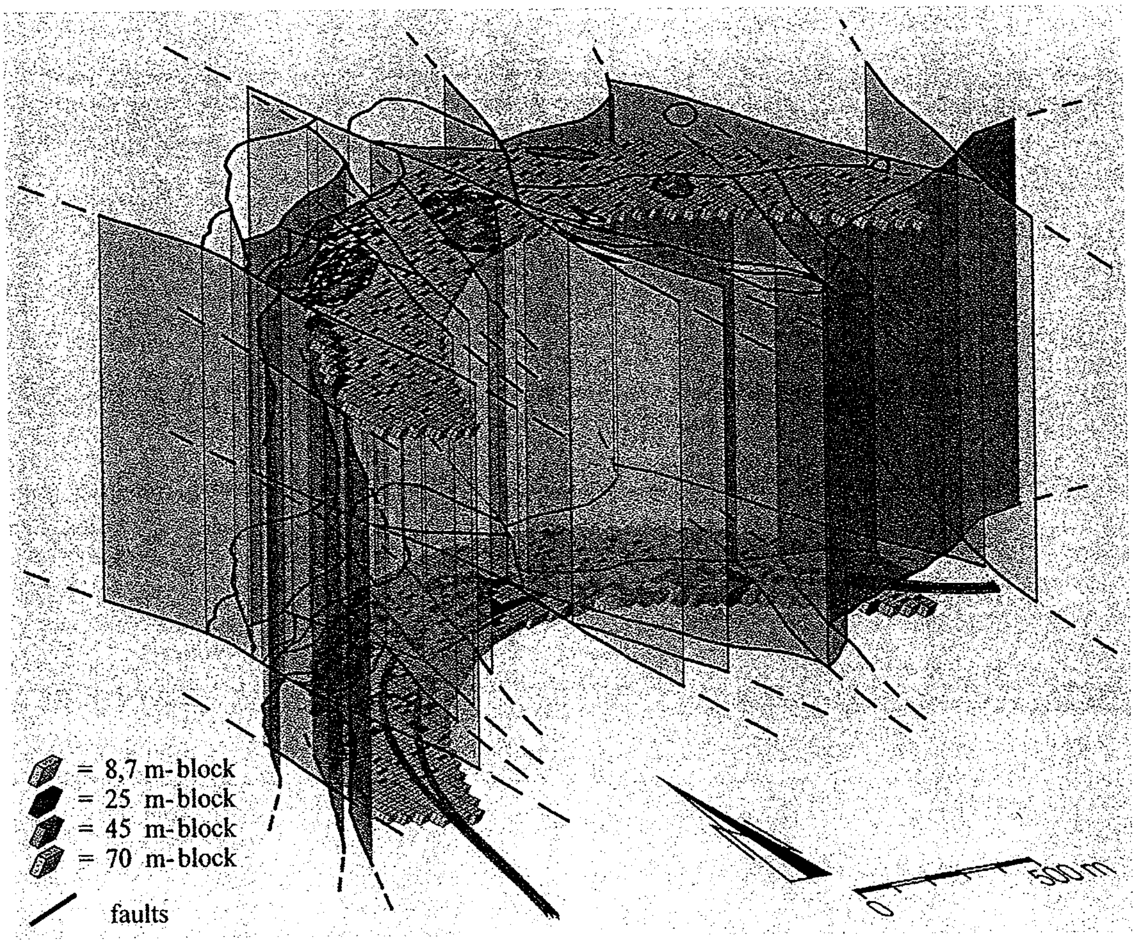


Fig. 7 The 3D-model of the alignment corridor (tunnel Spital) showing the complex internal structure of the tectonic melange. Rectangular elements with different block sizes are arranged in an upper level at surface and at the tunnel level (To allow for a visualisation of the tunnel level both levels were separated. The vertical distance is not at scale).

Bild 7 *Das 3D-Modell des Trassenkorridors zeigt die komplexe interne Struktur der tektonischen Melange. Quaderförmige Elemente mit verschiedenen Blockgrößen sind in einem Horizont an der Oberfläche und im Tunnelniveau angeordnet (aus Gründen der Visualisierung des Tunnelniveaus wurden die beiden Horizonte nicht maßstabsgetreu separiert).*

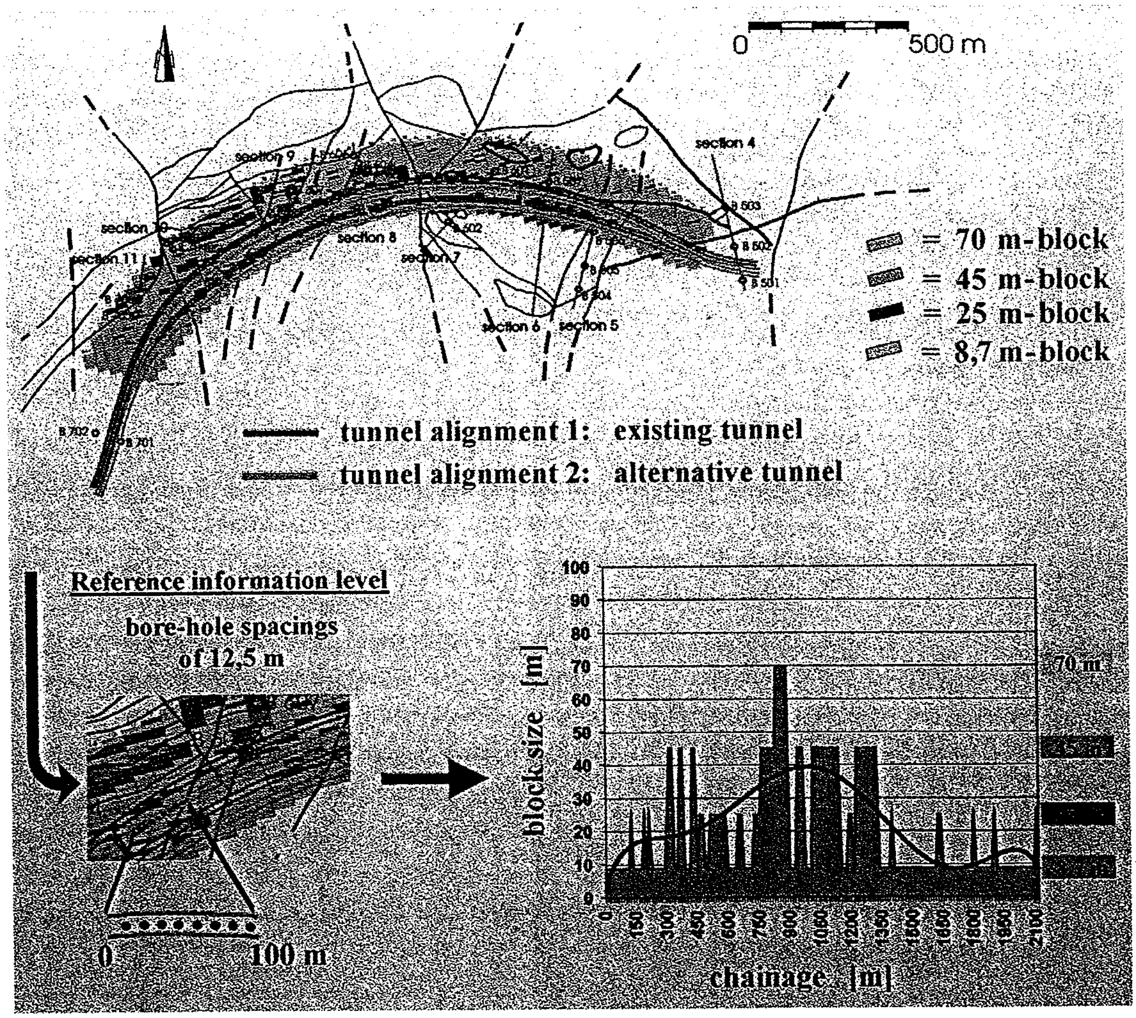


Fig. 8 Alternative studies to determine block size distributions by vertical drilling along the alignment. The reference block size distribution refers to bore-hole spacings of 12.5 m.

Bild 8 *Variantenstudie zur Ermittlung von Blockgrößenverteilungen mit Hilfe von Vertikalbohrungen entlang der Tunneltrasse. Die Referenzblockgrößenverteilung bezieht sich auf Bohrlochabstände von 12,5 m.*

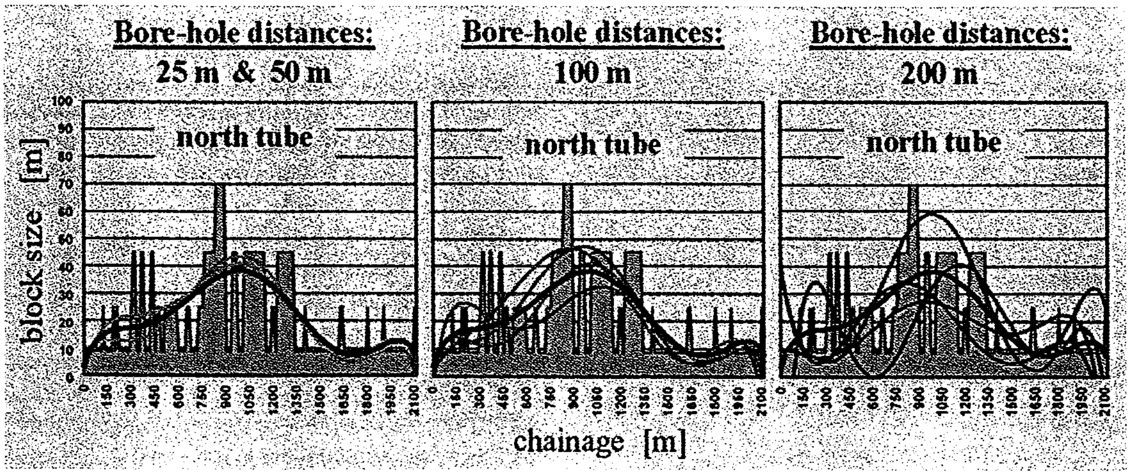


Fig. 9 Assessment of block size distributions along the north tube of alignment 1. Iterative analysis of the accuracy of block size prediction depending on different bore hole spacings (12.5 m = black trend line = reference line; 25 m; 50 m; 100 m; 200 m).

Bild 9 *Ermittlung von Blockgrößenverteilungen entlang der Nordröhre der Tunneltrasse 1. Iterative Analyse der Genauigkeit der Blockgrößenprognose in Abhängigkeit von verschiedenen Bohrlochabständen (12,5 m = schwarze Trendlinie = Referenzlinie; 25 m; 50 m; 100 m; 200 m).*

the tunnel face. The total drill core length fundamentally influences the level of information. The minimum drill core length should be approximately ten times the estimated maximum block size (3). For the most economic determination of the block matrix ratio borings should be oriented perpendicular to the blocks longest axis (Figure 2).

To improve data acquisition for determining block volumetric proportions photogrammetrical methods have been applied (20). Figure 3 exemplifies the 2D-morphometry at the tunnel face. Representative block geometries are acquired from precise 2D-data obtained from the face and are converted analytically into corrected block size distributions (BSD) describing 3D-block dimensions (21). This new method provides the most accurate determination of true block sizes based on stereological principles.

Evaluation of melange specific rock mass behaviour

To examine the correspondence between the rock mass behaviour and bimrock specific features block volumetric proportions, block sizes and contact frequencies (block/block, block/matrix, fault/matrix) are evaluated from the results of face mapping and are correlated with the results of displacements monitoring ("Behaviour Evaluation Method", 19). It is shown that the different behaviour characteristics, which include significant geometrical features as well as displacement parameters lead to three basic rock mass types. These are block-dominated rock mass, intermediate rock mass and matrix-dominated rock mass. These three rock mass types correspond to five behaviour types. The evaluation exhibits an excellent agreement between displacements and the melange-specific geometric features (Figure 4).

To better understand the stress redistibutions in the rock mass, 2D-Finite Element models (22) were used to evaluate local stress concentrations and critical states during the excavation. Significantly different shear strains between stiff elastic blocks and the weaker plastic matrix induce shear stresses at block boundaries potentially creating dangerous states of stress (Figure 5).

Establishment of a problem related 3D model

From all the available information, including the geological investigation data and the results of the geological face mapping during construction a detailed 3D rock mass model has been developed. The model consists of a geological evaluation at the surface and at the tunnel level. It facilitates the determination of rock mass strength and the optimisation of site investigations as well as the construction.

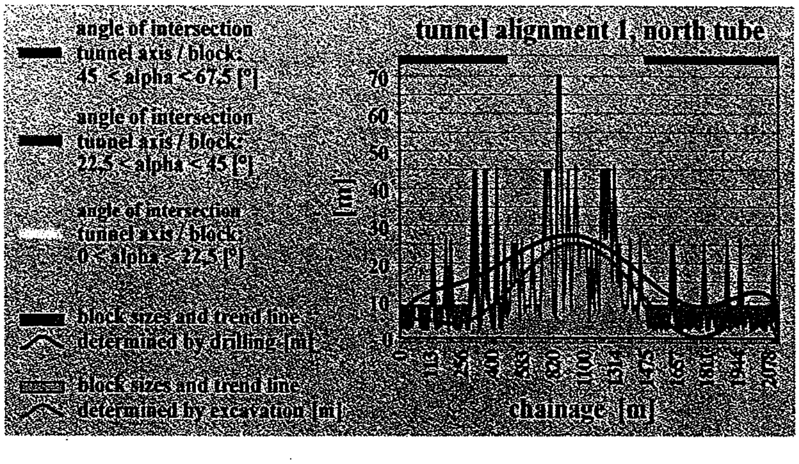
An exponential block size distribution was calculated from the observed data and is included in the model (Figure 6). The melange has been modelled as a heterogeneous, highly anisotropic continuum consisting of equally sized rectangular rock mass elements (Figure 7). Each element contains one block. As a result, the extreme heterogeneity is reduced to four different block sizes: 8.7 m, 25 m, 45 m and 70 m. Blocks are approximated as lenticular ellipsoids. They dip at 65°, which is parallel to the average foliation. The discrete brittle faults of the Mur-Mürztal-Graben system are modelled by matrix-dominated zones with 8.7 m elements.

Optimisation of site investigations

The model is used to examine the efficiency of drill hole patterns, total drill core length and the

Fig. 10 Comparison of block size prediction by drilling with block sizes evaluated by simulated excavation (tunnel alignment 1, north tube). The good correspondence of both trend lines indicates a high accuracy of block size prediction by drilling.

Bild 10 *Vergleich der Blockgrößenvorhersage durch Bohrungen mit der Ermittlung von Blockgrößen mit Hilfe eines simulierten Tunnelvortriebs. Die gute Übereinstimmung der beiden Trendkurven verweist auf eine hohe Genauigkeit der Blockgrößenvorhersage mittels Bohrungen.*



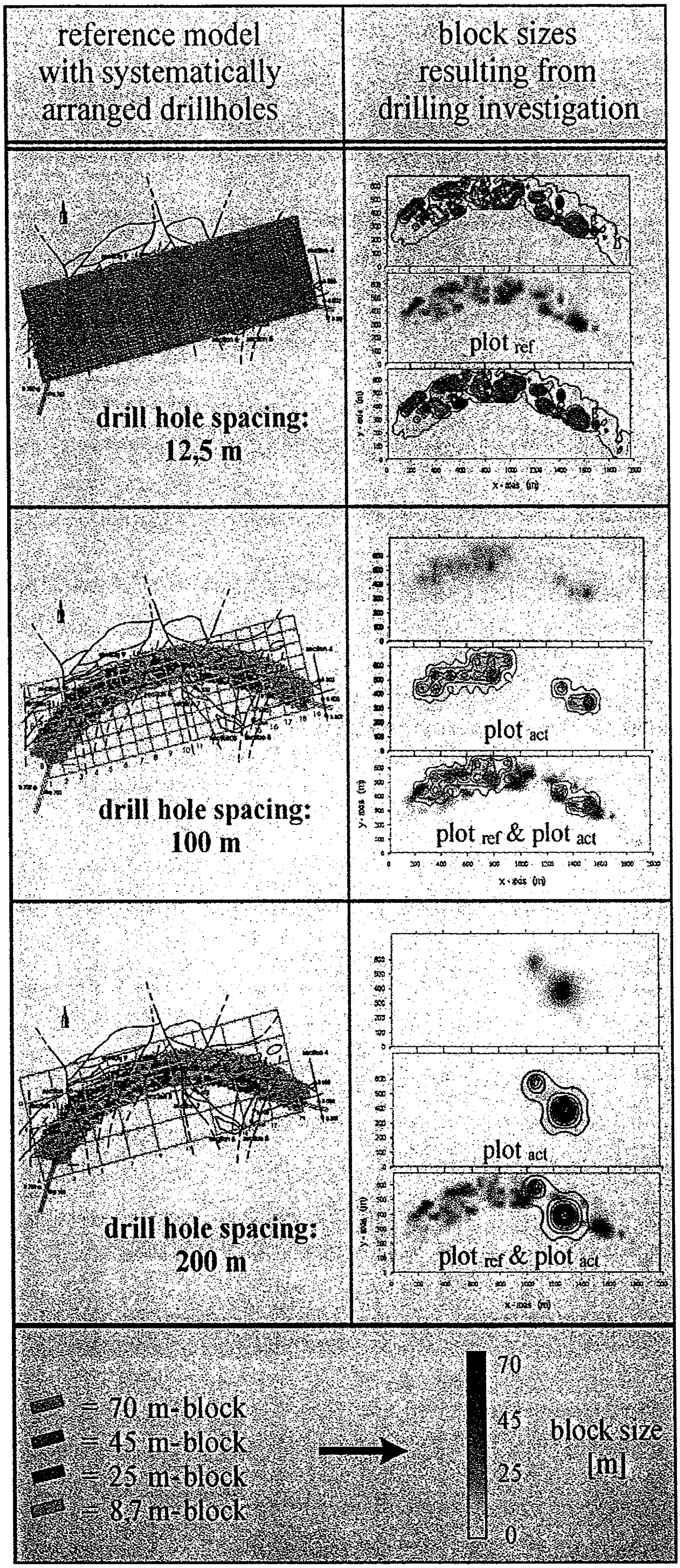


Fig. 11 Simulation of investigating the alignment corridor by arrangements of drillholes (drill hole spacings 12.5 m, 100 m, 200 m).

Bild 11 *Simulation einer Tunnelkorridor-Erkundung mittels systematisch angeordneter Bohrungen (Bohrraster 12,5 m, 100 m, 200 m).*

reliability of the prediction. To show the influence of the drill-hole pattern on the investigation of the block size distribution, the spacing of borings within the tunnel alignment corridor were varied. Drilling arrangements along two tunnel alignments have been investigated (tunnel alignment 1: existing tunnel, tunnel alignment 2: alternative tunnel, Figure 8).

The arrangement of drill hole locations was also varied to examine the most economic borehole spacing (12.5 m; 25 m; 50 m; 100 m; 200 m). In Figure 9 the accuracy in the block size prediction is estimated qualitatively by comparing trend lines related to the borehole spacing. Increasing the borehole spacing produces trend lines that show deviations from the reference trend line (12.5 m spacing). It is shown that borehole spacings up to 100 m give adequate results. Drilling results from borehole distances exceeding this threshold value of 100 m are not reliable. Enlarging the distances up to 200 m provides block size-trends that reflect significant uncertainties.

Block size distributions resulting from the simulated drilling investigations along the tunnel axis are compared with block intersection lengths revealed by the simulated excavation. This evaluation is done by simulating different intersection lengths of the tunnel axis with blocks varying in size and orientation. The results are used to determine the accuracy of the block size prediction at the tunnel level based on core drilling (Figure 10). This simulation shows an excellent agreement between the block size trend lines evaluated from both drilling and the excavation. This demonstrates that drilling is an adequate method to investigate the complex structure of tectonic melanges.

Based on the results of the simulated drilling investigations, the entire alignment corridor has been investigated by systematically arranged drill holes. The drill hole distances have been varied from 12.5 m to 200 m. Figure 11 shows that a realistic model of the tectonic melange is achieved by drill hole arrangements of at least 100 m distance. Drill hole spacings exceeding 100 m give unreliable results. Density plots of the drill hole pattern with a 200 m spacing reveals a significant lack of information.

Assessment of rock mass strength

Evaluating block sizes and block volumetric proportions per element enables the extrapolation of the three basic rock mass types (matrix-dominated, intermediate, block-dominated, Figure 4) over the entire model. The three rock mass types are qualitatively allocated strength properties. It is assumed that increasing block sizes and block volumetric proportions lead to increasing rock mass strength. This assumption is confirmed by an excellent agreement of rock mass types with the results of displacement monitoring (Figure 12).

Determination of sections with the potential for support reduction

On basis of the 3D-melange model the possibility exists to determine tunnel sections with the potential for support reduction. Basically, radial displacements decrease when excavating large blocks.

The length of support controlling tunnel sections in blocks depends on the scale of engineering interest (tunnel diameter and relevant geotechnical boundary conditions, such as overburden). An evaluation was performed that may serve as an example for tunnels excavated in block-in-matrix systems. The intersection lengths between the tunnel axis and blocks ("real excavated sections") were determined over the entire tunnel length.

The project specific support controlling intersection length was determined to be 1.5 tunnel diameters (15 m). The trend line of block intersection lengths revealed by the simulated excavation for the north tube of tunnel alignment 1 indicates the potential for support reduction between chainages 550 and 1 400 m (Figures 13, 14).

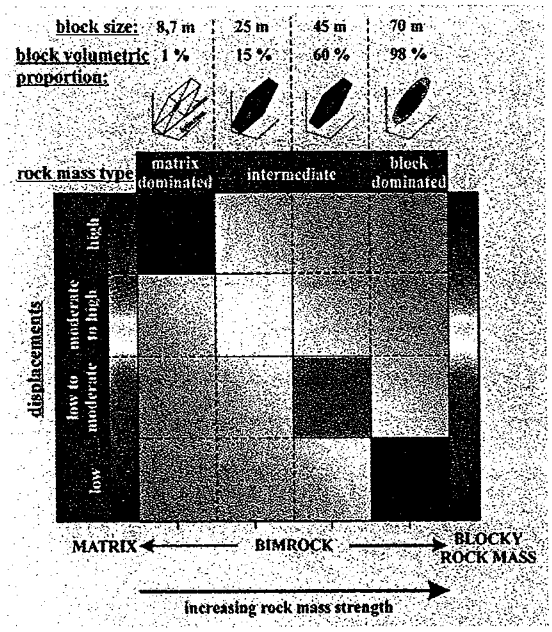


Fig. 12 Block sizes and block volumetric proportions qualitatively plotted against displacements. Block volumetric proportions are mean values of five different block positions per rectangular element.

Bild 12 *Blockgrößen und Blockvolumen-Anteile qualitativ aufgetragen gegen Verschiebungen. Die Blockvolumen-Anteile sind Mittelwerte aus fünf verschiedenen Blockpositionen pro Quaderelement.*

The calculations also show that the south tube of alignment 1 has a potential for a support reduction for approximately 50 % of the length. No potential for support reduction exists along

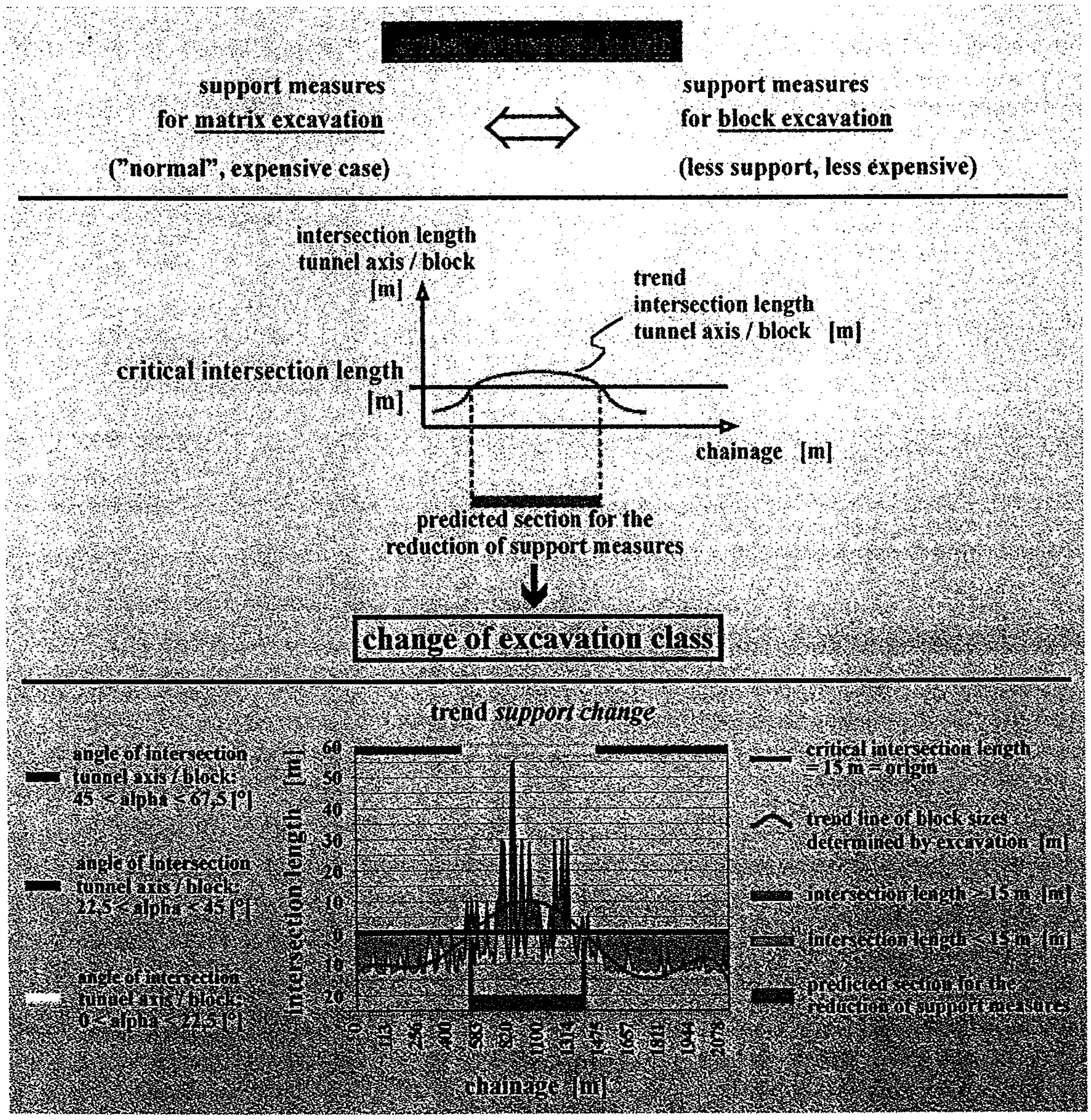
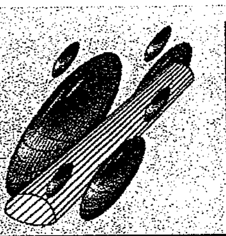


Fig. 13 Determination of the support controlling intersection lengths between tunnel axis and blocks (tunnel alignment 1, north tube).

Bild 13 *Bestimmung von den Ausbau bestimmenden Verschnittlängen zwischen der Tunnelachse und Blöcken (Tunneltrasse 1, Nordröhre).*



		sections with the potential of support reduction			
		total length [m]	total length [%]	from chainage [m]	to chainage [m]
alignment 1	north tube $\Sigma = 2115$ m	850	40,2	550	1400
	south tube $\Sigma = 2020$ m	1018	50,4	432	1450
alignment 2	north tube $\Sigma = 2115$ m	–	–	–	–
	south tube $\Sigma = 2020$ m	353	17,5	1100	1453

Fig. 14 Calculation of the potential for support reduction for the actual and the alternative alignment.

Bild 14 *Berechnung des Potentials einer Stützmittelreduktion für die bestehende und die alternative Tunneltrasse.*

the north tube of tunnel alignment 2, whereas 17 % of support reduction potential exists for the south tube of alignment 2.

Conclusions

Tunnelling in a tectonic melange of high structural complexity requires a geotechnical relevant characterisation of bimrock specific features according to the scale of engineering interest. Based on such a state of the art characterisation, the construction of a tunnel can be optimised. It is important to develop a problem related three-dimensional rock mass model. As demonstrated in this study deterministic and probabilistic data are systematically combined and completed with geometrical and numerical model simulations. With the possibility to serve the interests of owners as well as contractors, the results of the case study tunnel Spital provide a practical example for future tunnel projects, contributing to more economic and safe tunnel constructions in tectonic melanges.

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