Tunnelling in Fault Zones – State of the Art in Investigation and Construction

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Faults are elongated, complex zones of deformation, ranging from decimetres to kilometres in magnitude. For engineering projects the so called brittle fault deserves our particular attention. This type of fault zone is generated in the upper 5 to 10 km of the Earth's crust. A regular pattern of shear and tensile fractures has developed in brittle faults, reflecting the geometry of the strain field and, consequently, the orientation of the principal stresses (1, 2).

The brittle rock deformation, such as particle size reduction by crushing of grains and reorientation of grains by shearing, generates the characteristic fine-grained gouge (3, 4). Low-temperature solution transfer substantially contributes to the alteration of fault rocks, in particular of gouge, through transformation and neoformation of clay minerals (5, 6, 7).

Brittle faults are geotechnically significant because of their substantial heterogeneity in rock mass properties. Brittle fault zones consist of randomly occurring units of more or less undeformed, unaltered rock, called "knockers" or "horses" (8). These mainly lenticular units exhibit a fractal distribution of dimensions, ranging from the microscale to hundreds of meters in length and are typically surrounded by highly sheared fine-grained gouge and fractured, brecciated rock mass which appears to be flowing around the horses in an anastomosing pattern. The ratio of weak clayey gouge matrix to rock blocks of different sizes, shapes and strengths is extremely variable (Figure 1). E. Medley has introduced the term „bimrocks" to characterise tectonic block-in-matrix-rocks (9, 10, 11).

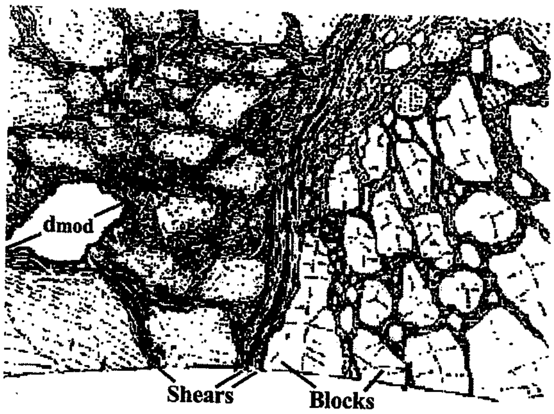

Fig. 1 Typical outcrop of chaotic block-in-matrix rock (11).

Bild 1 *Typischer Aufschluß einer chaotischen Melangezone (11).*

Groundwater conditions are also highly variable in brittle fault zones. Water pressures and flow direction may change dramatically across fault zones. Accordingly effective drainage and support measures for underground excavations become extremely difficult.

Brittle fault zones are a great challenge for geologists and engineers involved in the design and construction of tunnels (12).

To successfully cope with severe geotechnical problems, which usually are encountered by tunnelling through a fault zone, a realistic three dimensional geological model based on a geotechnically relevant investigation and characterisation of the fault zone has to be established. A

Tunnelbau in Störungszonen – Stand der Technik der Vorerkundung und der Bauausführung

Tunnelbau in Störungszonen erfordert spezielle Aufmerksamkeit und Know-how in allen Phasen des Projekts. Ein Großteil der Schwierigkeiten, die bei der Durchörterung von Störungszonen auftreten, sind auf die Heterogenität der Störungszonen zurückzuführen. Geotechnische Aspekte der Erkundung und der Charakterisierung von Störungsmaterial werden behandelt. Eine technisch und wirtschaftlich befriedigende Baudurchführung gelingt nur, wenn der Bauvertrag eine flexible Anpassung an die aktuellen Gebirgsverhältnisse erlaubt. Das geologische Modell muß während der Bauausführung laufend aktualisiert werden. Darauf aufbauend kann eine laufende Anpassung an die Gebirgsverhältnisse erfolgen. Fallbeispiele demonstrieren die Schwierigkeiten des Tunnelbaus in Störungszonen und zeigen neuere Entwicklungen auf dem Sektor des Tunnelausbaus.

Tunnelling through brittle fault zones requires special considerations during all phases of a tunnel project from design to construction. The geotechnical problems during construction relate primarily to the substantial heterogeneity of fault zones. Geotechnical aspects of fault characterisation and problems of investigating a fault zone are discussed. It is demonstrated that a technical and economical optimization of construction can only be achieved by a flexible contractual set-up which allows for adaptation of the construction method on site. In this context it is emphasised that, based on a continuous evaluation of geological and geotechnical monitoring data, the predicted geological model continuously is adjusted to the observed conditions. Based on the updated model, excavation and support is adjusted accordingly. The principal geotechnical difficulties and adequate measures to cope with those problems during excavation of tunnels in brittle faults and the development of advanced support technology are demonstrated by case studies.

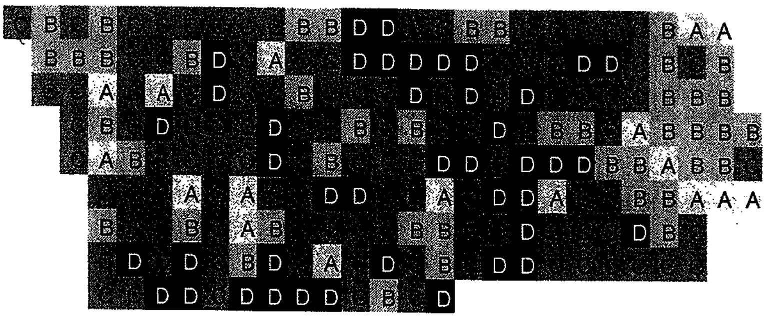

Fig. 2 Koralmtunnel, Austria: TBM risk assessment for route preselection (A – low risk, D – very high risk).
Bild 2 *Risikobewertung für TBM-Vortrieb beim Koralmtunnel (A – geringes Risiko, D – hohes Risiko).*

sound geotechnical assessment of faults, followed by three dimensional modelling, has to continue through all design stages from route selection, preliminary, tender and final design to construction. This approach is essential to technically and economically optimize the design and construction of tunnels.

Investigation / design

Route selection / conceptual design

The investigation for the route selection is usually based on the review of existing data, the evaluation of satellite images (LANDSAT-TM, SPOT-PAN) including DM-data ("digital elevation model") as well as aerial photographs and on studies of selected outcrops. Main investigation target is the assessment of the fault pattern and the principal understanding of fault kinematics.

The route preselection study of the "Koralm Tunnel" (length 30 km, maximum overburden approximately 1 700 m) in Austria may serve as an example. For the preselection of tunnel routes a corridor with a width of approximately 12 km and a length of roughly 25 km has been classified with respect to TBM tunnelling risk (Figure 2). The key classification parameter besides discontinuity orientation, height of overburden and lithology was the adverse influence of major faults. It was assumed that extensional faults with trace lengths of more than 10 km which developed in areas with high densities of lineaments will have the worst influence on a TBM performance (13). In such faults significant interruptions of the TBM excavation, requiring time consuming remedial measures due to squeezing rock conditions and associated high water inflow were anticipated.

Environmental impact assessment / preliminary design

Investigation

During this design step a first geometrical and a preliminary mechanical model of the fault zone has to be established. Site investigations require detailed engineering geological mapping (scale usually not smaller than 1 : 5 000) and subsurface investigations by geophysical survey, trenches, trial pits, core drilling and borehole tests. Laboratory tests, including mechanical and mineralogical analyses, will contribute to the characterisation of intact rock properties. Brittle faults are usually concealed under considerable thickness of overburden making it necessary to infer their presence indirectly from morphological evidence. Significant are more or less continuous linear, steep relief features, so called fault escarpments. One further type of surface feature that helps locate and trace brittle faults are long elongated depressions which are often associated with seeps and/or swamps, landslides and creeping areas.

It is emphasised that lithological sequences offsets, generally considered the main indication of a fault, tends to be difficult if not impossible to identify in the field. Features found on rock exposures may provide us with important indications of fault zones including preferred orientation of major joints, severe fracturing and slickensides with striations indicating the most recent tectonic slips and relative movements.

Paleostress analyses to a certain degree allow to reconstruct the deformational history of the project area. Based on such analyses, extensional and compressional fault domains can be distinguished that may have geotechnical implications. For example, in extensional domains, characterised by normal or oblique-slip extension faults, a deep-seated, open-jointed rock mass or joints healed by secondary minerals may prevail. The initial stress situation here may be characterised by the lack of confining pressure, whereas in compressional regions, indicated by reverse and strike-slip faults and by oblique-slip compression faults, a high confining pressure may exist.

Exploring brittle fault zones by means of core drilling is a very exacting job requiring an experienced geologist, a particularly skilled drilling crew, and high-quality drilling equipment. Both equipment and technique must be selected to suit the particular ground conditions of the fault zone.

Also, to obtain satisfactory information from core drilling, high core recovery must be achieved. The drilling operations should be carried out with great care under the supervision of an experienced specialist and in such a way as to avoid washing out fine-grained gouge material and disturbing the shear structures.

Appropriate results are obtained by drilling in faults continuously with double or triple tube core barrels. As a proper flushing agent, the polymer GS 550 is recommended. Like bentonite, it avoids the disintegration of the drilling core and promotes drillhole stability by forming a filter skin on the wall of the hole. Unlike bentonite, the extremely thin GS 550 filter skin is transparent.

Repeated changes between dry and wet drilling methods, as is common when drilling "block-in-matrix-rocks", should be avoided because it reduces the drilling rate and lowers the quality of core samples.

The engineering geologist's core logs should specifically record the ratio between fine-grained gouge matrix and rock fragments, the degree of alteration and fracturing, as well as the surface properties of discontinuities and their inclination to the borehole axis.

A kinematic structural geological analysis on selected drill cores is typically performed to differentiate between extensional and compressional domains Surface characteristics of discontinuities, including secondary growth minerals and solution phenomena are key parameters for this kinematic analysis. The kinematic evaluation of drill cores should be substituted by an in situ analysis by means of the "Acoustic Borehole Televiewer" which investigates orientation and densities of discontinuities.

Additional borehole in-situ-testing in fault zones may consist of hydraulic borehole tests such as slug-pulse tests, and dilatometer tests, which are used to obtain hydraulic parameters and data relating to the deformability of a rock mass. However, due to the extreme variability of fault zones with alternations of weak and hard rocks, the execution of the tests is risky and time-consuming and the obtained data are only reliable with some reservations.

Groundwater elevations and fluctuations are typically monitored by stand pipe or piezometer installations to provide a continuous, long-term check on the groundwater conditions. Due to the hydrogeological variability along fault zones, quite a large number of such instruments are needed.

The exploration of fault zones by direct investigation methods should be supplemented by geophysical methods. Gamma-log measurements are preferred which provide information on fault zones dominated by clayey gouges or other conductive minerals. A conventional geophysical field survey incorporates refraction seismic methods and resistivity methods. More recently, reflection seismic methods have been successfully applied to get a better understanding of the fault geometry along a tunnel alignment. One problem with this method is the difficulty in precisely locating the obtained structural models.

Rock mass parameters

To adequately characterize the mechanical properties of rock mass within fault zones, we must mainly rely on laboratory core sample tests. However, it should be pointed out that the accuracy in determining rock mass parameters decreases with increasing weakness of the rock concerned. Conventional laboratory analyses should include triaxial and direct shear tests, swelling tests and quantitative clay mineral analyses. The risk of disturbing core samples, the problems involved in sample preparation and, finally, the extreme variation of test results all make it extremely difficult to obtain representative mechanical data. Experience has shown that reliable mechanical fault gouge data can be gained from drained direct shear tests on disturbed samples of grain size fraction < 40 μm.

Translating the laboratory results and results of field investigation into mechanical parameters, sufficiently describing the behaviour of a brittle fault zone is a very difficult task. Although various valuable procedures for determination of parameters are available (11, 14), experience and engineering judgement will always be required.

Design

In this project phase analytical calculations or very simple numerical models can be applied (15, 16). Figure 3 shows the result of an analytical analysis, which was performed recently for a road tunnel project in Greece, situated in an area with a very complex internal structure of thrust faults. Based on the geological model, laboratory test results, and experience from tunnelling in poor ground typical rock mass parameters have been estimated. Introducing different types of support for the different types of rock mass one arrives at a rough estimate of displacements to be expected. With this simple analytical method parametric studies can be performed very easily, like effectiveness of different support types, variations in rock mass parameters, or effects of different primary stress conditions. In addition critical sections can be identified and, if required, studied in more detail.

Tender design / construction contract

The main task of the tender design is the translation of geological and geotechnical data through

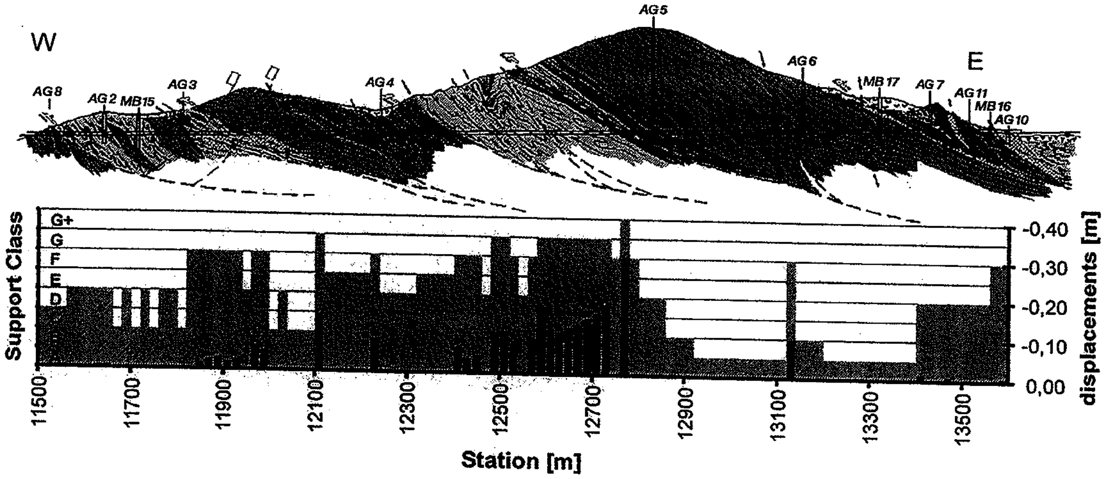

Fig. 3 Anilio tunnel, Greece: geological longitudinal section and results of analytical calculation of support and expected displacements.

Bild 3 *Geologischer Längsschnitt des Aniliotunnels, Griechenland, und Ergebnis der analytischen Abschätzung von Deformationen und Stützmittelklassen.*

mechanical analyses into an adequate tunnel design and construction contract (17). As the analytical approach of the previous design stage is a rough one, preliminary designed supports should be checked and modified, using numerical simulation models. Due to the still considerable effort required for such simulations, only a few typical sections are usually selected and computed. The model used shall match the geological conditions of the fault zone, which means that for jointed material rather DE-methods will be used, while for sections, dominated by more homogeneous gouge FE-codes are advantageous. In this phase the effectiveness and utilisation of the designed support is checked by those tools, and modified if necessary. The principal difficulties to be dealt with in this context are the uncertainties inherent in the geological prediction, the adequacy of the model used, and in the assessment of such factors as site management, quality of workmanship and support effects.

Construction contract

One of the key elements for successful tunnelling in difficult ground is the layout of the construction contract, and the role the owner plays during the execution of works. As the so called geological risk, at least to a certain extent, will always remain with the owner, it is wise to actively participate in the construction by providing an experienced supervision team.

For tunnel projects in fault zones the owner's site team should include following qualifications:

- Engineer in charge of contractual matters with strong geotechnical background,
- Geologist for documentation and short term prediction,
- Geotechnical engineer in charge of evaluation and interpretation of monitoring data, classification and support layout,
- Supervisors with foreman qualification,
- Surveying team for displacement monitoring.

The contract should guarantee enough flexibility to authorise modifications of excavation and support according to the type of rock mass encountered during tunnelling in the fault zone. Such procedures are essential for technical and economical optimization of the construction. This means that any potential geotechnical problem should be considered in the tender documents. Reasonable construction costs will be attained when the bill of quantities is adjusted to a realistic geological model of the fault zone.

Construction – problems and appropriate methods

Due to the frequently changing rock strength, deformability and groundwater conditions in brittle faults we have to provide construction methods with great adaptability to allow for uncertainties in the prediction of rock mass behaviour.

The principal geotechnical difficulties likely to be encountered when driving a tunnel through a fault zone are:

- Instability of the face,
- Excessive overbreak,
- Excessive deformation by squeezing or swelling fault rocks,
- Instability of intermediate construction stages,
- Frequently changing stresses and displacements,
- Excessive water inflow frequently associated with flowing ground.

The standard excavation sequence when driving a tunnel in a fault zone in Austria is top heading, then bench, and invert. The excavation is mainly performed using an tunnel excavator. Supports usually consist of rock bolts, shotcrete, wire mesh and steel ribs. The advance length in general does not exceed 1.5 m. Supplementary measures like forepoling, in extreme cases the installation of a pipe roof, or face support by bolting increase the stand-up time and stability of the face.

In other countries a preference for full face excavation methods can be observed. The stabilization of the face in that case often requires extensive bolting or other auxiliary measures. Although this in many cases may be technically feasible, time requirement and costs are much higher than with a sequential excavation.

Final design during construction

Despite careful investigations during planning phases a variety of geological and geotechnical uncertainties at the tunnel level will remain due to the extreme complexity of a fault zone. It will never be possible to accurately predict the complex ground conditions, for example, the block/matrix ratio, strength properties, primary stresses, groundwater situation. Consequently deformation rate, final deformation and required support can not be anticipated accurately enough. To avoid inadequate support as well as time and cost overruns due to geotechnical uncertainties the predicted geotechnical model has to be continuously updated. This task can only be achieved by continuous data recording, evaluation and interpretation through a geological and geotechnical site assistance.

Data recording

Geological face logging

An objective of recent research in our group is unbiased identification of structural features at the tunnel face achieved by electronic stereographic imaging using rotating CCD line-sensor-cameras (18). This method of geological documentation allows continuous updating of the existing geological model in 2D as well as 3D. With results of geotechnical monitoring the appropriateness of the generated model can be checked and by selective modifications of the model a best fit result can be achieved.

Geotechnical monitoring

An essential task for safe and economical tunnelling is geotechnical monitoring during excavation. Displacement measurements by geodetic methods have been used increasingly in recent years. This method allows the observation of three dimensional displacements providing extremely useful information. Due to the increased information obtained by absolute displacement monitoring additional instrumentation like extensometers, stress and strain measuring devices are used in special cased only. Geophysical methods have been increasingly applied for the prediction of rock mass structure and quality. Experience shows, that there is still some room for development.

Data evaluation and interpretation

A huge amount of data from geological face mapping and geotechnical monitoring is obtained during the tunnel excavation. A requirement for utilising the updated geotechnical model as a decision aid for tunnelling is an immediate and continuous evaluation of all recorded data from geological face logging and geotechnical monitoring. It is essential to correlate these data with all relevant information including support and excavation methods. For this purpose we have developed an electronic data management system which facilitates unbiased evaluation of geological, mechanical, hydrogeological data as well as excavation and support related information (19, 20). This data evaluation system for tunnelling (DEST) is structured into data bases with different hierarchic levels. The main advantage of this data base system is that it does not only serve as a data management tool, but that input data are automatically interpreted in terms of their influence on tunnelling. For the interpretation expert knowledge as well as statistical and probabilistic methods are used.

When displacement monitoring data in combination with geological data are properly evaluated and interpreted, construction and support can be optimally adjusted to the rock mass structure and the stability of the tunnel can be verified in time. It has been shown, that reliable short term prediction of the rock mass quality ahead of the tunnel face is possible by evaluating the spatial orientation of displacement vectors (21, 22).

One of the big problems is the prediction of the final tunnel closure in heterogeneous fault zones. Current research is tackling this problem (23). Using information from DEST, displacement monitoring, and geological mapping, good results for the prediction of the displacements are obtained.

Although various tools have been developed to ease interpretation of monitoring data, however, rock mechanical expertise and practical experience in tunnelling is still required on site. When geologists and engineers co-operate to jointly evaluate and interpret data from the continuous recording of rock mass conditions and in-situ monitoring of rock mass behaviour, it is possible to optimize excavation and support methods as tunnel driving proceeds.

Adequate tunnel support

Support types and quantities have to be adjusted according to expected deformations and potential failure mechanisms of the rock mass. For instance, bolt length and bolting pattern are mainly determined by the rock mass structure, intermediate construction stages and by the geometry of possible shear failures. High primary stresses combined with poor ground lead to squeezing conditions. The large displacements associated with squeezing posed serious problems in support selection in the past. Stiff supports in many cases cannot sustain the loads developing. Destroyed linings are the consequence, which require a considerable effort in repair and maintenance. In addition, continuous lining failures are a safety hazard for the crew, even if the overall stability is not an issue.

Some recommend the use of yielding steel arches in close distance in combination with lagging (24), partly to ease reshaping of the tunnel. The inadequate contact between rock and support leads to loosening and local concentrated loads. Reshaping should be avoided by all means, because of the extremely high costs and dangerous working conditions. It is emphasized that the heavily reinforced "advance core“ (25) is only one of the auxilliary measures to successfully cope with squeezing rocks.

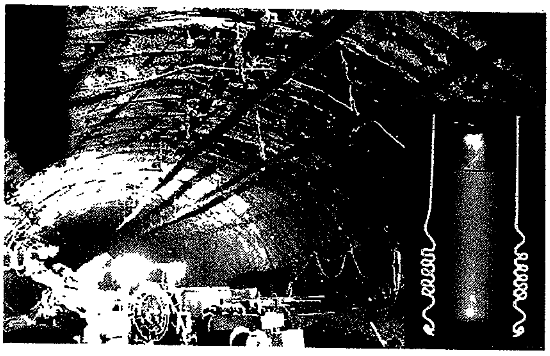

Fig. 4 Semmering basis tunnel: Shotcrete and Lining Stress Controllers (LSC) form a ductile support in a fault zone; right detail of a LSC.

Bild 4 *Verwendung von Stauchelementen in der Spritzbetonschale zur Erhöhung der Nachgiebigkeit, Aufweitung Semmering Basistunnel Pilotstollen; rechts Schnitt durch ein Stauchelement.*

The longstanding Austrian practice of leaving open gaps in the shotcrete lining to allow for deformation without lining failure has the disadvantage of poorly utilising the lining capacity. To combine ductility with resistance, a support system was developed and first applied at the "Galgenbergtunnel" in Austria (26). The basic idea of this support system is to integrate ductile elements into relatively stiff standard supports. The system consists of sets of concentrical cylinders, yielding a nearly bilinear load line (Figure 4). By varying number and dimensions of the so called Lining Stress Controllers (LSC), the system can be designed to the capacity of the linings used and displacements expected. Field applications and numerical simulations have shown the effectiveness of the system. (27, 28). A big advantage of the system is, that it is not sensitive to even abrupt changes in rock mass quality, as the capacity of the yielding elements at all phases is lower than the capacity of the lining.

Rockbolts are efficient elements to "homogenise" the rock mass, and to prevent or at least control failure of the rock mass. When using grouted bolts, one should be aware, that the bond between bolt, grout, and rock is a sensible system. A systematic investigation into this subject has resulted in a considerable improvement of the bolt performance (35).

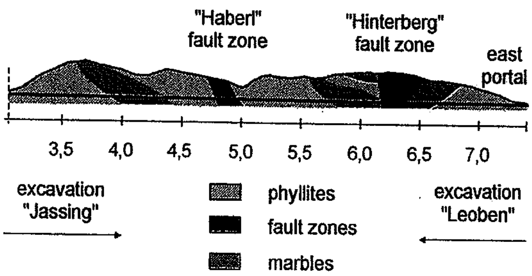

Fig. 5 Galgenbergtunnel: Simplified geological longitudinal section.

Bild 5 *Vereinfachter geologischer Längsschnitt durch den Galgenbergtunnel.*

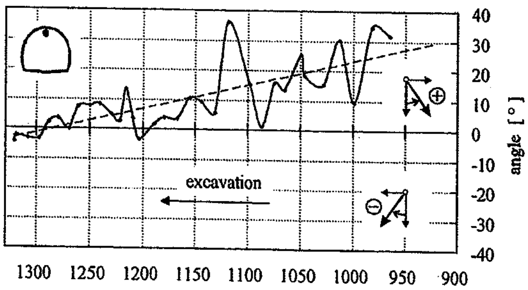

Fig. 6 Trend of displacement vector orientation along Hinterberg fault, showing significant trend.

Bild 6 *Trend der Verschiebungsvektororientierung der Firste entlang der Hinterbergstörung mit ausgeprägter Tendenz.*

Generally, a fast ring closure is beneficial for the stability and limitation of displacements of tunnels in fault zones. This can be achieved by excavating full face, short benches or by applying a temporary invert during top heading. The disadvantage of the full face approach has been discussed earlier. Short benches on the first glance appear to be attractive, but interference between the areas of excavation, both operational and in terms of stress redistribution limit this procedure to tunnels with low cover.

Fault zones at tunnel portals or under shallow cover create extremely critical stability situations with characteristically high initial deformation rates. In such cases, it may be necessary to subdivide the face and use for example advancing side galleries for bigger tunnels.

Extremely poor ground conditions in fault zones, such as flowing ground or excessive water inflow, may require side-gallery solutions and/or special ground treatment ahead of the excavation operations by grouting and drainage.

Case studies – Fault zones at the Galgenbergtunnel

The "Galgenbergtunnel" has a total length of 5 462 m. The tunnel was constructed form 1993 to 1995. The maximum overburden thickness is 260 m. The tunnel cuts through extremely variable ground, consisting of gneisses, quartzites, phyllites, greenschists and marbles, belonging to different tectonic units (Figure 5).

The folded and faulted lithological series trending generally WSW-ENE intersect the tunnel axis at an acute angle. The two major fault zones, the "Hinterberg" fault and the "Haberl" fault, have proved to be excessively difficult to tunnel through (29, 30).

Although five years passed since the completion of the tunnel project, and some development in tunnel technique took place, especially in the fields of evaluation of monitoring data and tunnel support, the case histories may be still of interest.

Hinterberg Fault

This fault zone, located between station 959 m and 1.342 m (heading Leoben), has developed between two units of massive marble. Source rocks are imbricated graphitic and carbonatic phyllite, greenschist and thinly bedded marble. The orientation of foliation planes indicate a E-W trending syncline structure with a fold axis dipping gently to the west. Slickensided shear planes most commonly dip steeply to the SSE and occasionally to the SE and NE.

The main characteristic of this fault zone is its extreme heterogeneity concerning the ratio of soft, clayey gouges to variably fractured rock mass. Despite a chaotic fault structure, it has been confirmed by statistical evaluation that the amount of clayey gouges and the degree of rock mass fracturing increases significantly along the tunnel from NE to SW.

Due to the heterogeneity of the rock mass, prediction of the tunnel performance was extremely difficult. Sections with low initial deformation exhibited long lasting displacements, while other sections stabilized rather quickly after high initial displacements. Determining the amount of overexcavation and support required was therefore extremely difficult. At the beginning of the fault zone, a rather stiff support approach was believed to limit deformations. Considerable deformations resulted in shear failures of the shotcrete lining and broken bolt heads. Open longitudinal gaps in the top heading lining were introduced and the rock bolt length and density increased. The round length was kept at 1 m. The deformation gaps in sections with extreme displacements closed completely. Due to extreme heterogeneity of the rock mass the prediction of final displacement was difficult. Consequently reshaping was required for some sections. When the excavation approached the end of the fault zone, a sudden collapse at the face of the top heading occurred without warning (31). The ensuing investigation revealed that a combination of unfavourable circumstances caused the failure, including:

- Sudden alternations of relatively stiff and soft sheared rocks,
- Low friction angle of the fault gouge ($\phi = 12$ to 14°),
- Unusual primary stress situation.

The trend of the displacement vector orientations from back analysis indicated an arch type initial stress situation within the fault zone (Figure 6). This unusual primary stress condition is caused by a lateral creeping of the fault material wedged in between the two massive marble units (Figure 7). This resulted in a higher maximum principal stress, and the development of potential shear failures in directions not usually experienced during tunnelling.

Aside the tragic accident which caused the death of one miner, the displeasing aspect of the collapse was the discovery that the support system already successfully applied on many kilometres of tunnels had shortcomings under unusual circumstances as encountered in this fault zone. Research following this accident eventually led to the support system described above.

Haberl Fault

The Haberl fault was encountered between stations 1 760 and 1 990 m (Jassing heading East). The fault zone developed in graphitic phyllite and occasionally greenschist, meta-sandstone, calcareous phyllite and platy marble. The undulating, mostly sheared foliation planes generally dip gently to the south. Additional shearing, which generated clayey gouges and fault breccia, took place on moderately to steeply NE and SW dipping shear planes.

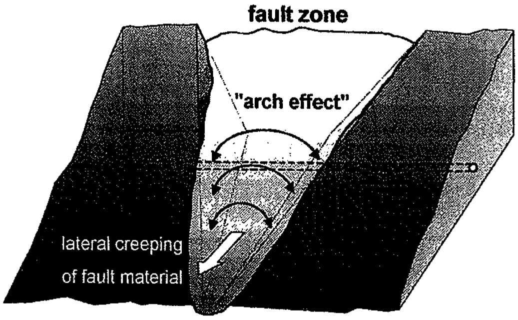

Fig. 7 Development of arch type primary stress in the Hinterberg fault (simplified model).

Bild 7 *Modellvorstellung der Entwicklung einer gewölbeartigen Verspannung in der Hinterbergstörung.*

The Haberl fault zone is characterised by pervasive homogeneous shearing which shows brittle and ductile deformation features. From the geotechnical standpoint, the most important feature of the fault zone is the alternating sequence of hard and soft rock layers.

With the experience from tunnelling through the Hinterberg fault, it was agreed that support and excavation should be modified for the tunnel construction in the Haberl fault (26, 30, 32). The modifications included:

- Reduction of the top heading height to 4.5 m to increase face stability,
- Application of 8 to 12 m long regroutable self drilling bolts,
- Integration of yielding steel elements in the shotcrete lining.

The modifications were targeted to reduce displacements in the excavation area and to guarantee rock bolt performance even after big deformations, thus increasing stability and safety. Technically the solution was convincing. Final displacements did not exceed 15 cm, nearly a magnitude smaller than at the Hinterberg fault zone. At no time was there any sign of instability.

The reduction of displacements in the soft rock layers prevented high stress concentrations in the hard rock layers. Thus the risk of a brittle failure of the stiff layers as experienced in the Hinterberg fault zone was minimised.

Due to the time consuming installation of regroutable bolts and the reduction of the top heading height, the excavation rate could not be increased over an average of 1.7 m per day, increasing construction time and cost. On the other hand, no reshaping or repairs were required on the 350 m of tunnel where this modified construction method was applied.

Discussion

Tunnelling through the Hinterberg fault zone was considerably affected by abrupt changes of deformability and strength of the rock mass. Deformation magnitudes varied over a wide range with a maximum of crown settlement of approximately 1 m (Figure 8). The vector orientation of the crown showed a significant trend indicating the arch type orientation of initial principal stresses. Strong local variations of displacement vector orientation point to the heterogeneity and abrupt changes in rock mass stiffness.

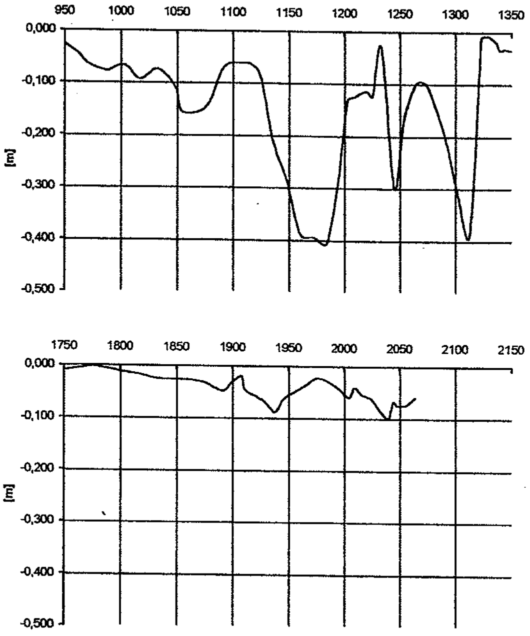

Fig. 8 Deformation magnitudes: trend of crown settlement 15 m behind face; Hinterberg fault (top) and Haberl fault (bottom).

Bild 8 *Trend der Firstsetzungen 15 m hinter der Ortsbrust, oben Hinterbergstörung, unten Haberlstörung.*

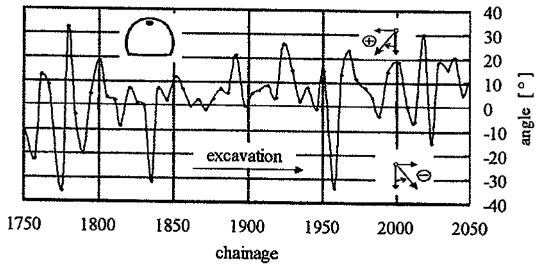

Fig. 9 Trend of displacement vector orientation along the Haberl fault, showing strong variations due to the heterogeneity of the rock mass.

Bild 9 *Trend der Verschiebungsvektororientierung entlang der Haberlstörung mit starken lokalen Variationen, welche die Heterogenität des Gebirges zeigen.*

In the Haberl fault zone deformation magnitudes did not differ significantly. The vector orientations varied widely reflecting the complicated structure of the fault zone with sudden changes between stiff and soft rocks. A significant trend of vector orientations, showing any unusual primary stress situation was not found (Figure 9).

Conclusion

When tunnelling in fault zones, we must strive to achieve comprehensive knowledge of the discontinuity structures, of the mineralogical and mechanical properties of the fault rocks and of the hydrogeological conditions. This more complete picture is absolutely crucial for reliable geotechnical characterisation and interpretation. A geotechnically relevant classification of a faulted rock mass must consider its deformation mechanism.

Despite utmost care it is inevitable that the model of the fault zone established during site investigations contains uncertainties. As a consequence it is essential to update the geotechnical model by an immediate and continuous evaluation of all data recorded during construction. This continuous updating facilitates an optimization of the tunnel construction, with specifically tailored support elements and excavation sequences adjusted to the behaviour of the rock mass in the fault zone.

The lessons learned from tunnelling through fault zones are:

- ➪ The more heterogeneous the rock mass is, the more care has to be taken in the support selection. It turned out that even large units of competent rock within faulted rocks have to be heavily reinforced, as they are subject to stress concentration.
- ➪ A key parameter for the performance of the tunnel is the internal angle of friction of the rock mass. Consequently, more attention should be paid to the determination of this crucial parameter during investigation.
- ➪ The displacement vector orientation trend is a reliable indicator of variations in rock mass stiffness ahead of the face and should be used routinely for short term prediction when tunnelling through a fault zone (22, 33). In addition it can at least qualitatively provide information on primary stress orientation (34).
- ➪ Tunnelling through fault zones is costly and time consuming. Careful engineering and continuous updating of the design based on monitoring data and increased knowledge of the geological structure and material parameters at site are essential for a successful tunnel construction.
- ➪ Support elements and excavation sequence should be adjusted to the behaviour of the rock mass. Recent investigations led to an improvement of rock bolts for use in poor ground conditions (35). The integration of yielding elements into the lining allows a better use of the lining capacity together with an increase of lining ductility, while limiting the lining stresses to a level well below its capacity. Improvements on this new support system have been made by our group (27,28). The effect of yielding elements integrated into the lining are also described in (36).
- ➪ It still is very difficult to predict the final convergence of a tunnel in a fault zone. Research is currently carried out in our group to develop a tool for a reliable prediction of displacements, based on displacement monitoring data and short term prediction (23, 37) We are confident that this new tool to evaluate geotechnical monitoring data will facilitate to minimise reshaping of tunnels in fault zones due to unexpected large displacements.

Tunnelling in fault zones is a task requiring sound engineering, readiness to continuously learn during construction, and excellent workmanship. Techniques applied shall be up to date and robust. There is no room for theoretical, sophisticated discussions without practical relevance.

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