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Tunnelling in Fault Zones – State of the Art

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ABSTRACT

Alpine fault zones are complex structures, exhibiting highly heterogeneous rock mass conditions. In addition the permeability can vary in a wide range. High displacements, stability problems, and ground water inflows are common phenomena observed during tunnelling through fault zones.
Besides the choice of an appropriate construction method for such conditions, the safety and long-term stability of the underground structure are major issues.
The paper addresses investigation methods and targets to obtain the key parameters determining the rock mass behaviour, as well as rock mass characterization methods, criteria for the selection of appropriate construction methods, depending on the expected conditions.
Even with the most advanced investigation and design methods uncertainties with respect to geological structure, rock mass parameters, and hydrological conditions remain. A continuous updating of the ground model thus is essential for safe and economical tunnelling. Advanced methods of short-term prediction and investigation ahead of the face during construction are presented.
State of the art excavation and support methods are shown and future developments discussed

1. INTRODUCTION

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 kilometres 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 (Mandl 1988,1999). 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 (Scholz 1990, Twiss et al. 1992). Low temperature solution transfer substantially contributes to the alteration of fault rocks, in particular of gouge through transformation and neoformation of clay minerals (Riedmüler 1978, Wu 1978, Klima et al. 1988). Brittle fault zones consist of randomly occurring units of more or less undeformed, unaltered rock, called „knockers" or „horses" (Goodman 1993). These mainly lenticular units exhibit a fractal distribution of dimensions, ranging from the micro scale 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


Figure 1. Typical composition of a brittle fault zone

horses in an anastomosing pattern. The ratio of weak clayey gouge matrix to rock blocks of different sizes, shapes and strengths is extremely variable. Medley has introduced the term "bimrocks" to characterise tectonic block in matrix rocks (Medley 1994, 1998, 1999). The extreme stiffness contrast between blocks and matrix leads to strongly heterogeneous displacements and secondary stress distribution along the tunnel during and after excavation.
Groundwater conditions are also highly variable in brittle fault zones. Water pressures and flow direction may change dramatically across fault zones.
To cope with the problems usually encountered when tunnelling through fault zones, a realistic three dimensional geological model based on a geotechnically relevant investigation and characterisation of the fault zone has to be established. Modelling has to continue through all design stages from route selection to construction. Powerful on-site engineering is essential to identify hazards, select appropriate mitigation measures, and thus technically and economically optimise the design and construction of tunnels.

2. INVESTIGATION AND ROCK MASS CHARACTERIZATION

It is essential to focus the investigation in the route selection phase on risk relevant parameters. The investigation for the route selection is based on the review of existing data, the evaluation of satellite images including digital elevation model data, 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.
During the preliminary design a first geometrical and a preliminary ground model, containing rock mass parameters and hydraulic conductivities of the fault zone has to be established. Site investigations require detailed engineering geological mapping and subsurface investigations by geophysical survey, trenches / trial pits, core drilling and borehole tests. Laboratory tests 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, like more or less continuous linear, steep relief features, so called fault escarpments, or elongated depressions which are often associated with seeps and/or swamps, landslides and creeping areas. While lithological sequences offsets tend 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 reconstructing the deformational history of the project area, allowing distinguishing extensional and compressional fault domains.
Both equipment and technique for core drilling 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 to avoid washing out fine grained gouge material and disturbing the shear structures by using double or triple tube core barrels and polymer flushing agents.
The 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 drill cores is performed to differentiate between extensional and compressional domains. This evaluation of drill cores should be supplemented by an in situ analysis by means of the „Acoustic Borehole Televiewer" which investigates orientation and densities of discontinuities.
Hydraulic tests such as slug pulse tests are used to obtain hydraulic parameters 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 often are not representative. Due to the hydrogeological variability along fault zones, quite a large number of stand pipe and/or piezometer installations are needed to record groundwater levels and fluctuations. The exploration of fault zones by direct investigation methods should be supplemented by geophysical methods.

To adequately characterise the mechanical properties of rock mass within fault zones, we must mainly rely on laboratory core sample tests. The accuracy in determining rock mass parameters decreases with increasing weakness of the rock concerned. 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.

Translating the laboratory results and results of field investigation into mechanical parameters, sufficiently describing the behaviour of a brittle fault zone is a difficult task. Although procedures for determination of rock mass parameters are available (Medley 1999, Hoek 1999), engineering judgement cannot be replaced.

4. KEY CONSTRUCTION ASPECTS IN FAULT ZONES

Major problems encountered during tunnelling in fault zones are excessive overbreaks and collapses, large, heterogeneous and unsymmetrical displacements, long term creep, and excessive water inflows.

The boundary between larger overbreaks and collapses is not sharp. Here a collapse is defined as an instability resulting in severe damage to already installed support, while overbreaks are limited to the face and unsupported span. Overbreaks generally are associated with poor rock mass quality in combination with too long unsupported spans or face instability. The consequences are a hazardous working environment, and the need to fill up overbreaks. The heterogeneous stress distribution due to strong stiffness contrasts within fault zones increase the probability of excessive overbreaks in the vicinity of the boundary between relatively weak and stiff rock. (Moritz et al. 2004).

Collapses in fault zones are either developing from excessive overbreaks, caused by overloading of inadequate supports, or brittle failure of the rock mass. An especially unfavourable phenomenon is the brittle failure of stiff blocks within the fault. The stiffness contrast within a fault zone leads to stress concentrations in the stiffer sections, which may fail suddenly without much warning. (Schubert et al. 1995, 2000).

Figure 2. Failure of stiff lining at the Gotthard basis tunnel due to excessive deformation of the rock mass

Grossauer (2001) investigated the influence of stiffness contrasts in heterogeneous rock masses and found significant increases in stresses in the stiff sections. Such examples demonstrate the importance of a thorough understanding of the spatial structure of a fault zone. Tunnelling through a relatively massive block, one is tempted to reduce the supports in such sections. It is emphasised, that traditional classification methods, which use the rating of the face conditions only to decide on the applicable support lead to an underestimation of the support, as they do not consider the stress concentrations in stiff blocks.

The weak fault material in combination with high overburden can lead to large displacements in the course of tunnelling. Attempts to stop such displacements with stiff supports frequently result in spectacular lining failures (Figure 2).

The estimation of final displacements is a rather difficult task. In addition, the rock mass structure and relative orientation of major features to the tunnel axis dominantly influence quality and quantity of displacements. With different orientation of the major rock mass features to the tunnel axis different mechanisms can develop (Huber et al. 2005). Also the displacement characteristics significantly change with the orientation of the dominant features in relation to the tunnel axis (Goricki et al. 2005).

Long lasting deformations, commonly referred to as creeping can be observed in faulted rock mass in many cases can be attributed to the time dependent deformation characteristics of fault gouges. Experience in some very heterogeneous fault zones has shown that long term displacements also can be associated with failure of the more competent blocks. After the failure of a stiffer block, the stresses have to be redistributed, leading to a load increase in the weak material, and in previously less loaded stiff blocks. In many cases this is falsely interpreted as creeping.

While real creep is difficult to handle, the latter described “apparent creeping” can be dealt with by systematically reinforcing the sections, where better rock mass prevails, thus preventing its failure.

Unexpected ground water inflows can have catastrophic consequences and are a serious hazard for the tunnel crew. Detection of water bearing faults during construction is possible only by probing ahead in sections with a potential of water inflows. In case the water is circulating, the recording of the rock mass temperature can help in identifying such zones, as a drop in temperature is usually associated with ground water flow.

Sealing of water bearing fault zones can be extremely time consuming and costly. A thorough understanding of the rock mass structure can help in minimizing the remedial measures.

5. FINAL DESIGN DURING CONSTRUCTION

Despite careful investigations during the planning phase a variety of uncertainties at the tunnel level will remain due to the complexity of a fault zone. Consequently deformation rate, final deformation and required support can not be anticipated accurately enough during design. To avoid inadequate support as well as time and cost overruns due to the uncertainties the geotechnical model has to be continuously updated. This task can only be achieved by continuous data recording, evaluation and interpretation through geological and geotechnical site assistance. Traditional geological face mapping lacks accuracy and is biased. Unbiased identification of structural features at the tunnel face can be achieved by electronic stereographic imaging (Fasching 2000, Gaich et al. 2003). This method of geological documentation allows continuous updating of the existing geological model in 3D

Displacement measurements by geodetic methods allow the observation of three dimensional displacements providing extremely useful information. Additional instrumentation like extensometers, stress and strain measuring devices need to be used in special cased only. Geophysical methods for the prediction of rock mass structure and quality have not achieved the required reliability up to now.

Data evaluation and interpretation

To use the huge amount of data from geological face mapping and geotechnical monitoring obtained during the tunnel excavation as a decision aid, an immediate and continuous evaluation of all recorded data from geological face logging and geotechnical monitoring is required. Reliable short term prediction of the rock mass quality ahead of the tunnel face is possible by evaluating the spatial orientation of displacement vectors (Steindorfer 1998). The prediction of the final tunnel closure in heterogeneous fault zones has been greatly improved by special software (GeoFit®, Sellner 2000), which allows predicting the “normal” development of displacements, and final displacements. Although various tools have been developed to ease interpretation of monitoring data, rock mechanical expertise and practical experience in tunnelling is still required on site.

Figure 3. Application of a ductile lining system using Lining Stress Controllers (LSC) at the Semmering basis tunnel

As the geological risk is always with the owner, an active participation is required. The owners’ team should include competent geological/geotechnical staff.

6. ADEQUATE TUNNEL SUPPORT AND CONSTRUCTION SEQUENCE

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 large displacements. 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, lining failures are a safety hazard for the crew, even if the overall stability is not an issue.
Reshaping should be avoided by all means, because of the extremely high costs and dangerous working conditions.
To combine ductility with resistance, ductile elements are integrated into relatively stiff standard supports. 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 (Moritz, 1999).
Rock bolts 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 (Blümel 1996).
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 full face approach requires heavy face support. 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 limits this procedure to tunnels with low cover.
Extremely poor ground conditions in fault zones, such as flowing ground or excessive water inflow, may require multiple excavation stages and/or special ground treatment ahead of the excavation by grouting and drainage.

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. The complete picture is absolutely crucial for reliable geotechnical characterisation and interpretation. A geotechnically relevant classification of a faulted rock mass must consider its deformation mechanisms and characteristics.
Despite utmost care it is inevitable that the model of the fault zone established during site investigation 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 optimisation of the tunnel construction, with specifically tailored support elements and excavation sequences adjusted to the behaviour of the rock mass in the fault zone.
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.

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