Influence of Faults on Tunnelling

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Abstract

Zusammenfassung

Introduction

Many geotechnical problems arise when tunnelling through fault zones. Faults are complex zones, ranging from decimetres to kilometres wide, in which shear deformation is intense. Fault zones in the upper 5 to 10 kilometres of the Earth's crust, the so called brittle faults, consist of an anastomosing complex of shear fractures (MANDL, 1988, SCHOLZ, 1990, TWISS & MOORES, 1992, etc.). Brittle fault zones are highly heterogeneous, consisting of fractured, brecciated rocks separated by fine-grained fault gouges. Low-temperature solution transfer contributes to the alteration of the faulted rocks through transformation and neoformation of clay minerals (KLIMA et al. 1988, RIEDMÜLLER, 1978, WU, 1978). A regular pattern of shear and tensile fractures develops in these zones, reflecting the geometry of the strain field and, consequently, the orientation of the principal stresses. Slickensides with striations indicate the most recent tectonic slips and relative movements.

A characteristic phenomenon of brittle fault zones is the random occurrence of units of more or less unaltered, undeformed rock, called "knockers" or "horses" (GOODMAN, 1993). These mainly lenticular units of rock mass develop in different dimensions and can reach magnitudes of up to several hundreds of metres. These units are surrounded by fine-grained gouge material, which appears to be flowing around the "horses" in an anastomosing pattern.

The geotechnical significance of a fault zone lies in its substantial heterogeneity. The ratio of soft clayey gouges to rock fragments of different sizes, shapes and strengths is extremely variable.

Another factor subject to substantial variation is groundwater. Unfavourable groundwater elevations (plus pressure head, where confined) and flow directions destabilise excavations and make effective drainage and support measures extremely important.

Principal geotechnical difficulties likely to be encountered when driving a tunnel through a fault zone are: instability of the face; excessive overbreak and deformation from squeezing and/or swelling fault rocks; instability of intermediate construction stages and, excessive water inflow frequently associated with flowing ground (RIEDMÜLLER, 1997).

To illustrate the influence of faults on tunnelling, we present three case studies from recent tunnel headings in the Austrian Alps. The tunnels described in this paper form part of the Austrian high

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speed railway system.

Fault Zone at the Inntaltunnel

The ”Inntaltunnel”, a double track tunnel 12.756 m long penetrates quartzphyllites (”Innsbrucker Quarzphyllit”) which form the Pre-Alpine crystalline basement of the Northern Calcareous Alps. The maximum overburden thickness is approximately 350m. Due to its position at the boundary between Northern Calcareous Alps and the gneiss massif of the Central Zone (”Ötztalkristallin”), the quartzphyllite series has been subjected to intensive tectonic deformation which has generated shear zones oriented generally in the direction of strike of the phyllites. (LEIMSER & KÖHLER, 1994). A major brittle fault zone intersecting the tunnel axis at an acute angle between stations 2700 m and 4800 m (North Lot), has caused difficulties during tunnel excavation. This fault zone consists of alternating layers of clayey gouge, cataclasite and phyllite, varying in thickness from decimetres to tens of metres. Dipping 20° to 45° to the NW, the fault zone cuts through the gently SW dipping phyllites.

Excavation and support were governed by considerable displacements. Approximately at station 2.680 m deformations exceeded the deformability of conventional shotcrete – rockbolt support resulting in shear failures in the shotcrete lining and broken bolt heads. As at this time it was hoped that the fault would be of minor extent the basic approach previously applied was maintained with additional bolting and overexcavation for the first twenty to thirty meters. But monitoring soon showed even increasing displacements with further advance, requiring modifications to the construction sequence and support. To increase deformability, the shotcrete lining of the top heading was divided into three segments with two deformation gaps, a method well known from other projects ( ). The rock bolt density was increased, while the round length was kept at 1,0 m. The installation of the invert arch followed the bench excavation in a close distance, the distance to the heading face being between 100 and 120 m.

From station 2.680 m to approx. station 3.170 m crown settlements ranged between 3cm to 15 cm after one day, with final settlements between 30 cm to 60 cm. The deformation gaps in sections with higher displacements closed completely, occasionally leading to severe damages of the lining. Worst ground conditions were encountered between station 3.190m and 3.300 m. In this crucial tunnel section the first-day settlements reached values up to 23 cm with final displacements between 90 cm and 120 cm. The number of deformation gaps in the top heading lining was increased to four, plus free footings, in this way preventing shearing of the lining.

Up to approximately station 3.500 final crown settlements were recorded in the range of 60 cm to 80 cm. In the subsequent section of roughly 700 m final displacements decreased to about 40 cm. The end of the fault zone was reached at approximately station 4.800 m, with crown settlements between 20 to 30 cm over the last 600 m.

The number of rockbolts with lengths of 6m and 8 m varied between 17 to maximum 29 per linear meter of top heading throughout the fault zone, while round length and shotcrete thickness were kept constant at 1,0 m, and 20 cm respectively.

Figure xx: Firstsetzungen ITT

The deformation behaviour was influenced by the foliation to a certain extent. The main influencing factor were shear planes striking more or less parallel to the tunnel axis and dipping to the NW. The combination of foliation and shear planes generated wedge type failures at the right sidewall, influencing the orientation of the displacement vectors. The difference in longitudinal displacements between left and right sidewall in the range of several centimetres was remarkable.

No indication could be found, that the primary stress situation was significantly influenced by tectonic processes. In general displacement rates smoothly decreased, indicating a “normal” stabilisation process. The varying stiffness of the rock mass within the fault zone made a prediction of the final displacements rather difficult. In a few areas, the amount of deformation was underestimated, requiring reshaping prior to installation of the inner lining.

Although the amount of displacements varied in a wide range within short distances, the general behaviour of the rock mass was very similar throughout the fault zone. This allowed a routine operation, with excavation rates around 4 m per day.

Due to the fact, that a fault zone of this extent and poor rock mass conditions had not been predicted, an additional excavation and support class was negotiated and added to the contract. Compared to the original construction program, an additional seven months were required to complete excavation. Some modifications of the construction sequence and the construction of an additional ventilation shaft prevented further time loss.

Fault Zones at the Galgenbergtunnel

The NE -SW oriented ”Galgenbergtunnel” has a total length (including cut-and-cover sections) of 6 108 m. 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 (Middle and Upper Austroalpine nappe system: Crystalline basement of the ”Gleinalm”, Permomesozoic ”Rannachserie” and Paleozoic Greywacke zone; CLAR 1965, FLÜGEL 1960, TOLLMANN 1959).

The folded and faulted lithological series trending generally WSW - ENE intersects 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 (BERGMAIR et al., 1996, HARER et al., 1996, RIEDMÜLLER, 1997).

”Hinterberg Fault”

This fault zone, located between station 959 m and 1 342 m (heading Leoben), has developed between two units of massive marbles. Source rocks are imbricated graphitic and carbonatic phyllites, greenschists and thinly bedded marbles of the Paleozoic, Upper Austroalpine Greywacke zone (”Veitscher Decke”). 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.

Main characteristics of this fault zone are the 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 from NE to SW. It is pointed out that a disastrous collapse happened in July 1994 at the southeastern boundary of the fault zone.

The fault zone was predicted precisely. 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 after high initial displacements rather quickly stabilised. The determination of the amount of required overexcavation and support therefore was extremely difficult. At the beginning of the fault zone a rather stiff support approach was believed to limit deformations to values, which the lining could sustain. Soon the method due to severe damages had to be changed to a similar one as applied at the Inntaltunnel. Size of top heading, lining thickness, rock bolt density, and round length were comparable, but the invert followed the heading face in a closer distance than at the Inntaltunnel.

When the excavation approached the end of the fault zone, a sudden collapse at the face of the top heading occurred without prior warning. The investigation of the cause revealed a combination of unfavourable circumstances:

- Sudden alternations of relatively stiff and soft sheared rocks
- low friction angle in sheared material (12°-14°)
- unusual primary stress situation

From the trend of the orientation of displacement vectors it could be deduced, that initial stress directions form an arch within the fault zone. This unusual primary stress is caused by a lateral creeping of the fault material wedged in between the two massive marble units. This results in a higher maximum principal stress, and the potential of shear failures developing in directions, usually not experienced during tunnelling.

Figure: Arch

Long lasting displacements in certain sections of the fault zone required additional bolting and partial reshaping. Remedial works of the collapse, additional reinforcements and reshaping lead to a considerable increase in construction cost and time.

Besides the tragic accident, the most unfavourable aspect of the collapse was the discovery, that the support system, which was applied on many kilometres of tunnels already very successfully did have shortcomings under unusual circumstances as encountered in this fault zone.

Haberl Fault

The ”Haberl” fault was encountered between stations 1.760 m and 1.990 m (heading Jassing Ost). The fault zone developed in graphitic phyllites and occasionally greenschists, meta-sandstones, calcareous phyllites and platy marbles of the greywacke zone. The undulating, most commonly 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.

The ”Haberl” fault zone is characterised by pervasive, homogeneous shearing, showing brittle and ductile deformation features. From the geotechnical standpoint, it is important that an alternating sequence of hard and soft rock layers within the fault zone exists.

With the experience from the Hinterberg fault, it was agreed to modify the support and excavation approach for the Haberl fault. The modifications included:

- reduction of the top heading heigth to 4,5 m to increase face stabilty
- use of 8 m to 12 m long regroutable self drilling bolts (IBI)
- integration of yielding steel elements in the shotcrete lining

The aim of all the modifications was to reduce displacements in the excavation area, and to guarantee rock bolt performance also after big deformations, thus increasing stability and safety. Technically the solution was convincing. Final displacements did not exceed 15 cm, being nearly a magnitude smaller than at the Hinterberg fault zone. At no time there was any sign of instability.
The reduction of displacements in the soft rock layers prevents high stress concentrations in the hard rock layers. Thus the risk of a brittle failure of the stiff layers as experienced at the Hinterberg fault zone is minimised.

Due to the reduced height of the top heading and the time consuming installation of the bolts, the excavation rate could not be increased over an average of 1,70 m per day, naturally increasing construction time and cost. On the other hand no reshaping and no repairs at all were required on the total 350 m, where this approach was applied.

Discussion

The three tunnels discussed had the same size, overburden in the fault zones was in the same range, and to a certain extent the rock mass had a *???similar composition???*. Still the performance of the tunnels in the different fault zones was quite different. While at the Inntaltunnel in general a smooth transition between rock masses with different deformability prevailed, at the Hinterberg fault zone abrupt changes had to be dealt with. The excavation in the Haberl fault zone was dominated by mixed face conditions, with the alternation of stiff and soft rock layers.

To illustrate the different behavior in the three fault zones in figure xy the average displacement vector orientations of the top heading monitoring points are shown in stereographic projection, as well as the trend of displacement vector orientation of the crown along the three fault zones (small part of the fault zone at the Inntaltunnel only). While the trend of vector orientation in the fault zone at the Inntaltunnel is very smooth with low variations only, the one of the Hinterberg fault zone shows a significant trend, indicating the mentioned arching. Strong local variations show the heterogeneity and abrupt changes in rock mass stiffness. In the Haberl fault the vector orientations vary in a wide range, reflecting the complicated structure of this fault zone.

Fig. xy average vector orientation, trend lines

The lessons learned from tunnelling through the three fault zones are:

- the more heterogeneous the rock mass is, the more care has to be taken in the support selection. Also apparently more competent rocks within the sheared fault zone have to be properly reinforced, as they are subject to stress concentrations.
- the trend of the vector orientations proved to be a reliable indicator for variations in rock mass stiffness ahead of the face, and thus should be used for short term prediction routinely when tunnelling through a fault zone.
- tunnelling through fault zones always is costly and time consuming. A sound engineering and continuous updating of the design based on monitoring and increasing knowledge of the geological structure and material parameters at site are essential for successful construction.
- There is still room for improvement of support elements. Recent investigations led to an improvement of rock bolts in poor ground conditions (xx). The integration of yielding elements into the lining allow a better utilisation of the lining capacity. Improvements on the system are currently under development in our group.
- A key factor for the performance of the tunnel is the friction of the rock mass. Consequently during the investigation more attention should be paid to the determination of this crucial parameter.

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