The Influence of Discontinuity Orientation on the Behaviour of Tunnels

By Andreas Goricki, Edward A. Button, Wulf Schubert, Markus Pötsch and Roland Leitner

The evaluation of both rock mass and system behaviour are important tasks during tunnel design (1). Besides the requirement to appropriately characterize rock masses, the factors influencing the rock mass and system behaviour must be identified. One of the influencing factors to be considered is the relative orientation of the discontinuities to the tunnel axis. While several publications have explored this topic for general cases as discussed below, there is limited information comparing the predicted versus observed behaviour from tunnels in which the relationship between the tunnel axis and the discontinuity orientation dominated the observed response. Additionally, if the popular rock mass classification systems are utilized, and thus the rock mass is treated as an "equivalent continuum", the specific influence of the discontinuities on the deformation characteristics and failure modes is not considered.

In situations where the spatial relationship between the dominant discontinuity set and the tunnel axis influences the failure mechanisms it is necessary to understand the interaction between the rock mass and the excavation to optimize the construction and support methods during the design stages. Likewise, when the observational approach is used during tunnel construction it is necessary to understand how changes in the relative discontinuity orientation influence the system behaviour in order to properly interpret monitoring results and identify potential problematic conditions before they are encountered. Another goal during construction is to predict the final displacement magnitude and understand the relationship between the initial measured displacement and the final displacement magnitude.

The variation of the key rock mass parameters combined with transient stress conditions and various geometries leads to different failure

Der Einfluss der Gefügeorientierung auf das Verhalten von Tunneln

Es ist bekannt, dass die Orientierung von Trennflächen einen großen Einfluss auf die Verformungen und Bruchmechanismen bei Untertagebauwerken hat. In diesem Beitrag wird das Verformungsverhalten von Tunneln bei unterschiedlicher Schieferungsorientierung untersucht. Ergebnisse von zwei- und dreidimensionalen numerischen Modellen werden mit Beobachtungen bei ausgeführten Tunneln verglichen.

The orientation of the discontinuities of the rock mass has an important influence on the displacements and failure mechanisms occurring around an underground excavation. In this paper the displacements of the tunnel are investigated for different discontinuity orientations. Observations from sites are compared to 2D and 3D numerical calculations with similar parameter combinations. The different system behaviours and the various modes of failure are explained with focus on the variation of the discontinuity orientation.

mechanisms. These mechanisms can be categorized into two basic types of system behaviour:

- Falling and sliding of blocks from the tunnel roof, walls, and face,
- Stress induced failure of the rock mass surrounding the tunnel.

Additionally, the tunnel face and the tunnel sidewalls generally show different failure mechanisms due to differences in the excavation geometry, relative orientation and stress condition.

The failure mode of block falling and block sliding into a tunnel excavation has extensively been studied, e.g. by Goodman and Shi (2). The focus in this paper is set on the influence of the rock mass anisotropy on the stress induced displacements of the tunnel.

In rock masses composed of foliated or schistose rocks, where the persistence of the discontinuities is high and where local changes occur due to internal folding at the tunnel scale, understanding how the behaviour changes with changing relative orientation is invaluable in interpreting monitoring results and understanding the failure mechanisms associated with the local rock mass structure.

Review

The influence of the relative discontinuity orientation on the general tunnel behaviour was discussed by Rabcewicz (3) who compared orientations of the foliation, parallel to the tunnel axis with a vertical and horizontal dip, and perpendicular to the tunnel axis with vertical dip. From both a theoretical and observational viewpoint he concludes that the orientation perpendicular to the tunnel axis is the most favourable, as a natural arch forms around the tunnel in each layer. The most unfavourable one to his opinion is the parallel orientation with vertical dip, as the development of a natural arch is possible only in case the foliation has appropriate shear strength by friction or strong infillings.

Wickham (4) in his RSR concept considered the relative orientation between the tunnel axis and discontinuity orientation by grouping each discontinuity set into a general class ranging from very favourable to very unfavourable; the rating values decreased for more unfavourable conditions. Bienawski (5) integrated Wickham's recommendation into his RMR classification by introducing a negative adjustment factor for unfavourable orientations. However, the reduction of the ratings in both systems is minor, and leads to minimal changes in the recommended support.

It should also be noted that in the Q-system (6) the discontinuity orientation plays no role in the classification procedure.

Wittke (7) discussed the results of three-dimensional numerical models for four different relative anisotropy orientations. The discussed results included induced stresses, cross sectional displacements, as well as required cohesion for maintaining elastic behaviour.

The influence of rock mass anisotropy on the displacement vector orientation was also investigated by Tonon (8) using the program BEFE (9) to show that even when considering rock mass anisotropy the vector orientation can be used to identify changes in the rock mass deformability ahead of the face. Tonon showed that the trends of the displacement vector orientation are strongly influenced by the anisotropy.

Experience from various Alpine tunnels constructed over the past 15 years has shown a pronounced influence of the relative orientation of persistent discontinuities to the tunnel axis on the characteristic system behaviour.

Various basic cases are studied in this paper and the results of numerical simulations compared to observations on site.

2D Simulations

For situations where the strike of the discontinuities is parallel to the tunnel axis the general behaviour can be simulated using two dimensional analyses. It should be noted that simplified 2D simulations will not capture the longitudinal behaviour or how the displacements develop with increasing distance from the tunnel face. For this discussion simulations were made with the distinct element code UDEC (10) with different foliation dips (11).

In order to focus on the role that a single discontinuity set has on the characteristic displacements high block strength was used, while the discontinuities were assigned a relatively high deformability and low strength. The overburden was chosen to be 600 m. The basic input parameters for the models are given in Table 1.

The modelled tunnel was circular with a diameter of 10 m. The discontinuity dip was varied from 0° to 90° in 10° increments. Four of these simulations with the joint orientation at 0°, 30°, 60°, 90° to the maximum principal stress are discussed in more detail.

Additionally, a second model was run in which shearing through the layers was possible by locally introducing a secondary joint set ~~was incorporated~~ into the right side wall region. The basic material properties for rock and the foliation were the same as in the previous calculations, while the secondary joints had properties equivalent to the intact rock. Continuously recording the displacements allowed to observe the progressive development of the excavation damage zone.

Influence of discontinuity dip on displacement characteristics (2D)

Figure 1 shows the displacement vectors (grey), the shear displacement (red), and the joint opening (green) for a joint dip of 0°, 30°, 60°, and 90°, respectively. The simulation results show the in-

Table 1

Fig. 1 Results of UDEC simulations for joint dip of 0°, 30°, 60°, and 90°.

Bild 1 *Ergebnisse der UDEC Simulationen mit Klufteinfallen von 0°, 30°, 60°, und 90°.*

fluence of the joint orientation on the general deformation pattern and mechanisms. With the material parameters utilized a majority of the deformations arise from either slip or opening along the joints. It can be seen in these examples that in general the maximum displacements are normal to the joint planes as a result of joint opening and the high compliance associated with the assigned joint properties. Shear displacements tend to occur in the vicinity of the excavation perimeter where the discontinuities intersect the excavation at low angles. The shear displacements result in an increased displacement magnitude and local changes in the displacement vector orientation due to the superposition of both the normal and shear displacements. Due to the discontinuous system the displacement vector orientations can vary significantly within small distances depending on the location where shear displacements occur relative to the measurement point.

Figure 2 shows the development of the displacement vector orientations with increasing joint dip. For the cases of 0° and 90° dip angle the displacement vector at the crown shows no deviation from the vertical since the discontinuity dip is parallel to one of the principal stress axes of the primary stress. For intermediate inclinations the vector deviates up to 20° from to vertical in the direction of the joint normal. The same occurs at both sidewalls where the displacement vectors show a dominant horizontal orientation. Only small contributions from settlements can be observed. With increasing inclination an upward trend can be observed at the left sidewall while a downward trend can be observed at the right sidewall. This is caused by the rotated displacement pattern (see Figure 1). As the joint dip angle increases, the influence of the joint shear displacement becomes evident. In Figure 2 this phenomenon is indicated by two lines for both sidewalls from 40° dip to 80° dip. The lines beginning at 40° dip represent the displacement vector orientations which are predominantly influenced by the joint shear displacement while the other lines represent the displacement vector orientations which are predominantly influenced by the compliance normal to the joint dip.

Figure 3 shows the result of the second model in which shearing through the layers was facilitates by locally introducing a secondary joint set (grey dashed lines). It can be seen that initially the displacement vector orientation is similar to the cases where only a single discontinuity is modelled. However, as the shear strength of the secondary joints is exceeded and failure occurs, the displacement vector shows an irregular pattern where the dominant influence on the displacement vector changes from joint normal displacements to joint shearing. This phenomenon was regularly observed during the construction of the Strenger Tunnel as shown in Figure 4. In this example the foliation is dipping approxi-

Fig. 2 Influence of relative joint dip on the displacement vector orientation. Second line from 40° to 80° shows the influence of local shearing on the vector orientation.

Bild 2 *Einfluss des Fallwinkels auf die Verschiebungsvektororientierung. Im Bereich von 40° bis 80° Einfallen zeigt sich der Einfluss von lokalen Scherverschiebungen, weshalb hier die Vektororientierungen von zwei benachbarten Punkten dargestellt werden.*

Fig. 3 Development of the displacement vector with increasing depth of the damage zone. The displacement vectors show the alternating joint normal displacements and shearing. Joint shear displacements are displayed in red, joint opening in green.

Bild 3 *Darstellung des Pfads der Verschiebungsvektoren auf der linken Seite mit Vergrößerung der Scherzone. Deutlich ist der Wechsel zwischen Scheren parallel und Deformation normal zur Schieferung zu erkennen. Scherverschiebungen an den Klüften sind in rot, Kluftöffnungen in grün dargestellt.*

Fig. 4 Displacement vector orientation measured in the Strenger tunnel clearly showing alternation of dilation normal to and shearing along foliation on the right sidewall.

Bild 4 *Verschiebungsentwicklung in der Kalotte des Strenger Tunnels, wobei sich am rechten Ulm deutlich der Wechsel zwischen Dilatation normal und Scheren an der Schieferung zeigt.*

mately 40° to 50° against the tunnel direction, and striking at a relative orientation of approximately 25° (clockwise) to the tunnel axis.

3D Simulations

In order to investigate the development of the vector orientation for discontinuities not parallel to the tunnel axis as well as the influence of the face position on the displacement characteristics 3D simulations were carried out with FLAC 3D (12). Four basic geometries were investigated; the strike and dip of the plane of anisotropy are given in Table 2.

Model Parameters

In order to simulate the anisotropic failure response of a foliated or schistose rock mass the ubiquitous joint model was used with an isotropic-elastic constitutive law. In this manner only the plastic deformations contribute to the anisotropic behaviour. If an anisotropic material law is used the elastic behaviour would enhance the anisotropic nature of the simulation as can be seen in (7, 8). The material properties and boundary conditions for the simulations are given in Table 2. The excavated area is that of a typical top heading for a tunnel with a diameter of 12 m. No support was utilized in the simulations.

Influence of anisotropy orientation on the displacement characteristics

The following examples show how both the displacement magnitude and its rate relative to the excavation advance vary in relationship to the rock mass anisotropy.

Figure 5 shows the development of the displacements behind the tunnel face (normalized by the total displacement) for the models with a vertical anisotropy striking both perpendicular and parallel to the tunnel axis (Cases 1 with perpendicular and Case 2 with parallel strike). It can be seen in the diagram, that in Case 1 relatively high crown settlements occur within the first excavation step (approximately 37 % of the final settlement behind the face). For Case 2 only 22 % of the settlements occur during the first excavation step. However, the crown settlement occurring behind the face position for Case 2 is twice as large as that for Case 1 (137 mm to 67 mm).

For Case 3 both the crown settlement and its rate fall between Cases 1 and 2; while for Case 4 the initial crown settlement rate is larger than for Case 2 and the final settlement magnitude is slightly less.

Influence of anisotropy orientation on displacement vector characteristics

The simulations for Cases 3 and 4 were performed to allow a comparison between the calculated deformations and observed displace-

Table 2

Fig. 5 Normalized total displacements behind the tunnel face for perpendicular (Case 1) and parallel (Case 2) vertical discontinuities.

Bild 5 *Auf die Endverschiebung bezogene Entwicklung der Verschiebungen hinter der Ortsbrust für vertikale Schieferung mit dem Streichen normal (Fall 1) und parallel zur Tunnelachse (Fall 2).*

Fig. 6 Displacement vectors of Cases 3 and 4 from the numerical 3D simulation in cross and longitudinal sections

Bild 6 *Verschiebungsvektoren aus der 3D-Simulation für die Fälle 3 und 4 im Quer- und Längsschnitt.*

ments. Figure 6 shows the displacement vector characteristics of these two simulations in cross sections both perpendicular and parallel to the tunnel axis. To allow a comparison to the monitored data the displacements displayed are those occurring after the excavation of the section, with the "zero reading" one metre behind the face.

The simulation results from Case 3 (strike 15° from the tunnel axis, dipping 70° against the excavation) shows that as the strike deviates from parallel the response becomes more heterogeneous. The lower side walls of the top heading show a distinct anisotropic response. The crown displacements deviate from vertical towards the right (in the direction of sliding on the anisotropic planes). The springline displacements show a similar pattern. The vector orientation on the left side of the excavation points against the excavation direction while the points on the right side of the excavation show a vector orientation pointing in the excavation direction.

The simulation results from Case 4 (dip direction clockwise 40° off the tunnel axis, dip 25° in excavation direction) show a distinctly different pattern than Case 3. The crown displacements have the largest magnitude and deviate to the left from the vertical. This differs from the deviation in Case 3 (in the direction of simple sliding) since it is not kinematically possible to slide on the anisotropy planes due to the dip into the rock mass. This deviation results from reverse shearing on the anisotropy planes, as well as dilation perpendicular to them. Both of the lower side wall points show an anisotropic response with the smallest displacements occurring on the right side where shearing in either direction on the anisotropy is minimized. The displacement vector orientation of all points shows a tendency against the excavation direction.

Figure 7 shows the displacement characteristics from the Strenger tunnel where the orientation of the foliation is comparable to that of Case 3. It can clearly be seen, that the displacement vectors of the side walls have different longitudinal directions. The lower right side wall shows the beginning of shearing along the foliation, as excavation proceeds, a process as shown in Figures 3 and 4.

Figure 8 shows an example from the Inntal tunnel, where the behaviour was dominated by closely spaced faults, with a dip direction between 30° to 50° clockwise from the tunnel axis and a dip of around 30° in direction of excavation. It can be seen that the largest displacements occur at the crown while the smallest displacements are observed at the right side wall. The vector orientation from the beginning points against the excavation direction for all three points, with an increasing trend, as the face distance increases.

Fig. 7 Observed displacements in the Strenger Tunnel at a section with the foliation striking approximately 20° clockwise from the tunnel axis and dipping approximately 60° against the excavation direction.

Bild 7 *Verschiebungsvektororientierung eines Querschnitts am Strenger Tunnel. Der Winkel zwischen Tunnelachse und Streichen er Schieferung ist rund 20° im Uhrzeigersinn, das Einfallen rund 60° gegen die Vortriebsrichtung.*

Fig. 8 Observed displacements in the Inntal Tunnel at a section, where closely spaced faults with a dip direction of approximately 40° clockwise from the tunnel axis and a dip of approximately 30°.

Bild 8 *Gemessene Verschiebungen an einem Querschnitt im Inntaltunnel, wo engständige Störungen mit einer Einfallsrichtung von rund 40° im Uhrzeigersinn und einem Einfallen von rund 30° in Vortriebsrichtung das Verhalten bestimmt.*

Conclusion

It has been demonstrated that changes in the relative orientation between discontinuities and the excavation can lead to changes in how the rock mass responds to the excavation. Relatively simple mechanisms, tensile fracture and localized shearing, can combine at different rates to produce complex deformation patterns. Non-persistent secondary joints can result in large deviations from the behaviour associated with just a single discontinuity and their role in the failure process must be considered.

The effects of the relative orientation of the dominating discontinuities and the tunnel axis on the displacements, support requirements, construction time and costs can be dramatic (13). A careful analysis of the influence of the discontinuity orientation not only leads to a better design of excavation and support, but also allows an improved interpretation of displacement monitoring data during construction.

The analysis and interpretation of the changes in the displacement vector orientation to a certain extent allows short term predictions of the rock mass conditions ahead of the tunnel face (14). To correctly interpret deviations in the displacement vector orientation, caused by a major change in the rock mass quality, the characteristic vector orientation resulting from the spatial orientation of the foliation or dominating discontinuity set must be known.

References

1. OEGG: *Guideline for the Gemechanical Design of Underground Structures with Conventional Excavations*. Austrian Society for Geomechancis, 2000
2. Goodman, R.E. ; Shi, G.H.: *Block Theory and its Application to Rock Engineering*. New Jersey: Prentice Hall, 1985.
3. Rabcewicz, L.v.: *Gebirgsdruck und Tunnelbau*. Wien: Springer, 1944.
4. Wickham, G.E. ; Tiedemann, H.R. ; Skinner, E.H.: *Ground Support Prediction Model, RSR Concept*. Proc. Rapid Excav. Tunnelling Conf., pp. 691-707. New York: AIME, 1974.
5. Bieniawski, Z.T.: *Engineering Rock Mass Classifications*. Wiley and Sons, 1989.
6. Barton, N. ; Lien, R. ; Lunde, J.: *Engineering classification of rock masses for the design of tunnel support*. Rock Mechanics 6 (1974), No. 4, pp. 189-236.
7. Wittke, W.: *Rock Mechanics*. Berlin: Springer-Verlag, 1990.
8. Tonon, F.: *Three-Dimensional Modelling of Underground Excavations and Estimation of Boundary Conditions in Rock with Fabric*. Doctoral Thesis, Univ. Colorado-Boulder, 2000.
9. Beer, G.: *Boundary Element-Finite Element Code (BEFE)*. 1999.
10. Itasca: *Universal Distinct Element Code (UDEC)*. Version 3.2. 1999.
11. Pötsch, M.: *Parametric studies with UDEC for the quantification of the influence of joint set properties on tunnel deformations*. Project. Institute for Rock Mechanics and Tunnelling, Graz University of Technology, 2001.
12. Itasca: *Fast Lagrangian Analysis of Continua (FLAC)*. Version 2.2. 2002
13. Huber, G. ; Westermayr, H.: *Einfluss der Gefügeorientierung am Strenger Tunnel*. Felsbau 23 (2005), No. 5, pp. xxx-xxx.
14. Steindorfer, A.: *Short term prediction of rock mass behaviour in tunnelling using advanced analysis of displacement monitoring data*. Riedmüller, Schubert & Semprich

(eds), Gruppe Geotechnik Graz, Heft 1. 1997.

Authors
Dipl.-Ing. Dr.techn. Andreas Goricki, 3G Gruppe Geotechnik Graz ZT GmbH, Elisabethstraße 22, A-8010 Graz, Austria, E-Mail goricki@3-G.at; MSc. Dr.techn. Edward A. Button, ETH Hönggerberg, Geologisches Institut, Switzerland, E-Mail button@erdw.ethz.ch; o.Univ.Prof. Dipl.-Ing Dr. mont. Wulf Schubert, Dipl.-Ing. Markus Pötsch, Dipl.-Ing. Roland Leitner, Graz University of Technology, Institute for Rock Mechanics and Tunnelling, Rechbauerstraße 12, A-8010 Graz, Austria, E-Mail schubert@tugraz.at, poetsch@tugraz.at, r.leitner@tugraz.at

Table 1 Material properties used in the UDEC simulations.

Tabelle 1 *Materialeigenschaften für die UDEC Simulation.*

σ_v	15.9 MPa	k_0	0.7
Block parameters		Joint parameters	
K	16 000 GPa	k_n	5 000 MPa/m
G	8 000 GPa	k_s	2 500 MPa/m
c	20 Mpa	c	0
φ	40°	φ	15°
σ_t	5 MPa	σ_t	0

Table 2 Material properties and boundary conditions for the 3D simulation. The strike directions are measured clockwise from the excavation direction.

Tabelle 2 *Verwendete Materialparameter und Orientierung der „Schieferungsflächen“. Die Streichrichtung ist relativ zur Tunnelachse im Uhrzeigersinn angegeben (Vortriebsrichtung = 0°).*

Intact rock		Joints		Stresses	
K	800 MPa	c	0.01 kPa	σ_v	12.5 MPa
G	480 MPa	φ	20°	k_0	0.5
c	50 MPa	i	10°		Both horizontal stresses equal
φ	35°				
i	0°				

Case	Strike of foliation	Dip of foliation
1 (90/90)	Perpendicular to tunnel axis	Vertical
2 (00/90)	Parallel to tunnel axis	Vertical
3 (15/70)	15° to tunnel axis	70° against the excavation direction
4 (130/25)	130° to tunnel axis	25° in the excavation direction