Displacement Vector Orientations in Tunnelling - What do they tell?

by
Harald Golser and Albert Steindorfer

Abstract

On site observations show, that the spatial orientation of monitored displacement vectors is influenced by the rock mass structure. In particular strong deviations in the vector orientation can be observed when tunnelling in a heterogeneous rock mass. Following the idea of local heterogeneity determining the displacement pattern of a tunnel, it could be concluded, that the primary stress situation should also influence the displacements of a tunnel. Some research on this topic has been conducted at the Institute of Rock Mechanics and Tunnelling at the University of Technology in Graz Austria during the past years. The paper summarises the findings of this research and on site observations.

Zusammenfassung

Erfahrungen beim Durchörtern von Störungszonen haben gezeigt, daß die räumliche Vektororientierung der Verschiebungen stark von den Gebirgsverhältnissen beeinflußt wird. Besonders beim Vortieb in heterogenen Störungszonen können starke Abweichungen in der Vektororientierung auftreten. Neuen Erkenntnissen zufolge können auch die Primärspannungsverhältnisse aus dem gemessenen räumlichen Verschiebungsverhalten eines Tunnels abgeleitet werden. Verschiedene Forschungsarbeiten haben sich in den letzten Jahren mit diesem Thema befaßt. Die Arbeit gibt einen Überblick über die bisherigen Ergebnisse.

1. Introduction

Tunnelling in poor and heterogeneous ground is a difficult task due to the frequently, and in many cases, abruptly changing ground conditions. Even with a good geological investigation, uncertainties with respect to the local rock mass structure will always remain. This especially applies for tunnels with high overburden. For such conditions, reliable short term prediction capabilities during tunnelling would ease the decision making process on site with respect to support selection and determination of required overexcavation to allow for displacements.

Geodetic methods are increasingly used for displacement monitoring in tunnelling. Those methods allow the determination of displacements in three dimensions. However on site only two of the three components measured are commonly used for interpretation, while the longitudinal displacement is mostly neglected.

In Austria monitoring data from tunnels in heavily faulted rock (1,2) showed that longitudinal displacements could reach considerable amounts. When systematically evaluating the vector orientation of (L/S) - the ratio between longitudinal displacements and settlements - it showed that the average vector orientation is approximately 10° against the direction of excavation. It was found that deviations from the "normal" vector orientation indicate zones of different stiffness ahead of the face (3).

The value of this observation is that a relative increase or decrease in longitudinal displacements indicates a change in the rock mass quality much earlier than the increase or decrease of radial displacements, making the spatial orientation of displacement vectors a valuable tool for short term prediction.

Attempts to verify the observations on site by numerical simulations started in our group in 1992 and are continuing (4,5). Meanwhile also other researchers are active in this field (6).

2. Numerical Simulations

2.1. General

To evaluate spatial displacements in tunnelling only 3D models are applicable. In the past BE methods have been used for this purpose (4,5). Certain limitations of the method, in

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SITU Research Initiative, University of Technology, Institut for Rockmechanics and Tunnelling, Rechbauerstrasse 12, A-8010 Graz, Austria
Fax: (43) (316) 873 8117, e-mail: golser@fmt.tu-graz.ac.at

particular the step by step excavation and plastic material behaviour make it necessary to use a Finite Element model. The following is a brief description of the model used for the analyses.

Fig.1: 3D Finite Element Model (1$^1/_2$ columns)
Bild1: 3D Finite Elemente Modell

The numerical analyses are carried out using the "Boundary Elements and Finite Elements code BEFE (**7**,**8**). The 3D Model exists of about 10.000 linear, isoparametric finite elements. The boundary conditions are displayed in figure 1. Assumptions include plane strain conditions at the model boundaries and linear-elastic material behaviour. The model consists of 2,5m and 20m slices with a total length of 240m. The tunnel is circular with a diameter of 10m. The tunnel is excavated full face and round by round, leading to 70 load cases until station 192,5m.
The primary maximum stress is generally taken to 40 MPa, the Ko-value is 0,5.

To arrive at sufficiently accurate results some model conditions have to be observed:

- Size of elements and the thickness of the slices should not change in the area where reliable results are required (**9**).
- A minimum ratio between the cross section area and the length of the model must be maintained. The distance from the tunnel axis to the horizontal and vertical model boundaries must not be less than 40% of the total length of the model. Otherwise results from longitudinal displacements will be strongly influenced by the boundaries.
- Because of the longitudinal boundary conditions, reliable results cannot be obtained until 2,5 tunnel diameters (in this case 25m) away from the boundary of the model. This section can be excavated in one step using a thick slice without effecting the accuracy of the results.

2.2. Evaluation of results

Numerical results show the total deformation, including the displacements ahead of the face,. while. monitoring data show only a portion of the deformation. This is because measurements at the earliest start at the face. In order to to compare data from simulations with data from monitoring, a part of the calculated total displacement path has to be subtracted. Due to the fact that longitudinal displacements change direction twice in the vicinity of the face, absolute monitored values strongly depend on the location of the zero reading. This is demonstrated in Figure 2, where the total displacement path is shown, as well as the paths for zero readings at the face and one round behind the face.
For the computations shown in this paper, the point of reference was taken at the tunnel face, which compares to a zero reading at the face. In practice zero readings are taken at some distance behind the face.
Due to this, displacement vector orientations from the computations will differ from those measured on site, generally tending to point more in the direction of excavation than the measuring results. Nevertheless, the relevant phenomena qualitatively are not affected by this assumption.

Fig.2: Influence of the location of the "zero reading" on the evaluated displacement vector orientation; a) total displacement path; b) monitored displacement path in case of "zero

reading" at the face; c) monitored displacement path in case of "zero reading" 5 m behind the face ($1^1/_2$ columns)
Bild 2: Einfluss des Orte der Nullmessung auf die ermittelte Verschiebungsvektororientierung; a) vollständiger Verschiebungspfad; b) ermittelter Verschiebungspfad bei Nullmessung an der Ortsbrust, c) ermittelter Verschiebungspfad bei Nullmessung 5 m hinter der Ortsbrust

2.3. Influence of relatively "soft" rock ahead of the face

For the simulation of a tunnel approaching "soft" rock, the model is split into two regions of different material stiffness, 2.000 MPa for E_1 and 400 MPa for E_2. The boundary between "stiff" and "soft" rock is at station 102,5. The Poisson ratio is taken to 0,25.
Figure 3 shows the trend lines of the normalised displacement vector orientations. Displayed are trends of the crown point 2.5m (1/4 D), 5.0m (1/2 D) and 7.5m (3/4 D) behind the tunnel face. Up to station 80, "normal" displacement vector orientation can be observed. Depending on the distance of the trend line to the face the vector orientation in the homogeneous, unaffected area is between 8° and 15° in the direction of excavation. With decreasing distance to the transition, the vectors tend to point more against the direction of the excavation. The deviation of the vector orientation from the "normal" starts 22m (>2D) ahead of the stiffness transition. Normalisation of the vector orientation is observed at the same distance after the transition. It is interesting to note, that the trend taken at 7,5m behind the face shows a larger deviation from the "normal" (20°) than the trend 2,5m behind the face (17°).
The orientation of the "normal" vectors are the same in both "soft" and "stiff" material, although the radial displacements in the "soft" material are a multiple of those in the "stiff" material. Figure 4 shows a comparison between the trend lines of the settlement and the displacement vector orientation. It clearly can be seen, that the change in rock mass stiffness can be recognised much earlier when using the vector orientation trend than by evaluating the radial displacements only.

Fig. 3: Trend lines of displacement vector orientation of the crown point, trends shown 2,5m, 5,0m, and 7,5m behind the face when approaching comparatively "soft" rock.
Bild 3: Trendlinien der Verschiebungsvektororientierungen des Firstpunktes
bei Annäherung an "weicheres" Gebirge; Trendlinien 2,5m, 5,0m, 7,5m hinter der Ortsbrust ($1^1/_2$ columns)

Fig. 4: Comparison between trends of settlement and displacement vector orientation (L/S), when excavation approaches relatively "soft" rock.
($1^1/_2$ columns)
Bild 4: Vergleich der Trendlinien von Setzung und Vektororientierung (L/S) bei Annäherung des Vortriebes an verhältnismässig weicheres Gebirge

2.4. Influence of relatively "stiff" rock ahead of the face

A second trial was performed to determine the influence of a relatively stiff rock ahead of the face using the same mesh as before. The E-moduli for the two regions are taken to E_1=2.000 MPa and E_2=10.000 MPa, boundary conditions and primary stress situation remain unchanged.
Compared to the previous model, the opposite trend of vector orientations can be observed when excavation approaches the "stiff" rock mass. With decreasing distance to the relatively "stiff" region, the vectors tend to point more in the direction of the excavation. The trend of the vector orientation 7,5m behind the face shows a deviation of 17° from the "normal", the trend 2,5m behind the face 13° from the "normal". The zone of influence within which the divergence of the vector orientations from the "normal" is observed is the same as in the previously studied case.

2.5. Stress conditions in the vicinity of the tunnel face.

Figure 5 shows the contours of the maximum principal stresses when excavation approaches “stiff” or ”soft” rock respectively, and under homogeneous conditions for comparison. The tunnel face is two round length (half a tunnel diameter) ahead of the transition. When approaching “soft” rock mass conditions, stress concentrations between the tunnel face and the region with “soft” rock develop. In case the excavation approaches “stiff” rock, a stress increase can be observed in the “stiff” material, with lower stresses between the face and the stiff region. The different stress conditions observed in the area of the heading influence the behaviour and thus the displacements of the tunnel.

Fig. 5: Contours of maximum principal stresses when approaching “stiff“ and “soft” rock respectively in comparison with homogeneous rock mass conditions. (1 column)
Bild 5: Maximale Hauptnormalspannungen bei Annäherung an “steiferes” bzw. “weicheres” Gebirge im Vergleich mit homogenen Gebirgsverhältnissen.

2.6. Tunnelling through rock mass with frequently changing stiffness

The next case studied is a sandwich type rock mass with a sequence of sections with different stiffnesses and of different length. The E-moduli of the different sections are: E_1=1.000 MPa, E_{12}=800 MPa and E_2=500 MPa. Other conditions remain as in the models described before. Figure 6 shows the structure of the model and the trend lines of displacement vector orientation. As shown from the previous computations, the heterogeneity of the rock mass significantly effects the displacement vector orientations.
It can be seen, that the relative difference in stiffness between two regions influences the magnitude of displacement vector orientation deviation from the “normal”. The diagram also shows, that the vector orientation within longer homogeneous regions normalises, while in short regions the trend changes without an intermediate normalisation.

This finding may ease decisions on site. When meeting better rock within a fault zone, a decision has to be made to what extent excavation and support shall be modified. This decision mainly depends on the length of the zone with better quality. Using the trend of the displacement vector orientation one can determine if the better region is short or more extended.
Figure 7 shows the maximum principal stresses, with concentrations in the “stiff” rock mass at the boundary between “stiff” and “soft” rock, and a reduction in the “soft” section. This effect is the more pronounced, the bigger the difference between the stiffness of neighbouring sections is.

Fig. 6: Trend lines of displacement vector orientation of the crown when tunnelling through rock mass with frequently changing stiffness; trends shown 2,5m, 5,0m, and 7,5m behind the face ($1^1/_2$ columns)
Bild 6: Trendlinien der Verschiebungsvektororientierung des Firstpunktes bei Durchörterung von Gebirge mit unterschiedlichen Steifigkeitsverhältnissen. Trendlinien 2,5m, 5,0m, 7,5m hinter der Ortsbrust

Fig. 7: Contours of maximum principle stresses when tunnelling through rock mass with frequently changing stiffness. ($1^1/_2$ columns)
Bild 7: Maximale Hauptnormalspannungen bei Durchörterung von Gebirge mit unterschiedlichen Steifigkeitsverhältnissen.

3. Influence of primary stress

3.1. Primary stress orientation

The influence of primary stress orientation on the deformation pattern is also investigated. Using the same numerical model as in the previously shown studies, the dip angle of the maximum primary stress component σ_I is varied from 60° from the horizontal (against direction of excavation) to 120° from the horizontal (towards direction of excavation). The values of σ_{II} and σ_{III} are chosen at 0,5 σ_I.
To evaluate of the results data points around the circumference of the tunnel at a distance of 5 m (1/2D) behind the face are selected. The normalised displacement vectors are shown in stereographic projection (5,10,11). The intersections of the displacement vectors with the upper and lower hemisphere were connected by lines. Figure 8 shows the intersections of the normalised displacement vector orientations for the upper and lower half of the tunnel with the lower, and the upper hemisphere respectively.
The results show a significant influence of the orientation of the primary stresses on the crown and invert, while the orientation of the displacement vectors at the sidewalls is nearly unaffected..

Fig. 8: Normalised displacement vector orientation for different primary stress orientations shown in stereographic projection (K_0=0,5). ($1^1/_2$ columns)
Bild 8: Räumliche Vektororientierungen für verschiedene primäre Hauptnormalspannungsrichtungen dargestellt in einer Lagenkugel (K_0=0,5).

3.2. Variation in far field stress

Not only the orientation of the primary stresses but also a variation of the relation of the single primary stress components influences the vector orientation. In Figure 9 normalised displacement vectors of a section 5 m behind the face are displayed for different far field stress situations.
Following cases were studied:

- Stress in vertical direction (σ_V) same as in longitudinal (σ_L), horizontal stresses perpendicular to the tunnel (σ_T) axis double and triple of the vertical stress ($\sigma_V = \sigma_L$, and σ_T = 2 and 3* σ_V respectively)

It can be seen, that with an increase of horizontal stresses perpendicular to the tunnel axis, the displacement vector in the crown increasingly tends to point in direction of excavation, while the vectors at the sidewalls show the opposite trend.

- Same horizontal stresses in longitudinal and transverse direction being double or triple the vertical stress ($\sigma_T = \sigma_L$, and σ_V = 1/2 and 1/3* σ_L respectively)

In this case the study shows an increasing trend of the displacement vector orientation at the crown to point more in direction of excavation with increasing ration $\sigma h/\sigma v$, while the orientation of the vectors at the sidewalls is the same for both cases.

- Same stresses in vertical and transverse direction, longitudinal stress increased to double and triple of the vertical stress ($\sigma_V = \sigma_T$) and σ_L = 2 and 3* σ_V respectively).

This stress situation results in a very pronounced vector orientation of the sidewalls in direction of the excavation.

Fig. 9: Displacement vector orientation for different far field stresses shown in stereographic projection. ($1^1/_2$ columns)

Bild 9: Räumliche Vektororientierungen bei unterschiedlichen Primärspannungsverhältnissen in Lagenkugeldarstellung.

The effect of varying K_0 was also investigated. K_0 values ranged from 0,5 to 0,9. The total displacement paths are shown in figure 10. It is observed that for high K_0 values the change in longitudinal displacements in the vicinity of the face is much higher, than for small K_0 values (step 1 and 2).

Fig. 10: Total paths of the displacement vector orientation of the crown with increasing K_0 values. ($1^1/_2$ columns)
Bild 10:Verlauf der Verschiebungsvektororientierung der Firste bei zunehmendem Seitendruckbeiwert

4. Conclusion

The evaluation of the displacement vector orientation can provide valuable information on changes in rock mass quality ahead of the face. The effect of the primary stress orientation and varying K_0 values was demonstrated for several basic situations.
These findings correspond well with observations from different tunnel sites.
Further studies are in progress using plastic material behaviour laws and further variations in the primary stress conditions.
For the tunnelling engineer the evaluation of the displacement vector orientation can improve the quality of the short term prediction, thus decreasing the number of “surprises” when tunnelling in heterogeneous ground. Modifications in excavation and support can be made in time, decreasing the necessity of later reinforcements and repairs. In addition information on the primary stress situation will help in the interpretation of observations on site, as well as in the support layout.
It must be emphasised that because the direction of the longitudinal displacement changes twice in the vicinity of the face, utmost care has to be exercised in monitoring and in interpreting monitoring data.

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Authors

Dipl.-Ing. Harald Golser, SITU Joint Research Initiative – Site Application, Institute for Rock Mechanics and Tunnelling, Graz University of Technology, Rechbauerstraße 12, A-8010 Graz, Austria

Dipl.-Ing. Dr.techn. Albert F. Steindorfer, Ingenieurgemeinschaft für Geotechnik und Tunnelbau, Mauracherstraße 9, A-5020 Salzburg, Austria.

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