Selective displacement monitoring during tunnel excavation

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1 Introduction

Determination of absolute displacements during tunnel excavation by geodetic methods has to a large extent replaced relative displacement measurements in Austria during the last decade. Detailed information on the method of monitoring can be found in (1). The increase in information has lead to additional possibilities in data visualization. The plotting of lines of influence, trend lines along the tunnel axis or displacement vectors in a plane perpendicular to the tunnel axis in addition to time histories have become common practice in many places. The development of efficient techniques for data evaluation and visualization, especially for tunnels with low overburden was initiated by Vavrovsky in the eighties (2,3).

Those improved tools have lead to a better understanding of geomechanical processes during tunnel excavation. Better adjustment of excavation and support to the geotechnical conditions, as well as a certain ability of predicting the ground reaction ahead of the tunnel face is possible with the help of the improved methods of data evaluation.

Even when these improved tools are used by experienced geotechnical engineers on site, occasionally changes in rock mass behavior are detected to late due to the lack of information on the parameters of the rock mass outside the visible excavation area. Tunnels with high overburden in poor and strongly heterogeneous rock are an ongoing engineering challenge around the world. Many projects have been delayed considerably when unexpectedly meeting fault zones. Several attempts are made to improve the prediction of the rock mass structure ahead of the face. Promising results in fault prediction have been obtained already with geophysical methods (4). Costs and time required for such tests still do not allow a routine application on a day to day basis.

Fig 1: Displacement monitoring at the Inntaltunnel

Recent experience on two tunnels, constructed in heavily faulted rock in Austria has lead to a further development in monitoring data processing. At the 12.7 km long Innsbruck railway bypass tunnel the displacement component in longitudinal direction has been used the first time for interpretation of monitoring data. Displacements measured in longitudinal direction in a large fault zone were considerable. In addition, the evaluation showed, that the ratio between radial and longitudinal displacement varied in a wide range. Matching the observed phenomena with the geological documentation, it was found that those changes in ratio could be used as indicators for changes in rock mass stiffness (5).

On the basis of the observations at the Innsbruck bypass tunnel a research project was initiated at the Institute of Rock Mechanics and Tunnelling at the Technical University of Graz. It was found, that changes in rock mass stiffness several diameters ahead of the face can be detected using the orientation of the displacement vectors in space. Monitoring data of a fault zone at the recently completed 5,3 km Galgenbergtunnel in Austria showed, that also deviations in primary stress orientation can be identified (6).

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Based on field monitoring data and geological documentation, numerical 3-D simulations have been performed, which confirm the observations on site. The findings allow a better evaluation of the stress situation around the tunnel and prediction of ground mass behavior in time. New tools for efficient data processing and visualization have been developed. The objective of those tools is a reduction of data and plots to be examined routinely. In order to achieve this goal, it is necessary to process and display monitoring data selectively.

2 Adequate data processing and visualization

Absolute displacement monitoring during tunnel excavation has triggered a rapid development in methods of data processing and visualization over the last couple of years. The introduction of new evaluation and display methods calls for a reassessment of the geomechanical relevance of traditional and new techniques. Some guidelines for interpretation of certain phenomena have already been established by P. Schubert and Vavrovsky (7,12), with emphasis on tunnels with low overburden. In the following we have compiled a few typical geotechnical situations met during tunnel excavation. Schematically the benefits of different methods of display will be shown for each situation. Examples shown are based on simplified monitoring data and numerical simulation results. Statements about relevance of information refer to tunnels with high overburden in relatively weak rock.

2.1 Time Histories

Vertical, horizontal, and longitudinal displacement components are plotted versus time. One or more monitored points of one measuring section can be shown on one plot. This way of display is familiar to most tunnelling engineers. Phases of construction usually are shown on the same plot to allow a correlation between construction and displacements.

Value of the information:

- *Observation of stabilization process*
  For this purpose basically the absolute magnitude of displacement is of not much interest. The displacement speed over time has to decrease continuously. Any acceleration indicates destabilization, unless caused by a subsequent excavation step (for example bench excavation).

Fig. 2: Typical time history diagram, showing expected behavior and indication of destabilization

- *Estimation of final displacement*
  In weak rock with high overburden, displacements can reach a considerable magnitude. To allow for the displacements without impairing the clearance profile, overexcavation is required. A good estimate of final displacements will help in saving time and money. A magic formula for estimating final magnitude of displacements does not exist up to now. Besides experience, of some help can be the approach of Panet (8), who on the basis of curve fitting obtained functions for time dependent tunnel closure.

Fig. 3: Final displacements extrapolated from few readings, using previous experience and actual geological situation

2.2 Lines of influence and Trend lines

Lines of influence are produced by connecting displacement values of a number of measuring points along the tunnel axis at the same time (similar to a deflection curve). In order to eliminate the influence of differences in distance between face and zero reading, displacement at the face is considered zero. Usually lines of influence are plotted for each component of the displacement vector separately.
Trend lines are produced by extracting values from the lines of influence in a constant distance from the face.

2.2.1 Lines of influence from absolute displacement values

For this type of plot, values of displacement components are used as measured, only corrected by the differences in the zero reading.

Value of the information:

- When showing several lines of influence on the same plot, good comparison of displacements along the tunnel axis is possible. Trends of relatively decreasing or increasing rock mass stiffness can be easily verified. Some extrapolation beyond the face is possible.

- Shows influence of each excavation step on already excavated and supported tunnel. An increase in area between two lines of influence in the excavation area indicates a weak zone or a discontinuity ahead of face. The influence of each construction activity on the displacement behavior of tunnel structure in the vicinity of the activity can be recognized easily.
  Trend lines (fig. 5) can be used to extrapolate displacements beyond the face; provide good overview of displacement development along the tunnel. Also used to identify zones of previously excavated zones with similar deformation behavior for determination of support.

  Fig. 4: Typical plot of lines of influence when excavation approaches weak zone

  Fig. 5: Lines of influence and trend line after excavation has passed weak zone

2.2.2. Lines of influence from relative displacement values

Those lines are used to show differential displacements between two points, for example the difference in settlement of crown to settlement of sidewall. Using quotients of displacement values of two points in most cases is to be preferred to the display of differences, as varying stiffness of rock mass may distort the result.

Value of information:

- Detection of weakness zones or faults outside the excavation area. In more or less homogeneous material, the settlement of the crown will be higher than the settlement of the sidewall. Higher settlement of sidewall than crown indicates failure of the ground besides sidewall, for example when approaching a more or less vertically dipping fault, crossing the tunnel axis in an acute angle. Ratio of sidewall settlement to crown settlement considerably increases well before the fault will be visible at the face, a fact that allows to take proper action in time (fig. 6).

  Fig. 6: Trend lines showing the ratio of the settlements left and right sidewalls to crown

2.3 Displacement vector orientation

Absolute displacement monitoring provides information on the displacement vector in space. Traditionally components of the total vector are displayed only, e.g. settlement, lateral displacement, and most recently longitudinal displacement. Additional information about the rock mass structure and deformation phenomena in the rock mass close to the tunnel can be obtained by using displacement vector orientations. Display of displacement vector orientation and it`s development over the time in a plane perpendicular to the tunnel axis has been introduced several years ago already. Later developments include the displacement in direction of the tunnel axis (6).

2.3.1 Plot of vector orientation in measuring section

Displacement vectors of several points in the measuring section are shown in a plane perpendicular to the tunnel axis. Settlement and lateral displacement components are used. Time dependent development of each vector can be displayed.

Value of information:

- displacement pattern indicates influences of rock mass structure (schistosity, joints, faults, etc.) Used to understand deformation phenomena, which allows custom tailored support design (for example rockbolt layout, spacing, orientation)

Fig. 7: Typical displacement vector orientation in cross section, indicating steep discontinuity besides sidewall

2.3.2 Orientation of displacement vectors projected in vertical / horizontal plane along tunnel axis

The orientation of the displacement vector in space is projected in planes parallel to the tunnel axis. Trend lines, showing orientation of displacement vectors in constant distance or time interval from face are used so far.

Value of information:

- vector orientation in a vertical plane along the tunnel axis (settlement and longitudinal displacement component): shows changes in rock mass stiffness well ahead of the face. When excavation approaches weaker material, the orientation of the displacement vector shows an increasing tendency against the direction of excavation. In case of stiffer material ahead of the face, the opposite tendency - relatively low value of longitudinal displacement and even displacement in direction of excavation - can be observed.

Fig. 8: Trend (1/2 diameter behind face) of displacement vector orientation in longitudinal section; typical development when excavation approaches weak material

- vector orientation in a horizontal plane along the tunnel axis (lateral and longitudinal displacement component): provides additional information on stiffness distribution in the rock mass outside excavation area. In combination with vector orientation in vertical plane used to identify rock mass structure in space.

2.3.3 Display of displacement vector orientation by stereographic projection

To make full use of the information available and to avoid the necessity of requiring several diagrams to obtain the displacement vector orientation in space, display of the orientation in stereographic projection similar to the display of discontinuities can be used (10). This method of display allows an easy correlation of deformation patterns to the geological structure. In addition all monitored vectors of one or more measuring sections can be plotted on one diagram. Currently this way of display is under test, using monitoring data from various alpine tunnels. First experience shows an enormous potential in short term prediction of rock mass conditions well ahead of the excavation.

Value of information:

- vector orientation provides information on stiffness distribution in rock mass, observed phenomena as above; powerful tool to detect changes in rock mass quality well ahead of face

- influence of rockmass structure on deformation behavior is shown

Fig. 9: Displacement vector orientation of crown and sidewalls in stereographic projection; typical development when excavation approaches stiffer rock mass

2.4 3-D plots of displacements or trends

Similar to the visualization of results of numerical simulations monitored displacement values or data processed from those values can be shown in the way of contour lines on the tunnel wall or in a plane development of the tunnel wall.

Value of information:

- good overview of displacements or trends over longer stretch of tunnel

- easy early detection of faults crossing the excavation in an acute angle

Fig. 10: Contour line plot of vertical displacements, showing influence of two faults crossing the tunnel in an oblique angle

3 Conclusion

Various ways of monitoring data processing and visualization exist at the moment. The number has significantly increased over the last decade, and we have added some more recently. It has been left to the user to understand the level and quality of information contained in each diagram and to use the information in an appropriate way. There is a certain danger of loosing control of the number of diagrams and miss essential information, which might be important for the stability of the tunnel for example. It is our conviction, that with proper use of the acquired monitoring data so called „unpredictable“ occurrences in tunnelling will be minimized in future. A few typical geotechnical situations have been selected to show the potential of each display technique, hoping that this information will be of some help to site engineers. A more comprehensive collection of examples in under preparation at the moment (11).

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References

1 Rabensteiner, K.: Advanced Tunnel Surveying and Monitoring; Felsbau 14 Nr. 2; 1996
2 Vavrovsky, G.M., Ayaydin, N.: Bedeutung der vortriebsorientierten Auswertung geotechnischer Messungen im oberflächennahen Tunnelbau, Forschung + Praxis, Band 32, Alba Fachverlag Düsseldorf, 1988
3 Vavrovsky, G.M.: Die räumliche Setzungskontrolle - ein neuer Weg in der Einschätzung der Standsicherheit oberflächennaher Tunnelvortriebe, Mayreder Zeitschrift., 33. Jg., 1988
4 Inazaki, T.: HSP: A new tool for detecting fractures ahead of tunnel face, Proceedings 8th Int. Congr. on Rock Mechanics,Vol. 2, Balkema Rotterdam, 1995
5 Schubert, W.: Erfahrungen bei der Durchörterung einer Großstörung beim Inntaltunnel; Felsbau 11, Nr. 6, 1993
6 Schubert W., Budil A.: The importance of longitudinal deformation in tunnel excavation, Proc. 8th Int. Congr. on Rock Mechanics, Balkema Rotterdam, Vol. 3, 1995
7 Schubert, P., Vavrovsky, G.M.: Interpretation of monitoring results, World Tunnelling, November 1994
8 Sulem, J., Panet, M., Guenot, A.: Closure analysis in deep tunnels, Int. J. Rock Mech. Min. Sci. & Geomech. Abst. 24, 1987
9 Heim, N., Rabensteiner, K.: Zusammenspiel Geologie / Meßtechnik am Beispiel des Sonnbergtunnels, Felsbau 13, Vol. 3, 1995
10 Steindorfer, A., Schubert, W., Rabensteiner, K.: Problemorientierte Auswertung geotechnischer Messungen, Felsbau 13, Vol. 6, 1995
11 Steindorfer, A.: Short term prediction of rock mass behaviour in tunnelling by advanced analysis of displacement monitoring data, Thesis at the Institute of Rock Mechanics and Tunnelling, Techn. Univ. Graz (under preparation)
12 Vavrovsky, G.M., Schubert, P.: Advanced analysis of monitored displacements opens a new field to continuously understand and control the geotechnical behaviour of tunnels; Proc. 8th Int. Congr. on Rock Mechanics, Tokyo,Vol. III, Balkema Rotterdam, 1995

Abstract

Geodetical displacement monitoring in tunnelling allows to determine the displacement vector in space of each measured point. The increase in information has lead to additional possibilities in data visualization. The number of ways of monitoring data processing and visualization has significantly increased over the last decade, and we have added some advanced display techniques recently. The increase in the number of possibilities calls for a reassessment of the geomechanical relevance of traditional and new evaluation and display methods. A few typical geotechnical situations have been selected to show the benefits and the potential of different methods of display for each situation.