Analysis of Time Dependent Displacements of Tunnels

By Wulf Schubert, Edward A. Button, Peter J. Sellner and Tülin Solak

Very little information exists today on the effect of transient processes during tunnelling. Recent and current research into the development of the strength and rigidity of shotcrete addresses one of the time dependent components of the tunnel response. The empirical relationships developed by Sulem and Panet in the mid 1980's (1) allow the effect of the stress redistribution due to the tunnel advance to be separated from the time dependent deformation of the rock mass.

With the improvements in computing power, 3-D models of the tunnel advance can also be used to evaluate the influence of the excavation advance but are rarely performed with complex time based constitutive models. Even with the available methods to empirically or numerically evaluate the time dependent deformations there has been little work done to identify the key factors and rock mass parameters which can be used explicitly to evaluate or predict the rate and magnitude of the rock mass's time dependent deformations.

When tunnelling in an environment in which the induced stress state exceeds the local rock mass strength it is likely that noticeable deformations will occur over time. In this situation several questions need to be asked by the tunnel engineer:

- How long will the deformations continue?
- At what rate or rates will they occur?
- What will be the final magnitude?
- Will new failures occur in the rock mass due to the strain?
- Can the lining withstand the strains?
- Does the lining have the capacity to stabilize the rock mass?

There is not a clear answer to these questions at the current time.

Both from the laboratory and from tunnelling experience we know that the more brittle a rock is the faster it loses its capacity to resist loads and will fail more rapidly when its strength is exceeded. During an excavation this brittle type of failure typically results in spalling or in extreme situations in rock or strain bursts. It has been observed that it requires very little support pressure to control the spalling process (2). However, for rock or strain bursts (i.e. when the stress is much greater then the strength) little can be done to prevent the failure and support systems are designed more for worker safety then preventing failure. It is also well known that weak "frictional plastic" rocks will often deform over a much longer period when their strength is exceeded. This usually is called "creep" or "squeezing" behaviour.

For rocks or rock masses that lie between these boundaries failure involves a complex interaction between the loss of internal cohesion (fracturing), the development of its frictional resistance, and kinematics. One may ask if it is pos-

Analyse zeitabhängiger Verformungen im Tunnelbau

Die Frage, welche Anteile der Gesamtverformung eines Tunnels aus der rein vortriebsabhängigen Spannungsumlagerung und welche aus dem zeitabhängigen Verhalten des Gebirges und Ausbaus stammen, ist weitgehend ungeklärt. Vorausberechnungen sind wegen der mangelnden Kenntnis der entsprechenden Einflussfaktoren und Parameter von großer Unsicherheit geprägt.

In diesem Beitrag werden analytische Funktionen, welche zeit- und vortriebsabhängige Komponenten enthalten, an gemessene Verschiebungsdaten angepasst. Durch Elimination des wegabhängigen Anteils kann der zeitabhängige Anteil an den Gesamtverschiebungen ermittelt werden.

Gemessene Verschiebungen von ausgewählten Bereichen verschiedener alpiner Tunnel werden mithilfe des Programms GeoFit analysiert, um die zeitabhängige Verschiebung zu ermitteln. In einem zweiten Schritt wird versucht, das zeitabhängige Verhalten mit der geologischen Situation und den Einflussfaktoren zu korrelieren.

Very little information exists on the question, which share of the total displacement of a tunnel is related to the pure stress redistribution due to the face advance, and which to the time effect. Due to the limited knowledge of the rock mass parameters and influencing factors modelling in advance is difficult and unreliable.

Analytical functions have been developed, which contain face advance and time dependent components. Using curve fitting techniques the function parameters are adjusted to match with the measured displacements. Eliminating the advance dependent component, the time dependent component of the displacements can be evaluated.

Measured displacements from selected areas of Alpine tunnels are analysed with the program GeoFit to determine the time dependent displacements. An attempt is made to correlate the time dependent behaviour to the geological situation and the influencing factors.

sible to identify, for different rock mass types, at which stress level the failure process will initiate in situ, and once this process begins how long will it continue given the local boundary conditions (stress level, kinematics, opening size and shape, and the support capacity). To answer these questions experience gained from case histories, innovative and well designed laboratory investigations, as well as theoretical relationships investigated with empirical or numerical models can be used. Case histories are used to show how the empirical relationships can be used to separate the effect of the tunnel advance from the "time dependent" rock mass deformations.

Basic Considerations

The simplest of all conceivable cases is when there are only elastic displacements caused by the stress changes due to the face advance, with the rock mass responding immediately to the stress changes. A typical example of such behaviour is shown in Figure 1. As soon as the excavation stops, displacements cease until the excavation is restarted.

Generally, displacements will have a time dependent component, with displacements continuing after the excavation has advanced considerably away from the monitoring section, or if there is an interruption in the advance. Figure 2 shows the displacements for the same advance related displacements as Figure 1, but including time dependent deformation. The magnitude of both the time dependent and advance related displacements are also shown.

In the analytical equation proposed by Sulem and Panet (1), the final magnitude of the advance dependent displacements is given by the parameter C, while the amount of the final time dependent displacements is given by the product m · C. Depending on the rock mass structure and stress level, the face advance will cause displacements up to a certain distance from the measuring section. This relationship is expressed by the parameter X. High X-values indicate that the face advance still influences the displacements after the excavation has progressed a large distance from the measuring section. In a similar way the parameter T controls the time dependent behaviour, with small T-values indicating that time dependent displacements cease a short time after excavation.

With three dimensional finite element simulations the parameters X and C, at least for elastic conditions, can be evaluated. It appears, that for a 10 m diameter tunnel the value of X for homogeneous conditions is around 5 to 6. With such a value of X the major share of the displacements occurs within three diameters behind the face. This corresponds well with observations from tunnels in a low to medium stress environment. For anisotropic and heterogeneous conditions the estimation of the parameters is more difficult. A few rules of thumb can nevertheless be established. In case of an excavation parallel to a steeply dipping foliation with low shear strength, the parameter X can be expected to be considerably higher than in the case of isotropic conditions. On the other hand, when excavating perpendicular to the foliation, the X-value will be rather low, due to the limited stress transfer back from the face. An increasing stress/strength ratio will increase the size of the failure zone and thus also increase the X value. It could be also shown, that a change in the rock mass stiffness influences the X and C parameters (3) in the sections well ahead of the boundary.

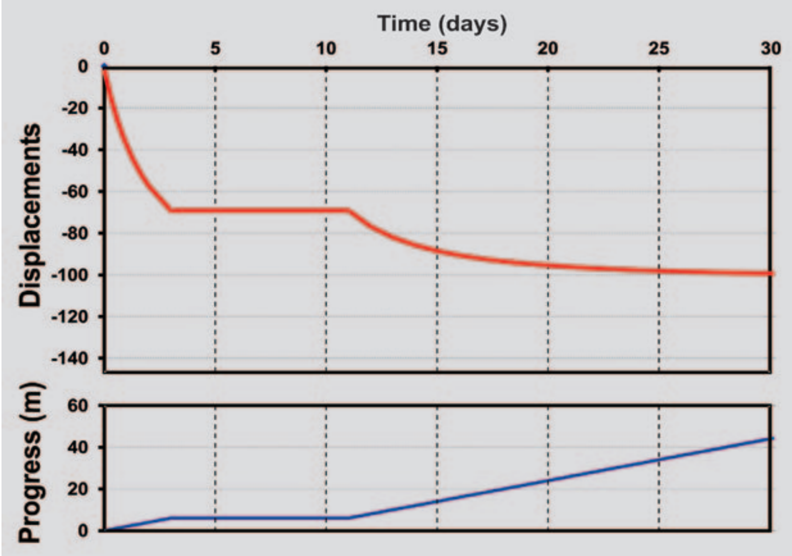

Fig. 1 Typical displacement history for a discontinuous advance without time dependent displacements.

Bild 1 *Typische Verschiebungsentwicklung bei nicht kontinuierlichem Vortrieb ohne zeitabhängige Deformationen.*

Evaluating Case Histories

Case histories provide the benchmark problems and when the documentation (deformations, geologic conditions, construction process, and installed support) is accurately and consistently documented can be used to identify characteristic behaviours and the influencing factors. When the documentation is inaccurate or not consist-

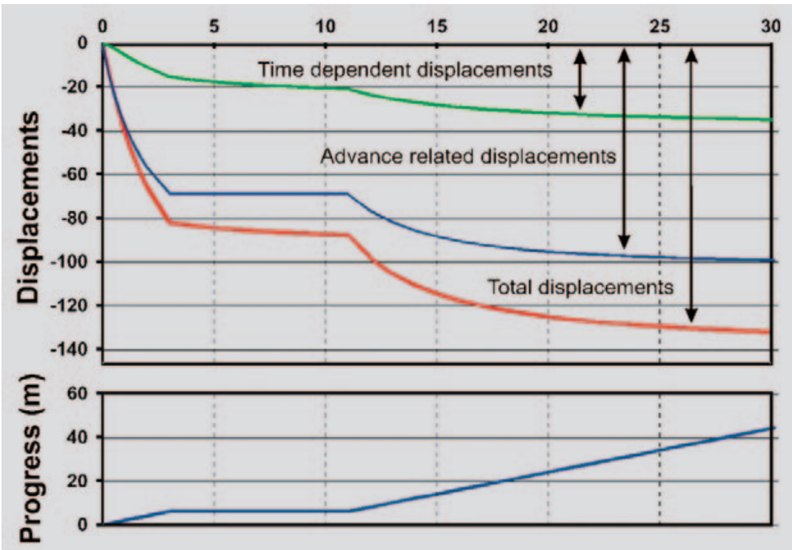

Fig. 2 Typical displacement history for a discontinuous advance with advance and time dependent displacements; the blue line represents the time dependent displacements.

Bild 2 *Typische Verschiebungsentwicklung bei nicht kontinuierlichem Vortrieb mit vortriebs- und zeitabhängigen Deformationen; die blaue Linie zeigt die Entwicklung der zeitabhängigen Verschiebung.*

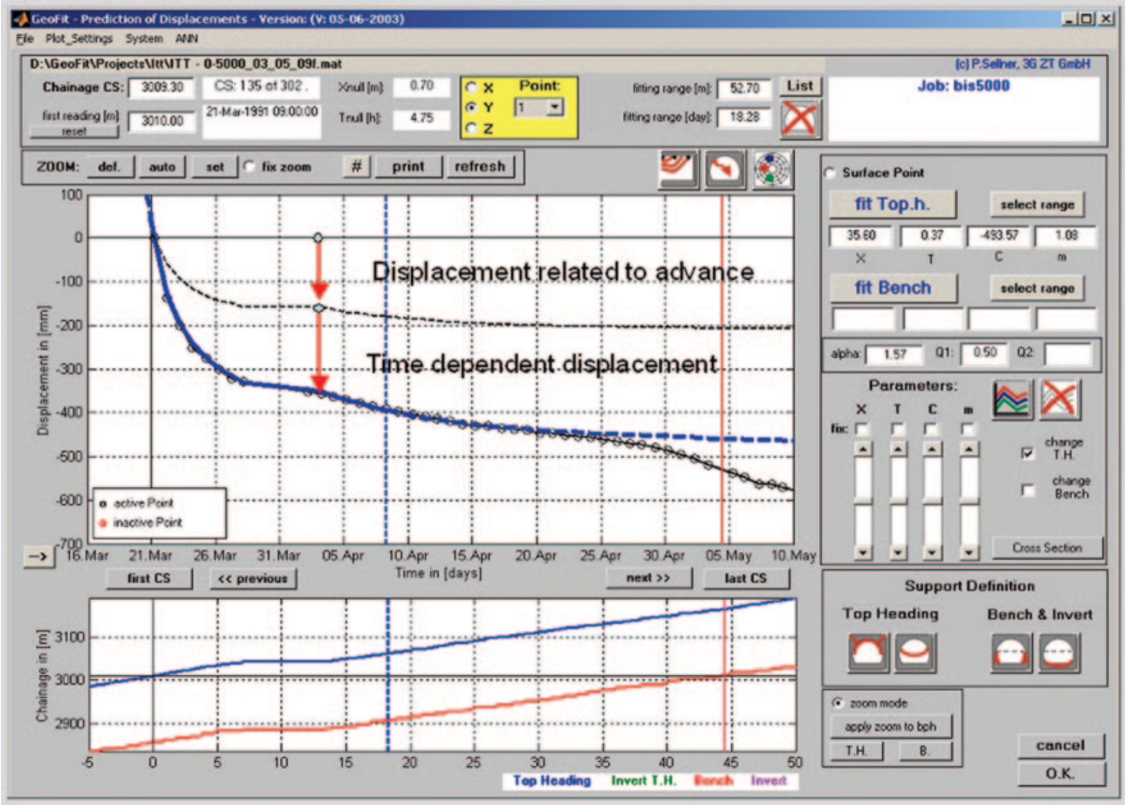

Fig. 3 Example of adjusting the function parameters to monitored results with discrimination between advance related and time dependent displacements; Inntaltunnel.

Bild 3 *Beispiel der Anpassung der Funktionsparameter an gemessene Verschiebungen mit Unterscheidung in vortriebs- und zeitbezogene Verschiebungen am Inntaltunnel.*

ent then very little quality information can be extracted from the data. We would like to stress the importance of quality documentation for utilizing case histories for advancing the art of tunnelling.

The recently developed computer code GeoFit (4) is based upon the formulations of Sulem and Panet (1) and subsequent modifications by Barlow (5) and Sellner (6). It allows for the monitored deformations to be rapidly evaluated using the four function parameters mentioned above combined with parameters defining the percentage of pre-displacements, the initial support capacity, in addition to an option for additional support. Once the monitored data is evaluated the total deformation magnitude can be divided into the deformations occurring due to the tunnel advance and the time dependent deforma-

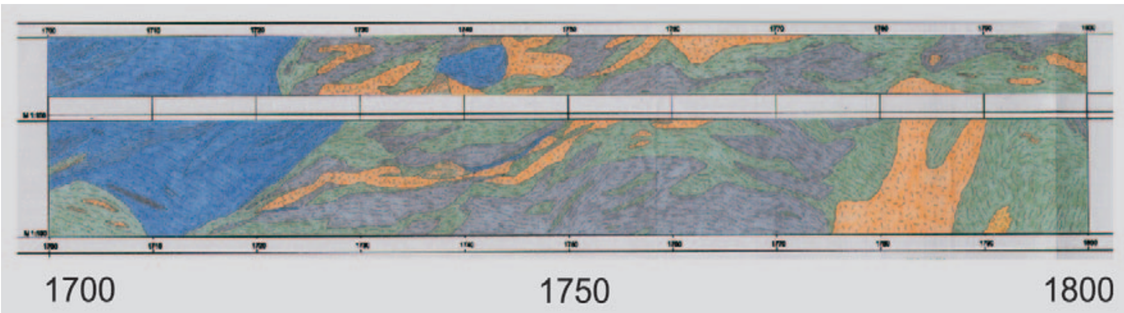

Fig. 4 Geological plan view of section 1 700 to 1 800 at the tunnel Spital, south tube.

Bild 4 *Geologischer Grundriss des Bereichs TM 1 700 bis 1 800 beim Tunnel Spital, Südröhre.*

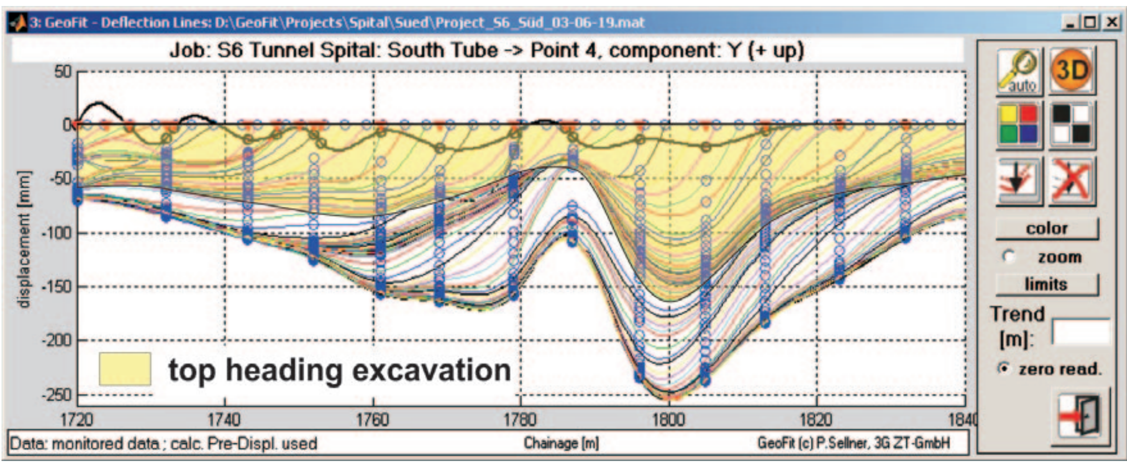

Fig. 5 Monitored settlements of the left sidewall. Settlements during top heading excavation are shaded yellow.

Bild 5 *Gemessene Setzungen des linken Ulmpunkts. Die Setzungen zufolge Kalottenvortriebs sind gelb hinterlegt.*

tions. This requires some practice and a solid foundation in mechanics to arrive at a reasonable solution, as a unique solution is not always possible. This applies especially for headings with constant advance rates, where it is difficult to distinguish between the advance and time dependent displacements.

Example Inntaltunnel

Figure 3 shows an example of the adjustment of the function parameters to the measured displacements for the top heading of a section in the Inntaltunnel. The dashed blue line represents the displacements calculated with the analytical function, while the measured values are displayed as small black circles. The deviation of the measured values from the calculated ones after April 20th results from the approaching bench excavation.

For this section a good agreement with the measured values could be obtained with a set of parameters where the time dependent displacements are approximately 55 % of the total displacements.

Example Tunnel Spital

This tunnel is located in a tectonic melange for its entire length (7, 8). The rock mass is composed of sheared phyllites surrounding blocks of dolomite, marbles and quartzite. The documented geological conditions for a section of the discussed results are shown in plan view in Figure 4. The rapid variations in rock mass stiffness and displacement kinematics associated with different block-matrix distributions result in highly variable displacement behaviours (9, 10).

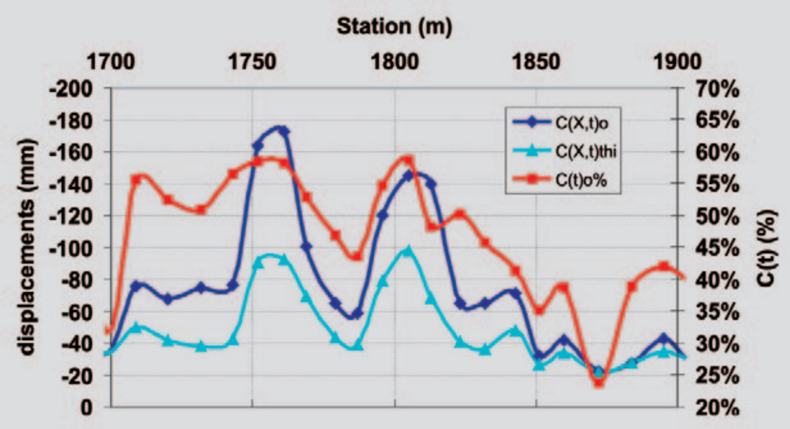

Fig. 6 Calculated settlements of the crown without and with temporary invert, and portion of time dependent displacements.

Bild 6 Errechnete Firstsetzungen ohne und mit temporärem Sohlgewölbe und zeitabhängiger Anteil.

Figure 5 shows the measured total settlements for the crown for the region discussed in the following examples. The first 100 m corresponds to the geological section shown in Figure 4. The increase in displacements associated with the matrix dominated zones as well as the decrease in displacements due to increased block proportions can be seen.

Figure 6 shows the calculated crown settlements for the top heading excavation both with and without a temporary invert for the same 200 m section of the tunnel. The percentage of the time dependent settlements is also shown. The largest displacement magnitudes and the largest time dependent displacements are associated with matrix dominated zones, while the decreased magnitudes at stations 1 770 to 1 790 and 1 875 are due to the increased block proportion in these zones.

It can be seen that the time dependent portion of the displacements increases in the matrix

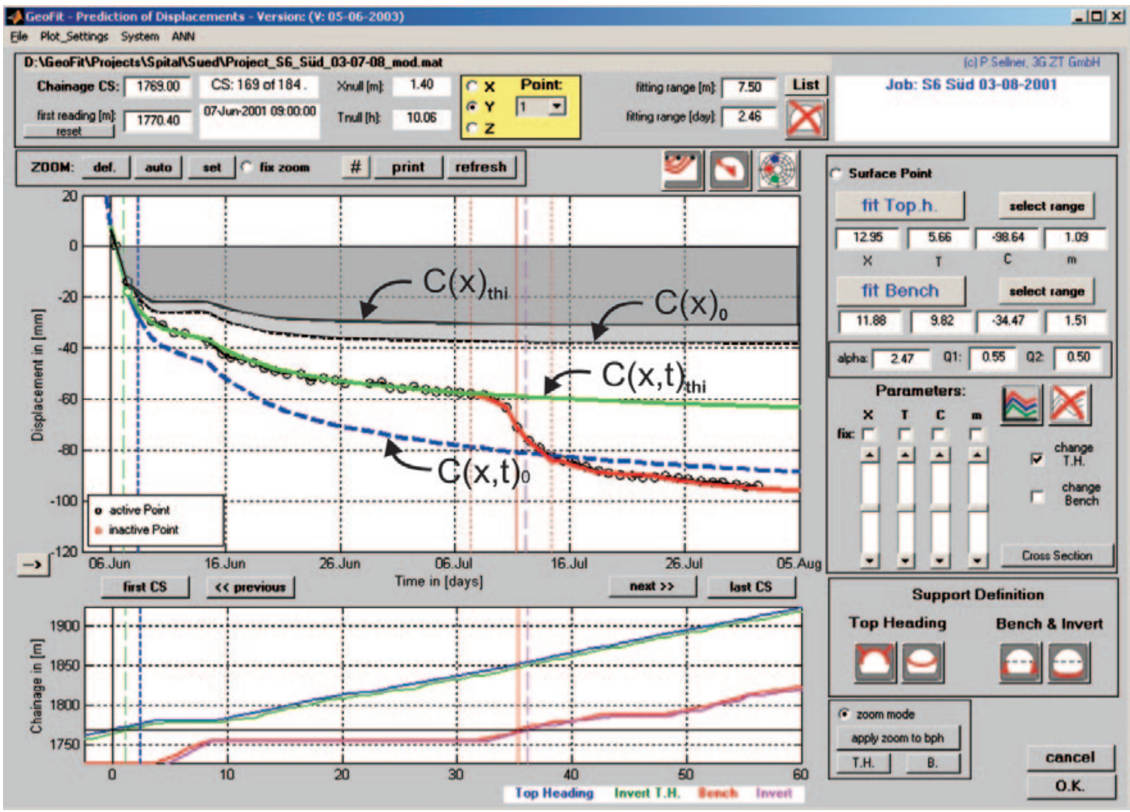

Fig. 7 Fitted displacements of the crown for a section with a relatively low percentage of time dependent displacements. The advance related displacements are shaded grey.

Bild 7 An die gemessenen Firstsetzungen angepasste analytische Funktion in einem Bereich mit relativ geringem zeitabhängigem Anteil. Die vortriebsabhängigen Verschiebungen sind grau hinterlegt.

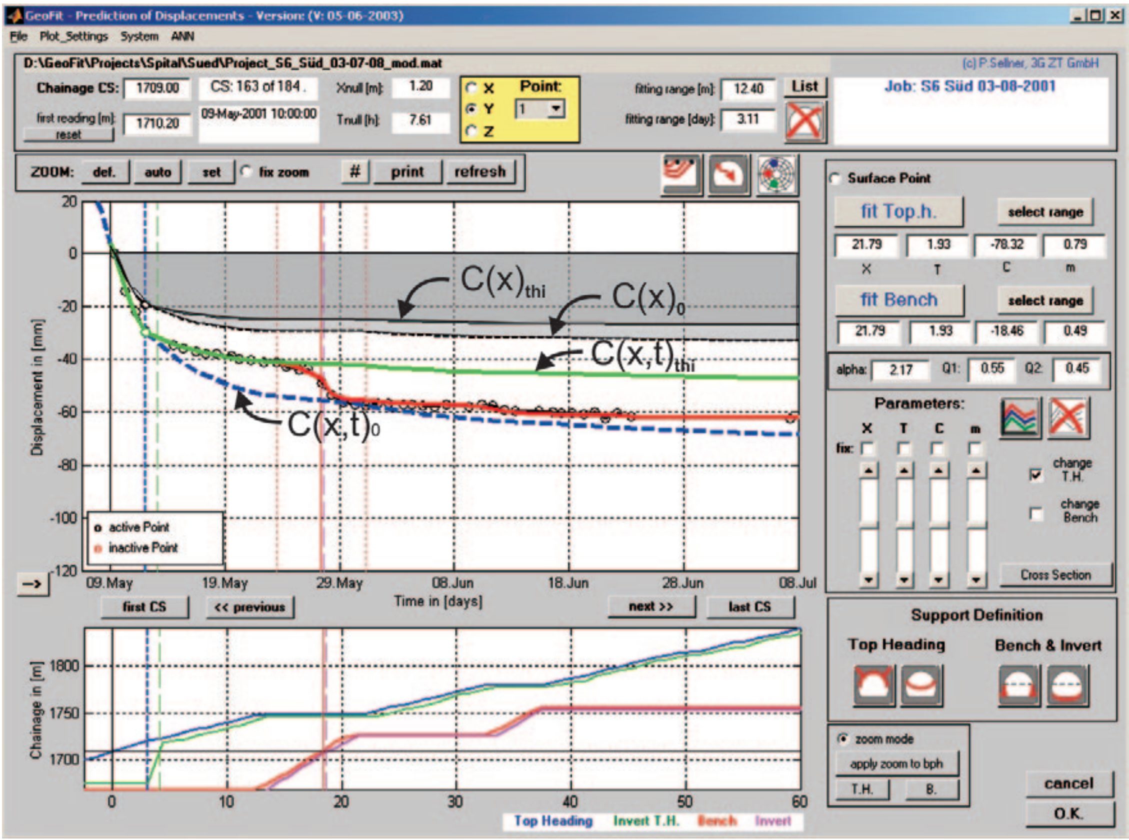

Fig. 8 Fitted displacements of the crown for a section with a high percentage of time dependent displacements. The advance related displacements are shaded grey.

***Bild 8** An die gemessenen Firstsetzungen angepasste analytische Funktion in einem Bereich mit hohem zeitabhängigem Anteil. Die vortriebsabhängigen Verschiebungen sind grau hinterlegt.*

dominated zone and decreases with higher block proportions. This is due to the differences in the rock mass stiffness and strength associated with different block proportions. As the stress level approaches or exceeds the rock mass strength it is expected that the magnitude of the time dependent settlements will also increase.

Two examples of fitted monitoring data are shown in Figures 7 and 8, respectively. Figure 7 shows a monitoring section at the transition to the first fault zone with a relatively low percentage of time dependent displacements. Figure 8 shows a section within the fault zone with the highest m and T values. In both of these sections a temporary invert was installed immediately following the top heading. The effect of the invert is modelled within GeoFit using the additional support function. The predicted displacement magnitude when considering the additional support is represented with the green line ($C(x,t)_{thi}$) and corresponds extremely well with the monitored data, represented with circles. The blue

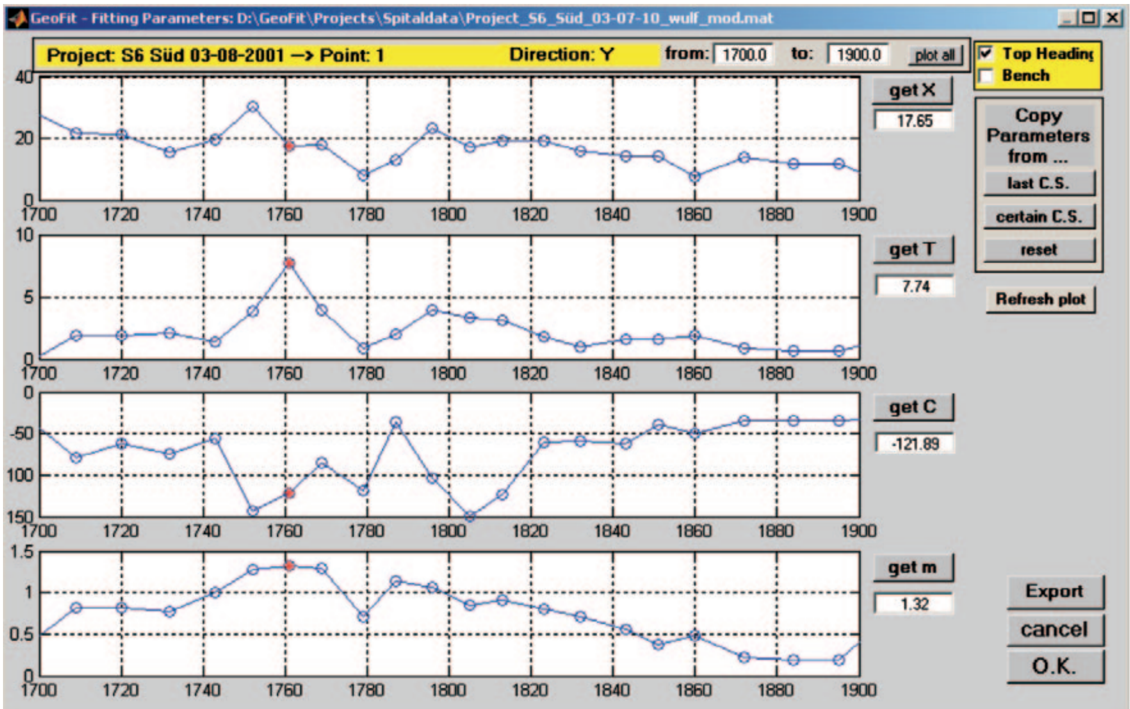

Fig. 9 Distribution of the function parameters X,T,C,m for the evaluated section.

***Bild 9** Funktionsparameter X,T,C,m für den diskutierten Bereich.*

line ($C(x,t)_o$) represents the predicted displacements if no invert is installed. The effect of the bench excavation is also shown for these examples, the prediction is represented with the red line. The shaded region represents the excavation related displacements associated with the top heading advance with ($C(x)_o$) and without ($C(x)_{thi}$) the temporary invert. The difference between C(x) and C(x,t) is the magnitude of the time dependent displacements.

It should be noted that for these examples the temporary invert influences the time dependent portion of the displacements to a much larger degree than the advance related displacements.

Evaluations of the monitoring data using the program GeoFit have shown that even with the heterogeneous displacement characteristics as shown above, there is a relatively smooth transition in the function parameters for each monitoring point (3).

Figure 9 shows the distribution of the function parameters for the crown settlements over the same 200 m section of the tunnel. As mentioned previously, the time dependent portion of the total displacements is related to the parameters m and T. It can be seen that as the tunnel passes though the matrix dominated fault zone (station 1 740 to 1 770) both parameters increase. They peak just before a large block that extends from station 1 770 to 1 790. The influence of the block can also be seen in the parameter X which decreases rapidly as the block is approached, then increases again as the next matrix dominated zone is encountered.

Figure 10 shows the percentage of the displacements that are related to time dependent effects both with and without the temporary invert, and the overburden.

Two items can be noticed on this diagram. Firstly, the use of the temporary invert reduces the time dependent portion of the displacements by approximately 10 %. This is due to the increase in support stiffness associated with ring closure and the associated higher lining utilization. Secondly, as the overburden decreases, the portion of the time dependent displacements also decreases. This is also noticeable in the distribution of function parameters shown in Figure 9. The parameters increase directly after the large block and then, after station 1 800, there is a consistent decrease of all the function parameters. For this example, as the overburden decreases below 40 m the time dependent displacements reduce to approximately 35 % of the total displacements compared to 55 % for the larger overburden. The extremely low percentage at approximately station 1 875 is related to the high block proportion combined with the lower stresses in this region. This demonstrates that the stress level (relative to the rock mass strength) directly influences the magnitude and rates of the time dependent displacements.

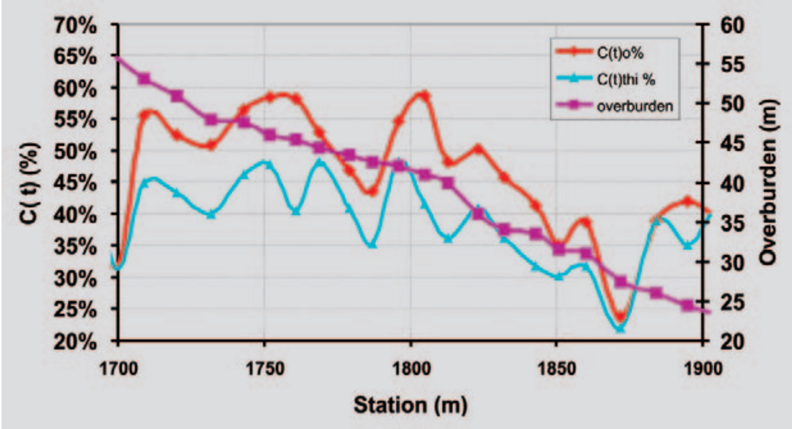

Fig. 10 Portion of the time dependent settlements with and without the temporary invert and the associated overburden.

Bild 10 *Anteil der zeitabhängigen Setzung mit und ohne temporäres Sohlgewölbe und Überlagerung.*

Example Strenger Tunnel

Figure 11 shows a displacement plot for the horizontal displacements for the lower left side wall point at a section in the Strenger tunnel. In this region the rock mass is composed of hard phyllites (UCS between 15 and 25 MPa), the foliation dips moderately to steeply towards the left. The overburden is around 600 m.

The initial displacements have a normal trend, however, when the excavation advance stops after approximately ten days, the displacements continue with an additional displacement of approximately 5 cm over ten days. When the excavation restarts, the displacements accelerate as expected. Normally the displacements would stabilize around this time. This is shown in Figure 12 by fitting the data using the program GeoFit. The prediction follows the data through the excavation pause indicating that the time dependent parameters are appropriate and for approximately three days after the excavation restarts. At this time the monitored values deviates from the prediction. The displacements continue in a slightly periodic trend (i.e. begin to stabilize then accelerate and so forth) over the next two months of available monitoring data. From the displacement trend it appears the rock mass is creeping. Is this the correct interpretation?

By definition “creep” occurs during a constant stress state and after significant strain or time the strain accelerates and failure occurs. In this example the induced stress state is considerably higher than the evaluated laboratory strength, so one would expect the failure to happen relatively rapidly indicated by a high initial displacement rate then stabilizing. As shown this is not the case.

The formulation in GeoFit allows uniform time dependent behaviour “i.e. creep” to be modelled. Even after considerable effort this and other monitoring sections in this region could not be fitted with reasonable parameter combinations accurately. A possible reason is discussed below.

As mentioned previously, it takes very little support pressure to prevent brittle failure in terms of spalling. However, when the cohesive to

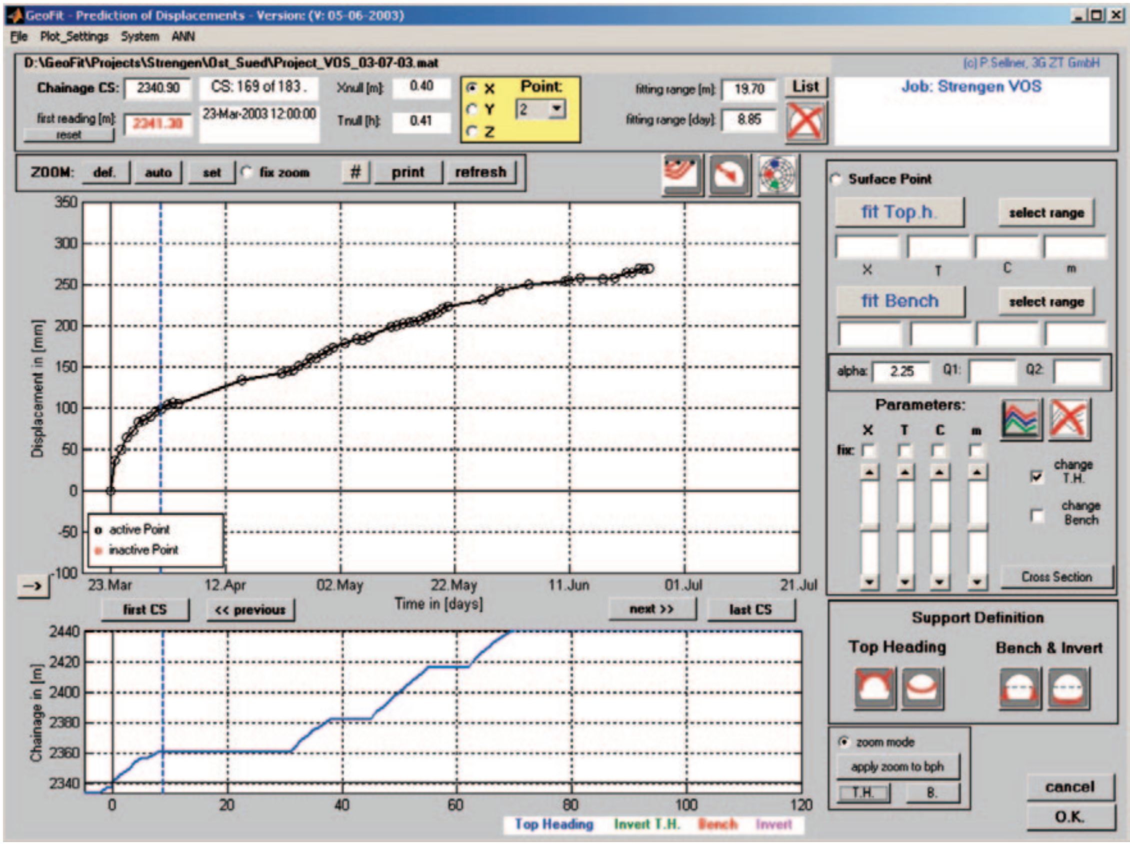

Fig. 11 Time settlement diagram from the Strenger tunnel.

Bild 11 *Zeit-Verschiebungsdiagramm vom Strenger Tunnel.*

frictional strength ratio is low, which is typical for mica rich phyllites, the frictional component of the strength is very important. To mobilize this strength confining stress is required. Any decrease in the confining stress would result in additional displacements.

It was discovered that in this section considerable heave, associated with foliation and fault bounded blocks, occurred in the invert. Figure 13 shows the results of a UDEC (11) calculation that demonstrates how the discontinuity bound blocks in the invert can move into the excavation.

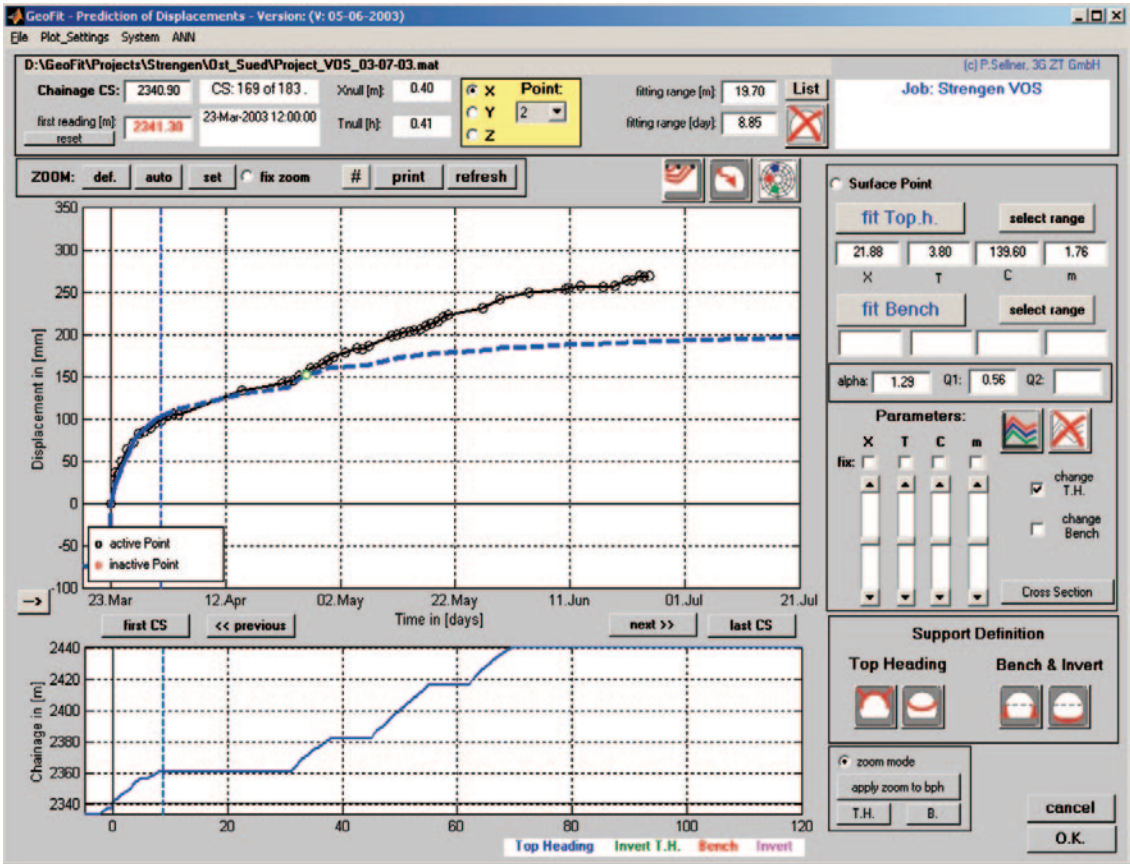

Fig. 12 Time settlement diagram showing the predicted normal behaviour (blue line).

Bild 12 *Zeit-Verschiebungsdiagramm mit prognostiziertem „Normalverhalten" (blaue Linie).*

This deformation occurred simultaneously with the abnormal deformations shown in Figure 12. The displacements in the invert result in a reduction of the confining stress in the vicinity of the bench area. This in turn results in increased deformations at the other monitoring points. This example demonstrates how changes in the deformational mode associated with different geological structures can affect the "time dependent" behaviour.

Conclusion

There are many aspects that effect the time dependent behaviours observed in tunnelling. The program GeoFit was used to evaluate the portion of the displacements related to the time dependent rock mass response. The examples shown from the Tunnel Spital show how in heterogeneous ground the increase in local stiffness and strength associated with high block proportions decreases the portion of time dependent displacements. It was also shown that as the stress level decreases there is a corresponding decrease in the time dependent rock mass displacements. For this example is was also shown that the installation of a temporary invert influences the time dependent displacements to a much larger degree then the advance related displacements.

The example from the Strenger Tunnel was used to demonstrate that the time dependent displacements in many cases are related to changes in the deformation mode and not necessary "creep" under a constant stress state. It has been observed that this is an especially important consideration when faults intersect a tunnel at low angles. In these cases, the "creeping" behaviour may initiate over the fault influenced zone when the fault exits the excavation and additional kinematic freedom is given to the fault bounded block.

Time dependent behaviour in tunnelling is a complex phenomenon. Many factors influence both the rate and magnitude of the time dependent displacements. Changes in the rock mass failure mode may result in increasing displacements with time. Modelling this type of behaviour is not straight forward and should be approached with caution if traditional creep or viscous material models are used.

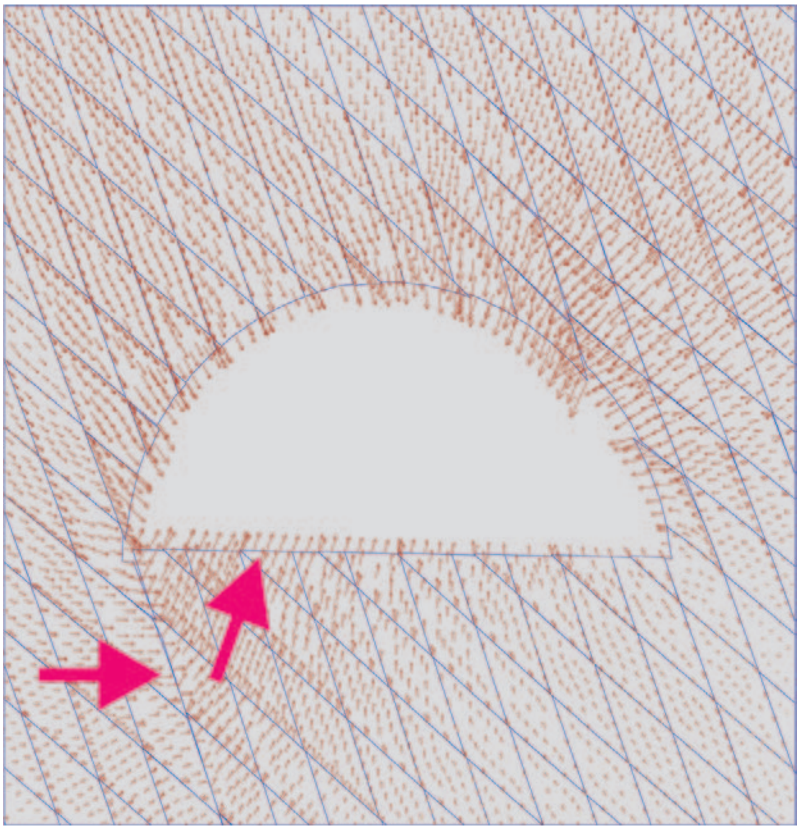

Fig. 13 Results of a UDEC calculation showing the potential for block heave in the invert.

Bild 13 *Resultat einer UDEC-simulation, welches das Potenzial des Herausdrückens eines Blockes aus der Sohle zeigt.*

References

1. Sulem, J. ; Panet, M. ; Guenot, A.: *Closure analysis in deep tunnels*. In: Int. Journal of Rock Mechanics and Mining Science 24 (1987), pp. 145-154.
2. Martin, C.D. ; Reed, R.S. ; Martino, J.B.: *Observations of brittle failure around a circular test tunnel*. In: Int. Journal of Rock Mechanics and Mining Science 34 (1997), No. 7. pp. 1065-1073.
3. Schubert, W. ; Grossauer, K. ; Kim, C.Y.: *Interpretation of Displacement Monitoring Results for Tunnels in Heterogeneous Rock Mass*. Hulla, J., Turcek, P. & Baliak, F. (eds.): "New Methods in Geotechnical Engineering". Proc. of the 6th international Geotechnical Conference, pp. 99-106. Bratislava, 2003.
4. 3-G: *Geofit Homepage. http://www.3-g.at/geofit/gfstarte.html*. Gruppe Geotechnik Graz, 2003.
5. Barlow, J.P.: *Interpretation of Tunnel Convergence Measurements*. Thesis, Dep. of Civil Engineering, University of Alberta, Canada, 1986.
6. Sellner, P.J.: *Prediction of Displacements in Tunnelling*. Ph.D. thesis, Graz University of Technology, Austria. G. Riedmüller, W. Schubert & S. Semprich (eds.). Schriftenreihe der Gruppe Geotechnik Graz, Heft 9. Graz, 2000.
7. Dissauer, J. ; Leitner, A. ; Mittelbach, H.: *Tunnel Spital – Tunnelbau in schwierigen Verhältnissen*. In: Felsbau 20 (2002), No. 1, pp. 40-48.
8. Püstow, H. ; Riedmüller, G. ; Schubert, W.: *Tunnelling in a tectonic melange of high complexity*. In: Felsbau 19 (2001), No. 4, pp. 34-42.
9. Button, E.A. ; Schubert, W. ; Riedmüller, G.: *Shallow Tunnelling in a tectonic melange: rock mass characterization and data interpretation*. Proc. NARMS-TAC (Hammah et.al. eds.), Vol. 2. pp. 1125-1132. University of Toronto Press, 2002.
10. Button, E.A. ; Schubert, W. ; Riedmüller, G.: *The Use of Monitoring Data and Geologic Documentation as a Basis for Defining Rock Mass Behaviour Types*. Hulla, J., Turcek, P. & Baliak, F. (eds.) "New Methods in Geotechnical Engineering". Proc. of the 6th international Geotechnical Conference, pp. 89-99. Bratislava, 2003.
11. Itasca: *UDEC Version 3.1. User's Guide*. Itasca Consulting Group, 2003.

Authors

Univ.-Professor Dipl.-Ing. Dr.mont. Wulf Schubert, MSc Edward A. Button, Institute for Rock Mechanics and Tunnelling, Graz University of Technology, Rechbauerstraße 12, A-8010 Graz, Austria, E-Mail schubert@tugraz.at, Dipl.-Ing. Dr.techn. Peter J. Sellner, 3G-Gruppe Geotechnik Graz ZT GmbH, Elisabethstraße 22/II, A-8010 Graz, Austria, E-Mail sellner@3-g.at, MSc Tülin Solak, KGM Ankara, presently researcher at the Institute for Rock Mechanics and Tunnelling, Graz University of Technology, E-Mail solak@fmt.tu-graz.ac.at