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TUNNEL MONITORING DURING THE EXCAVATION PHASE: 3-D KINEMATIC ANALYSIS BASED ON GEODETIC DATA

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Abstract

Tunnel excavation produces a re-distribution of stresses in the rock and a tendency for closure of the void produced – a tendency counteracted by the tunnel support shell. In some tunnels a very stiff support shell not permitting any ground deformation is selected. In other tunnels, excavated on the basis of the popular so-called "NATM" a quite different approach is adopted: A controlled deformation of the ground is permitted (i.e. limited closure of the rate of approximately 1%) and this gives the opportunity to the stresses to be partly released and a less stiff and less-expensive support system to be used. In this case, an accurate, systematic and continuous monitoring of the tunnel deformation is absolutely necessary during the excavation. In the last years, the introduction of modern total station instruments provided a simple, low cost and functional way to record the absolute 3-D displacements of a large number of controlled points (usually 3-5 points every approximately 10-20m). Such data from a number of tunnels were used to study: i) the distribution of deformation in the various tunnel sections, ii) the variation of maximum section closure along the tunnel axis, iii) the time-history of deformation and iv) the relationship between closures and ring closure delays.

1. Introduction

Tunnel openings tend to close under the geostatic stresses of the surrounding rock mass and, depending on the ground characteristics, this effect may cause either reduction of the excavated area or collapse. Thus, a basic requirement for the excavation of a successful tunnel is the control of section closure or of its instabilities, with the establishment of a detailed monitoring system to record tunnel deformation during the excavation and indicate the need for additional measures if convergence exceeds certain safety levels.

Furthermore, modern tunnel excavation is based on the principle of controlled deformation for permitting partial stresses relaxation and installation of a less stiff and more economic support. According to NATM (Kovari, 1993) and other techniques (shallow tunnelling, cut and cover etc.) monitoring is crucial for selecting the proper support system and provide a cost-effective solution to the requirement for stable tunnel sections.

In the past, deformation control was based on INVAR tapes and wires (Kovari and Amstad, 1993), while the contribution of geodesy to the tunnels construction was mainly limited to the optimization of the breakthrough accuracy (Kienast, 1995). Tapes provided a high accuracy (~0.13mm/10m; Dunnicliff, 1993) in deformation measurement but were expensive and time-consuming and could only measure changes in the distance between selected points fixed on the tunnel periphery. In the 1980's, however, the introduction of modern electronic total stations and levelling instruments made surveying very popular for many types of projects, including underground excavations. In the last years, geodetic techniques are widely used to tunnel excavations and provide a simple, inexpensive and functional way to control tunnel deformation during tunnel construction with an accuracy of a few mm which is very satisfactory for all projects.

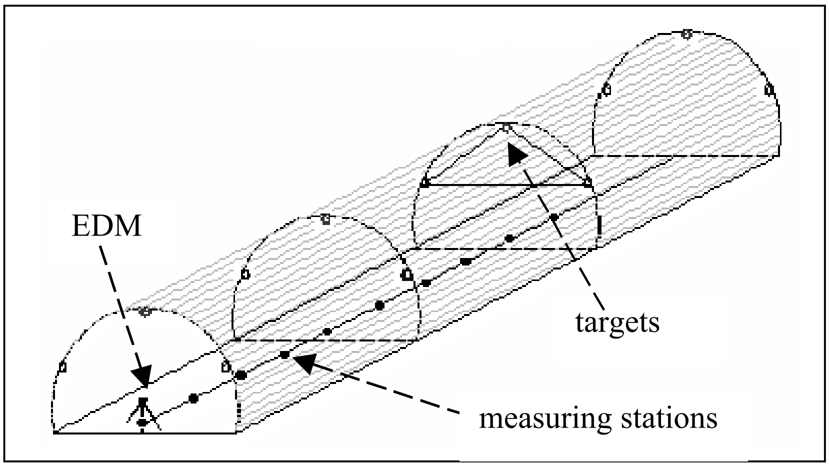

Figure 1: Arrangements of targets and of EDM measuring stations along the tunnel axis.

2. Geodetic monitoring of tunnel deformation

Total stations are placed on stations along the tunnel axis and record the 3-D coordinates of all targets fixed on the primary tunnel lining (support shell; Fig.1), shortly after the excavation with an accuracy of a few mm (or a few cm for >5km long tunnels). Geodetic measurements are taken periodically (usually once per day) until stabilization of the height of all targets is obtained (usually during a two-month period; Kontogianni et al., 1999).

Coordinates of stations are measured relatively to one or two stations outside the tunnel, on stable grounds, and all measurements refer to a local coordinates system suitable for the project. Recording measurements are transferred automatically to the computer at the end of each measurement epoch.

The large amount of geodetic data permits to estimate the absolute displacements of the targets and the final deformed profile of the sections. However, a more detailed analysis of the monitoring data may provide substantial information on the kinematics of the support system due to the imposed stresses and to the selected excavation procedure.

3. Kinematic analysis based on the geodetic data

The tunnels support shells react to the growing stresses of the surrounding rock mass tending to reduce the opening and this reaction induces a time-dependent deformation of the various sections. An attempt to explain the relationship between ground and lining requires the detailed recording of their interaction and the analysis of the monitoring data in terms of time-dependency, tunnelling method adjustments and local conditions. The geodetic observation of tunnel deformation provides several information concerning the behaviour of the excavated area and permits the understanding of the kinematics of the support shell. The most important parameters of shell kinematics are: i) the distribution of deformation in the various tunnel sections, ii) the variation of maximum convergence along the tunnel axis, iii) the time history of deformation and iv) the relationship between convergence and ring closure delays

3.1 Distribution of deformation in the various tunnel sections

A main characteristic of the observed deformation is that it does not correspond to a uniform radial section closure, but the amplitude of radial displacement is variable along the tunnel periphery. Geodetic monitoring provides absolute displacements for at least 3 points at each top-heading (i.e. upper part) section (one at the crown and two at the sidewalls) and 2 points at each bench (lower part) section (one at each side). Thus, the deformed profile of the excavated area can be obtained. An example is the measured non-uniform closure of the Tymfristos tunnel,

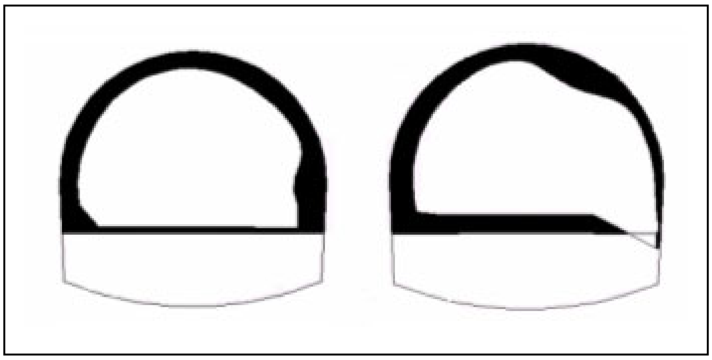

Figure 2: Representative deformed profiles from Tymfristos tunnel, Greece, a long time (1 year) after the excavation. Real scale convergence is indicated by black.

central Greece: at least nine targets were measured at each monitored section both prior to and after deformation. Displacements of all points were plotted on the tunnel section giving the final excavated area of the tunnel at several positions along the tunnel axis. Two selected deformed sections for Tymfristos tunnel, compiled on the basis of the survey data, are shown in Fig.2.

3.2 Variation of maximum convergence along the tunnel axis

In many tunnel cases a swell-type pattern of tunnel closure along axis is observed for areas of high deformation. In those cases there is evidence that deformation did not gradually develop at each section, but, on the contrary, it developed at certain sections and then propagated bi-laterally along a distance of several tens of meters, affecting neighbour sections. This mechanism for destabilization of previously stabilized adjacent sections and propagation of deformation along the tunnel axis has been observed in many cases by plotting maximum section closure along the tunnel axis. An example is the Bolu tunnel, north Turkey (Fig.3; Dalgic, 2002), where at locations of poor ground conditions and stoppage of excavations, extreme deformation occurred and spread to adjacent sections. A similar phenomenon occurred at the Frejus tunnel, France (Lunardi, 2000), where due to a temporary excavation stoppage, deformation increased at the tunnel face and propagated at both directions of the tunnel.

3.3 Time-history of deformation

One of the most essential parameters to test the effectiveness of the excavation method and the selected lining is the support shell deformation versus time. The continuous geodetic monitoring provide a completive set of data for plotting the deformation / time curves. The typical pattern of a time-dependent deformation can be represented by a curve of cumulative convergence which reaches asymptotically the final (stabilization) value after a short (~1 month) time period.

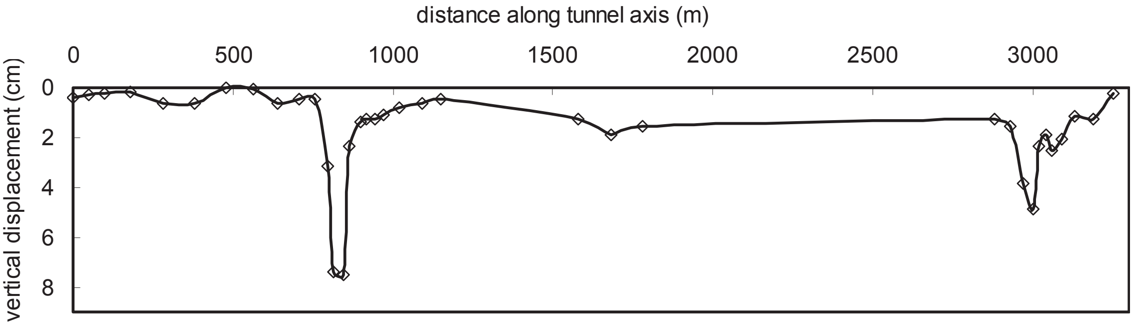

Figure 3: Local high convergence at points of high deformation affected adjacent tunnel segments as well, producing a swell-type deformation along a distance (data from Bolu tunnel, Turkey).

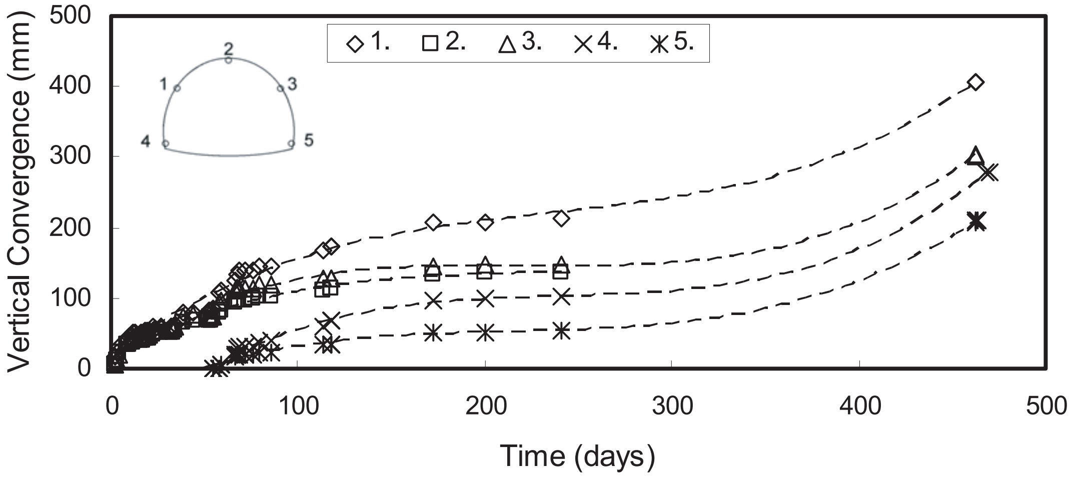

Figure 4: Resumed deformation after a stabilization period (between 170 and 240 days) for one section of the Kallidromo tunnel, Greece

However, some parts of some tunnels follow a different pattern of convergence. This last pattern reveals that some sections stabilize temporarily, following the typical stabilization curve described above, but some time after (a few days to a few months) deformation resumes and stabilizes to higher levels. This is a major threat for the tunnel construction and stability. One tunnel case of extreme closure, measured in detail by geodetic data is the Kallidromo railway tunnel (central Greece), in which large time-dependent deformations occurred and made necessary its re-excavation three successive times (Fig.4).

3.4 Closure in relation to ring closure delays

In most tunnels convergence ceased when the opening was fully supported and consequently deformation was stabilized to low levels. In some cases, however, the hysterisis between section excavation and ring closure (i.e. installation of the full support system around the tunnel periphery) played a significant role to the stability of the tunnel: in case of loose rock masses a long delay in ring closure may lead to extreme, unexpected deformation cumulating for a long time, even after the full support of the section.

However, the detailed geodetic recording of the tunnel closure time-history and the behaviour of the opening to the different stages of the excavation sequence is sometimes a warning to modify the excavation procedure and avoid large deformation for long times. This was the case with most sections of the Tymfristos tunnel during its re-excavation phase (Fig.5; Tsatsanifos et al., 1999). The belayed ring closure stimulated further ground deformation; extreme closure affected the stability of tunnel sections.

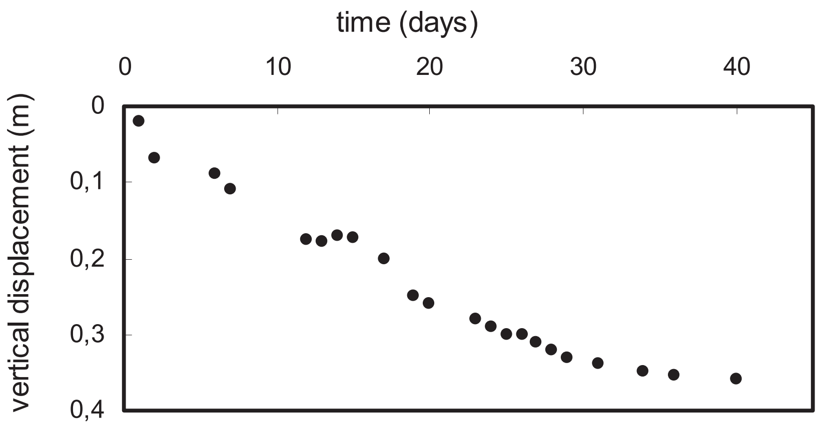

Figure 5: Vertical displacement of the crown for one representative section of the Tymfristos tunnel versus time. Arrow indicates invert (floor of tunnel) excavation. A few days later ring was closed (i.e. the tunnel periphery at this section was fully supported by steel rings and concrete) but deformation continues to cumulate.

4. Conclusion

Since the excavation of the first tunnels (Kienast, 1995) it was realized that deformation is a main factor controlling the failure and cost-effectiveness of underground excavation. In the last two decades, however, deformation monitoring, mostly based on geodetic methods, became a fundamental requirement for assessing the stability of underground openings and for quantifying the risk of unacceptable rock response.

Except for safety control, geodetic monitoring provides a wealth of data describing the 3-D kinematics of the support shell and the time-history of deformation depending on the excavation technique parameters (velocity, delays etc.). Such information can be input to back analyses for improving the geotechnical models of tunnel excavation and optimize the excavation process. Thus, it may lead to a more safe and economic project.

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