

A continuous tunnel monitoring system for both construction and service stages

Dinis da Gama, C.

Geotechnical Center, IST, Lisbon, Portugal

Copyright 2006, ARMA, American Rock Mechanics Association

This paper was prepared for presentation at Golden Rocks 2006, The 41st U.S. Symposium on Rock Mechanics (USRMS): "50 Years of Rock Mechanics - Landmarks and Future Challenges.", held in Golden, Colorado, June 17-21, 2006.

This paper was selected for presentation by a USRMS Program Committee following review of information contained in an abstract submitted earlier by the author(s). Contents of the paper, as presented, have not been reviewed by ARMA/USRMS and are subject to correction by the author(s). The material, as presented, does not necessarily reflect any position of USRMS, ARMA, their officers, or members. Electronic reproduction, distribution, or storage of any part of this paper for commercial purposes without the written consent of ARMA is prohibited. Permission to reproduce in print is restricted to an abstract of not more than 300 words; illustrations may not be copied. The abstract must contain conspicuous acknowledgement of where and by whom the paper was presented.

ABSTRACT: A method for calculating convergences in tunnels by means of measuring strains at several points of its contour is described. Either by using electrical resistance strain gages or fiber optics Bragg gratings attached to the steel arches of tunnel support, or bars that may be installed along vertical sections of the tunnel, provide the means to measure deformations of its periphery along time. Those strains are continuously converted into convergences so they may trigger alarm signals whenever tunnel stability is under risk, and may be immediately transmitted to a remote computer network in order to be closely surveyed by management authorities. Illustrative examples are presented on method reliability for both laboratory and field applications.

1. INTRODUCTION

The Extensometric Method for Monitoring Convergences in Tunnels (MEMCOT) was proposed by the author (Gama, 2004) to continuously facilitate the stability assessment of tunnels, either under construction or in regular service. Unlike the conventional methods that are utilized to measure convergences between pre-defined points at tunnel cross-sections, MEMCOT is not restricted to discrete localized targets, which are periodically surveyed, and is implemented without interrupting construction operations neither the regular service of tunnels.

Another advantage of this new process is the interactive availability of field data, instantaneously and continuously, as well as the calculation of convergence rates between any user-defined time intervals, along

orthogonal or inclined directions of space.

Because this methodology has clear evolutionary characteristics, it has been upgraded since its introduction, with diversified features and new approaches, which are described in the following paragraphs. Emphasis is put on the algorithm for displacement evaluation based on the theory of curved beams, with validation in two and three-dimensional laboratory experiments, together with full-scale applications.

2. MATHEMATICAL ALGORITHM

The theory of bending applied to curved beams allows the quantitative modeling of radial displacements in function of the axial strains that are being measured. According to Benham & Warnock (1973), if a beam with an initial radius R_l is submitted to a certain external load or moment, it bends in order to create an axial strain

simulation in order to analyze it and, mainly, to provide clear indications for immediate field inspections. Fig. 3 shows that graphical representation.

Table 1. Numerical values of external applied forces, strains and displacements (both measured and calculated)

Model section	Applied loads (N)	Test results		Calculated displacements (10 ⁻³ mm)
		Strains (10 ⁻⁶)	Displacements (10 ⁻³ mm)	
Crown (P4)	450	-52	158	134
	600	-60	214	201
	750	-78	249	233
	900	-85	297	271
Horizontal upper chord (P3 – P5)	450	-150	182	166
	600	-190	215	202
	750	-219	237	218
	900	-237	291	270
Horizontal lower chord (P2 – P6)	450	569	-227	-244
	600	733	-304	-332
	750	873	-346	-365
	900	1043	-402	-434

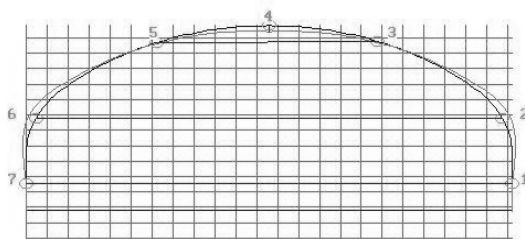


Fig. 3. Example of the deformed shape of a tunnel cross-section obtained upon a set of strain data measured at seven points, with respect to its original geometry

2.2. Real scale tests

The first application of this method to real tunnels happened in 2003, during the excavation of the Falagueira terminal of the Blue Line in the Lisbon subway. The excavation was regularly conducted and roof support was achieved through the application of THN-29 type of steel arches.

Electrical resistance strain gages were installed in several arches (seven for each arch) and their values were recorded. At the same time, convergences were measured by precision topography methods, so a

comparison of values was feasible. A clear agreement in the orders of magnitude was confirmed (Gama, 2004). Typical results of this phase are summarized in Fig. 4, revealing the evolution of the deformation of a certain steel arch in a period of 4 months.

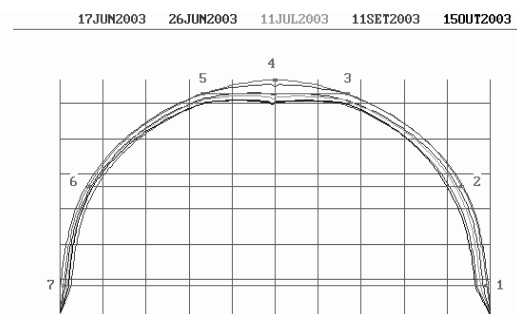


Fig. 4. Evolution of Falagueira tunnel shape at arch Pk 25+895.50

As far as the validation of the curved beams theory is concerned, the results obtained in Falagueira may be confirmed on the basis of the well-know “pressure arch” concept, which postulates the existence of a decompressed volume of ground above the tunnel that transmits its load to the support system.

This assumption involves the joint action of ground and support, deforming together under a compressive state, so the above mentioned variable y depends on the thickness of that pressure arch, as proposed by Terzaghi, and later on modified by several authors (see Fig. 5).

Based on the numerical values in Fig.5, the main curve is given by the following expression, with a correlation coefficient of 0.9926:

$$n = -5 \times 10^{-6} R^3 + 0.0009 R^2 - 0.0725 R + 2.69$$

where R represent the RQD of the surrounding ground.

It must be pointed out that when roof bolts are applied up and around tunnel walls, the value of y is equivalent to the active length of those bolts.

Application of this criterion to the Falagueira tunnel study was accomplished in two steps, as follows:

A – Vertical displacements at the center of tunnel roof

This was measured by precision topographic methods at the steel arch located at Pk 25+957.33, providing a maximum displacement of 4.30 mm at the center. For this same arch, the maximum strain measured at the strain gage was 619×10^{-6} .

As the arch's curvature radius was 4.95 m, the width of tunnel at its base was 10.24 m, and assuming this with the same magnitude of y (height of the pressure arch), making $n=1$ in the graph of Fig.5, for a RQD=40, the computed radial displacement reaches 4.54 mm.

B – Horizontal convergence

For comparison purposes, the measured data for the horizontal convergence had a maximum value of 3.40 mm, while the calculation with the above formula for the two radial displacements at opposite points conducted to a maximum convergence of 3.88 mm. These results contribute to the sought validation.

2.3. Three-dimensional laboratory tests

In order to evaluate three-dimensional effects of a circular tunnel model, submitted to various stress states and monitoring its behavior along four different sections (each one provided with five strain gages) located at various distances to the head of the

excavation, a series of tests were conducted, as Fig. 6 illustrates.

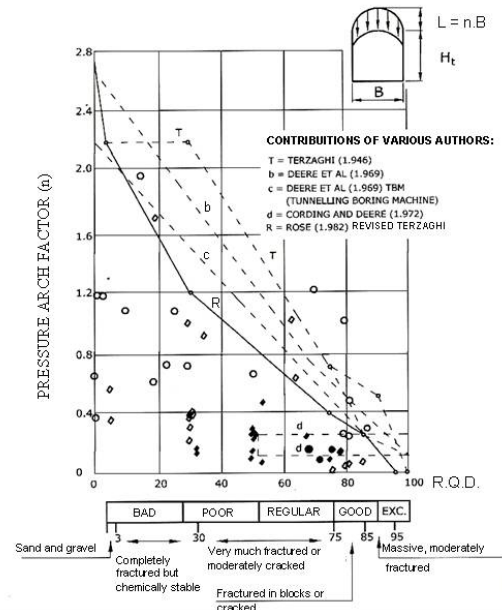


Fig. 5. Variation of pressure arch factor with the RQD of surrounding ground, for the size of the pressure arch above a tunnel with B width, according to Terzaghi, modified by Rose (1982) and after Ucar (2004)

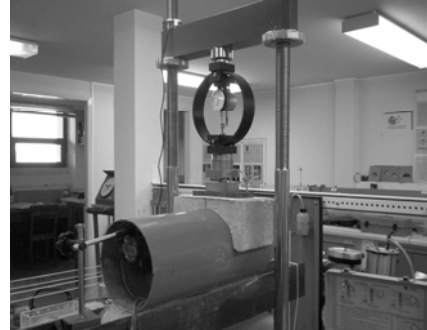


Fig. 6. Testing arrangement for loading a 3-D tunnel model

By recording the strains at those gages, as well as measuring convergences with digital dial gages, and upon calculating the corresponding displacements, a good correlation was obtained for those convergences, as shown in the graph of Fig. 7. In fact, a systematic deviation was detected between measured and calculated convergences, with a maximum range of 18%, being positive for horizontal

convergences and negative for those in the vertical direction.

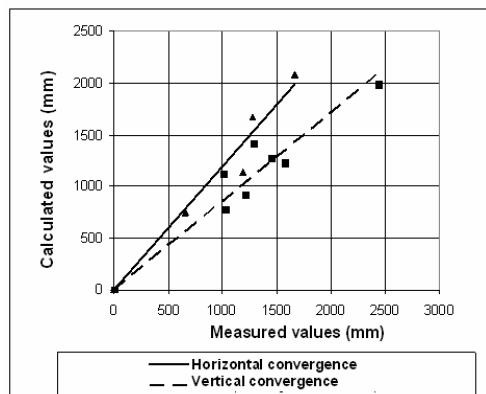


Fig. 7. Comparison of measured and calculated convergences for the 3-D model

3. OTHER APPLICATIONS

3.1. Tunnel in Singapore

For the design of a service tunnel in the subway system of Singapore, with a circular section having an internal radius of 2.86 m and an external radius of 3.12 m (see Fig. 8) a continuous monitoring system was sought during its construction. For that purpose the application of MEMCOT was simulated, through the consideration of various situations, both in the construction and the service phases. Extreme cases, such as the alternant tensions and compressions along the steel lining were studied, as Fig. 9 represents.

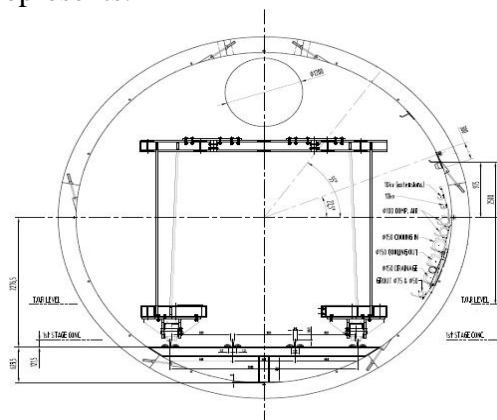


Fig. 8. Cross-section of service tunnel of Circle Line 4 & 5 (Singapore)

Besides the advantages offered by this method in terms of its application is not interfering with the construction process, there was a possibility for analyzing the maximum allowable strains along tunnel contour, during the service situation. The example of Fig. 8 reveals one of these solutions, allowing the possibility of correcting field operations whenever simulations lead to incorrect results.

MEMCOT - Each square is 1 m x 1 m
DEFORMED PERIPHERY IN 25-05-2005

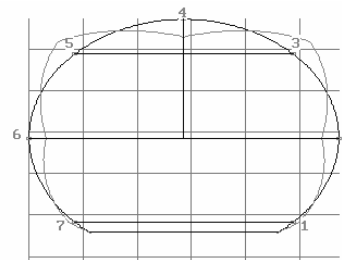


Fig. 9. Simulation results of steel arch subjected to alternative strains (enhanced deformations with respect to tunnel section)

3.2. Tunnels with settlements at the base of steel arches

Another application of this technique is related with a common situation in tunneling, when one or both feet of the steel arches penetrate the pavement, thus creating non-symmetric convergences and leading to early collapses. That phenomenon was also studied, provided there are available data on these settlements (for example, from measurements conducted with electro-levels), either through testing with small-scale models (Fig. 10), or by adjusting the already mentioned algorithm to deal with those situations (Fig.11).

A remarkable agreement was found between experimental results and mathematical predictions, which makes possible to simulate multiple situations of complex tunnel behavior, as long as field data on strains measured at support elements are available.



Fig. 10. Laboratory model of tunnel lining with deformable feet

MEMCOT - Each square is 1 cm x 1 cm
STRAINED PERIPHERY WITH STEEL ARCH
FOOT SETTLEMENT

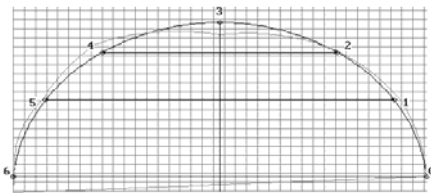


Fig. 11. Representation of deformed tunnel lining with settlement at the left foot

The reliability of the field data acquisition was recently enhanced through the use of fiber optics sensors in stead of electrical resistance strain gages, mainly to escape the negative influence of groundwater on the performance of these ones.

4. CONCLUSIONS

The growing importance of permanent monitoring in geotechnical workings in general, and tunnels in particular, is justified by contemporary safety requirements and environmental protection guidelines fulfillment, thus requiring maturated research efforts (Tsesarsky & Hatzor, 2006).

Under these orientations, expanding MEMCOT applications has been challenging, not only through improvements in the mathematical algorithm, but also in terms of upgrading the experimental settings by means of involving, among others, the following features:

- Installing four electrical strain gages in stead of just one at each monitoring point of tunnel lining;
- Using Bragg gratings fiber optics strain sensors;
- For existing tunnels in regular service, installing the set of sensors on bars that are externally attached to the actual support system, either made of inox steel or polyester.

Therefore, new improvements for this method are being developed for the purpose of providing greater flexibility, availability, less interference with ongoing operations, on-line availability of treated information at remote locations, possibility of supplying alarm signals when anomalous convergences happen and, last but not least, reduced monitoring costs.

REFERENCES

1. Benham, P. & Warnock, F., 1973 - *Mechanics of Solids and Structures*, Pitman, London
2. Gama, C. D., 2004 - A Method for Continuous Monitoring of Tunnel Deformations during Construction and Service Phases. *Proceedings of EUROCK2004*, Salzburg, Editor W. Schubert, pp.251-254.
3. Jimeno, C. L., 1997 - *Manual of Tunnels and Underground Workings* (in Spanish). Entorno Gráfico, Madrid.
4. Terzaghi, K., 1946 - *Rock Tunnel with Steel Supports*. Editado por R.V. Proctor and T. White. Commercial Shearing co., Youngstown, Ohio, pp.15-99.
5. Ucar, Roberto 2004 - *Manual de Anclajes en Ingeniería Civil*. Gráficas Arias Montano, Madrid.
6. Tsesarsky, M. and Hatzor, Y.H., 2006 - Tunnel Roof Deflection in Blocky Rock Masses as a Function of Joint Spacing and Friction. *Tunnelling and Underground Space Technology*, vol. 21, January 2006, pp. 29-45.