Permanent Control of Displacements in Tunnels

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ABSTRACT

Long term stability of tunnels requires periodic observation and maintenance in order to reduce collapse risks and prevent accidents to users. Those purposes may be attained with reduced costs if a permanent monitoring system is installed to detect and to relay information on anomalous displacements that may occur during tunnel service. Description is provided on a method aimed at continuously measuring convergences in tunnels by means of recording strains in several points of its contour, either by using electrical resistance strain gages or fiber optics Bragg gratings attached to the support arches or metallic bars that may be installed along vertical sections of the tunnel. These data may be immediately transmitted to the owner computer network and they may be programmed to trigger alarm signals whenever tunnel stability is under risk. Although the ideal solution for this process would be the long-term utilization of the monitoring system that accompanied construction, it is quite possible to implement it afterwards in operating tunnels. An example of this applicability is described in the article.

1. INTRODUCTION

The advantages of permanent monitoring are emphasized by many authors as a truly contribution to safety of many geotechnical workings due to the increasing importance of reducing both short and long-term risks, as well as implementing environmental protection actions whenever they are required. Under those guidelines, the author developed the so called “Extensometric method for monitoring tunnel convergence in service and construction phases” (Memcot), which has been registered in 2004, under the Portuguese national patent No.103.058 - INPI. This process was proposed to continuously allow 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 can be implemented without interrupting construction operations neither the regular service of tunnels.

The interactive availability of field data, instantaneously and continuously, is an interesting feature of the method, allowing also the calculation of convergence rates between any user-defined time intervals. The successive steps in the development of Memcot have been published elsewhere (Gama, 2004 and 2006) and it has been upgraded with new approaches, such as its application in a long railway tunnel in Lisbon, which is focused in this paper.

2. THE ‘MEMCOT’ METHOD

2.1 Mathematical algorithm

The basic theory of bending applied to curved beams includes the calculation of radial displacements in function of the axial strains that are being measured. Benham & Warnock (1973) describe the
bending analysis of a beam with an initial radius $R_1$ submitted to a certain external load or moment, which originates an axial strain $\varepsilon_x$, at a section located a distance $y$ to the neutral axis of the beam. That strain is given by the equation:

$$\varepsilon_x = \frac{y(R_1 - R_2)}{R_2(R_1 + y)}$$  \hspace{1cm} (1)

where $R_2$ represents the new radius of curvature after straining. Consequently, the radial displacement affecting that section is:

$$\delta_r = R_1 - R_2 = \frac{\varepsilon_x R_1(y + R_1)}{\varepsilon_x R_1 + y(1 + \varepsilon_x)}$$  \hspace{1cm} (2)

This expression is the basis of evaluating tunnel convergences upon knowledge of the measured strains at prescribed points of its contour and it has been confirmed by several types of experimental results obtained in both the laboratory and in the field. The most recent ones are presented below.

### 2.2 Two and three-dimensional laboratory tests

Research on this subject started with the performance of many lab experiments, firstly with steel arches (Gama, 2004) and subsequently in three dimensional tests (Gama, 2006). In both cases small-scale models of circular tunnels were created and afterwards submitted to various stress states that allowed the monitoring of its deformation behavior by means of five electrical resistance strain gages located at regularly located points of its perimeter. At the same time that strains at those gages were recorded, the convergences between various pairs of those points were measured with digital dial gages (and LVDT’s), so that a comparison of calculated and monitored displacements was possible. High correlations were obtained between those convergences, as it can be observed in Fig. 1 for the results with 2-D models, where the linear elastic behavior is always observed.

![Diagram](image)

**Fig. 1.** Variation of applied force with hoop strain and radial displacements (measured and calculated) at 5 strain gages in a 2-D model of a semi-circular tunnel.

In 3-D models, a systematic deviation was detected between measured and calculated convergences, with a maximum deviation of 18%, being positive for horizontal convergences and negative for those in the vertical direction (Fig. 2).
2.2 In situ tests

The first application of this method to real tunnels happened in 2003, during the excavation of the Falagueira terminal tunnel of the Lisbon subway Blue Line. 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 deformation recordings along a four month period were gathered. 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. 3, revealing the evolution of the deformation of a certain steel arch.

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. The assumption involves the joint action of ground and support, deforming together under a compressive state, so the above mentioned variable $\gamma$ depends on the thickness of that pressure arch, as proposed by Terzaghi, and later on modified by several authors (Ucar, 2004).
3. APPLICATIONS TO THE ROSSIO TUNNEL (LISBON)

The Rossio Tunnel is a railway facility built in 1890 with 2,807 m length. In July 2005 it was closed due to geotechnical problems in several sections and was submitted to a large rehabilitation work. Simultaneous to the construction repair bid, another bid was launched for the tunnel permanent monitoring system and, among other proposals that were presented, the Memcot option was selected. This fact led to the implementation of a series of experiments, which were mainly divided in two types, using models at lab scale (1/10) and natural scale (1/1). A short description of these tests follows.

3.1 Laboratory scale model tests

In view of the need for preparatory studies on the permanent monitoring of the Rossio Tunnel, a series of experiments were performed at laboratorial scale, to validate the applicability of the method considered for that effect. In this conformity, three bi-dimensional models of that tunnel section were prepared and submitted to diverse loading combinations.

The tests intended to find direct relations between radial displacements or convergences measured by seven LVDT’s and deformations obtained in seven Bragg gratings fiber optics strain sensors located symmetrically at the section periphery.

As the rehabilitated tunnel has two distinct types of geometry regarding the lateral walls (vertical in one and curved in the other) so the models had similar shapes. They were loaded by vertical and horizontal forces, either isolated or in association.

A total of 22 tests were conducted, which allowed the interpretation of model behavior under different loading conditions. In the obtained results there were many deviations in terms of symmetry of values, as well as changes of positive to negative on opposite points of measurement, which was unexpected because the applied stresses and the geometry of the arches were completely symmetrical.

The various tested situations are summarized in Fig. 4 in the form of three main cases for detailed analysis, with average values that were obtained in both strains and radial displacements, as well as the calculated ones.

Regarding the correlation between measured strain and radial displacements under the same applied forces, Fig. 5 shows a representative example.

![Fig. 4. Typical values of strains and radial displacements for the three lab models cases.](image-url)
y = 1.3741x  
$R^2 = 0.9725$

y = 0.5332x  
$R^2 = 0.9883$

y = 1.8385x  
$R^2 = 0.998$

y = 2.17x  
$R^2 = 0.9979$

Fig. 5. An example of correlation between measured strains and radial displacements obtained in lab experiments with the testing apparatus that was utilized.

3.2 Natural scale model tests

For the experiments, the seven fiber optics sensors were attached to inox steel bars that were later on connected to the metallic arches of the actual tunnel support system. The two kinds of sections are shown in Fig. 6.

Fig. 6. Shape and dimensions (in meters) of the two steel arches of support in Rossio tunnel.

For each model, only vertical load is exerted on the vertex point 4 though a steel chain and a pump. The loading levels reached 320 kg, with 40kg increases for each step.

For each model, a traditional method (with dial gauges) was used for displacement measurement, and then a total topographic station system in order to verify which one was more reliable. The strain measurements were captured by seven fiber optic sensors mounted at the inner surface of each arch and connected to a data acquisition system developed by the Fibersensing Company (Fig. 7).

Table 1. - The four types of large scale tests.

<table>
<thead>
<tr>
<th>MODEL</th>
<th>TEST</th>
<th>Support</th>
<th>Measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1A</td>
<td>No</td>
<td>LVDTs</td>
</tr>
<tr>
<td></td>
<td>2A</td>
<td>Yes*</td>
<td>Topographic</td>
</tr>
<tr>
<td>B</td>
<td>1B</td>
<td>No</td>
<td>LVDTs</td>
</tr>
<tr>
<td></td>
<td>2B</td>
<td>Yes*</td>
<td>Topographic</td>
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* Because of the constraints caused by the bolts linked to the wall, cases 2A and 2B led to irregular displacements.

Fig. 7. Fiber optics data acquisition apparatus.
The arches were mounted with and without support of the adjacent wall, in order to prevent the models from inclining or collapsing. According to the mounting means of the models and displacement measurement methods, four kinds of experiments were conducted in this research (see Table 1). Again, the comparison analysis between measured and calculated radial displacements (Fig.8) provided a clear indication on the method's reliability, with a maximum deviation of 14.6 %.

Fig. 8. Variations of strains and displacements for the seven FO sensors under the vertical loading of the natural scale model.

4. CONCLUSIONS

Permanent monitoring is becoming common in most geotechnical workings because of the increasing importance of safety as well as environmental protection measures, thus requiring new solution oriented techniques of research, as stressed by Tsesarsky & Hatzor, 2006. New improvements must be achieved for granting higher performances in terms of 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, hopefully, lower monitoring costs.

REFERENCES