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ESTIMATION OF THE STRAIN TENSOR IN TUNNEL SECTIONS, BASED ON GEOMETRIC (GEODETIC ETC.) DATA

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ABSTRACT

Monitoring of tunnel deformation during their excavation is based on measurements of displacements of either single points or contraction of selected distances across the tunnel section. Such data, however, due to measurement errors and local effects may not be consistent with each other, and cannot describe precisely the real behavior of the ground/support shell. In the present study, a theory introduced to estimate the ground surface strain field on the basis of surveying measurements is adopted in order to estimate the average strain of tunnel sections. This theory is based on the assumption of uniform deformation across the tunnel section and of measurements affected by random errors only and uses repeated monitoring data (displacements or distance changes).

The proposed theory was applied to deformation data from representative sections of the Acheloos Diversion Tunnel (Western Thessaly, Greece), subject to nearly uniform strain. Mean strain changes were estimated for various time intervals following the excavation. About one year after the excavation, maximum horizontal strain of ~1.3%, accompanied by practically negligible vertical strain, was computed.

1 INTRODUCTION

Deformation is a main factor controlling the failure and cost-effectiveness of underground excavations. For this reason deformation monitoring has become a fundamental requirement for assessing the stability of underground openings (Kaiser 1993). Deformation data are based on *in situ* geotechnical measurements (extensometers etc.) and tape measurements of selected distance changes, both providing information on local or relative dislocations only, or optical, geodetic records, which define absolute displacements of selected control points of tunnel sections (Kontogianni & Stiros 2001).

A main characteristic of the observed tunnel deformation through soft rocks and soils, however, is that it does not correspond to uniform radial section closure (Fig.1a) that could be accurately measured by any of the above methods. On the contrary, strain in many tunnels is uniform across the deforming area, but the amplitude of radial displacement is variable along the tunnel periphery (non-radial deformation, Fig.1b; Schubert & Schubert 1993; Kontogianni & Stiros 2003); furthermore, in many cases non-uniform and non-radial deformation is observed (Fig.1c) and occasionally causes instabilities and failures (i.e. Tymfristos tunnel and Kallidromo tunnel, Greece, Kontogianni et al. 2004). However, in the case of non-radial deformation (either uniform or not, Figs.1b,c), the strain of tunnel sections cannot be directly calculated.

In addition, deformation data are usually affected by measurement errors and local instability effects, and hence, where redundant observations are available, observations are not compatible with each other (Fig. 2b) and the deformation tensor cannot be estimated. In the past, there have been efforts at solving this problem on the basis of graphical techniques (Moosavi and Khazaei 2003).

In the present paper, we present an analytical solution inspired from the studies of seismic/tectonic deformation in areas of strike slip faulting. This approach is justified from the fact that in strike slip faulting environments, deformation is nearly planar, as is also assumed to be the case

with most tunnel sections; in general, a 2-dimensional model (i.e. on the basis of plane strain conditions) is assumed to simulate tunnel excavation (Hoek 2000; Leca et al. 2000).

The basic assumption of the proposed method is that deformation is uniform, i.e. that strain (i.e. the ratio of the distance change to the distance between two control points) is simply a function of the orientation of the line defined by two control points.

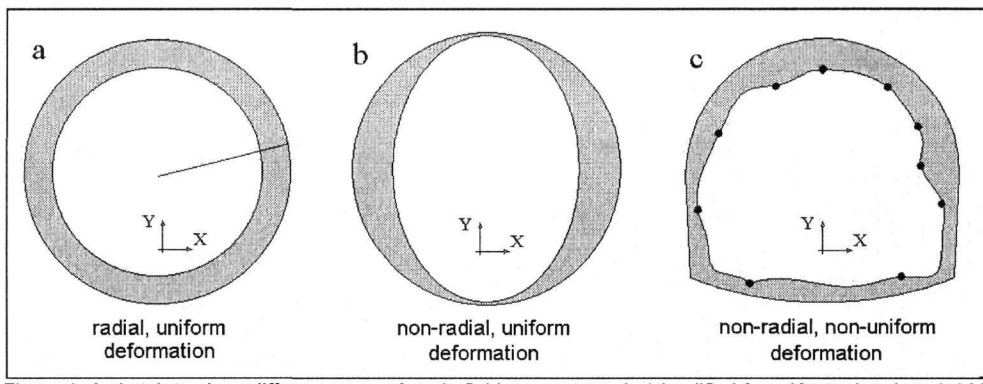

Figure 1. A sketch to show different types of strain field across tunnels (simplified from Kontogianni et al. 2004).

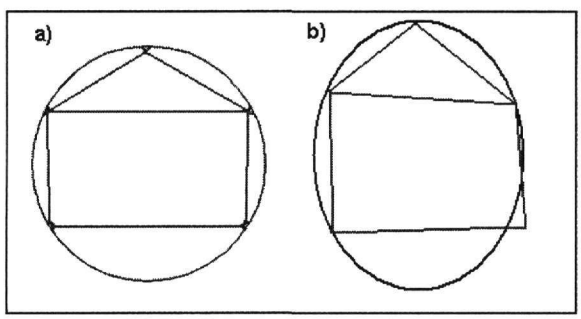

Figure 2. a) Observed line length changes across a tunnel section, using a tape, b) sketch of the deformed section (exaggerated): observations are not compatible with each other, and extended lines do not fit to an ellipse, mainly due to measurements errors.

2 ESTIMATION OF AVERAGE STRAIN IN TECTONICALLY ACTIVE AREAS

Frank (1966) based on the fact that strike-slip and transform faults produce two-dimensional uniform strain on the ground surface, was the first to compute the average strain field across such seismic regions. His study was based on repeated measurements of triangulation networks crossing fault zones and he estimated the average principal strains of his study areas. A basic requirement for this analysis is that measurements include random errors only. This analysis was later generalized and applied to several studies of surface deformation of the San Andreas, California, fault zone (Prescott et al. 1979; Savage 1983; Fig.3) and other regions.

In this analysis, it is assumed that a certain network of n lines covers a study area, for instance that of figure 3. Between two surveys the length of line i of initial length L_i was increased by an amount ΔL_i. Strain along this line is defined by the equation $\varepsilon_i = \Delta L_i / L_i$. Assuming a uniform strain, the observed strain ε_i along this line is related to E_{11}, E_{22} and E_{12}, i.e. the tensor components of strain along the x and y axes and the shear component of strain in a direction of the x axis (Fig.4), by the equation:

$$\varepsilon_i = E_{11} \bullet \sin^2 \theta_i + E_{12} \bullet \sin 2\theta_i + E_{22} \bullet \cos^2 \theta_i \qquad \textit{eq 1}$$

where θ_i is the approximate azimuth of the line (measured clockwise from north).

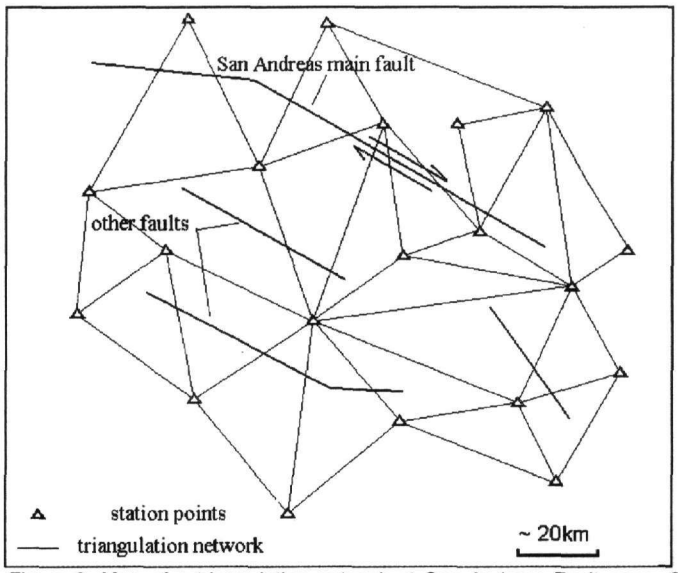

Figure 3. Map of a triangulation network at San Andreas Fault zone, California established for studying the strain tensor. Major faults are shown in black lines. Despite faulting, strain is assumed uniform, i.e. depending on the azimuth of the observation line only. After Savage (1983) simplified.

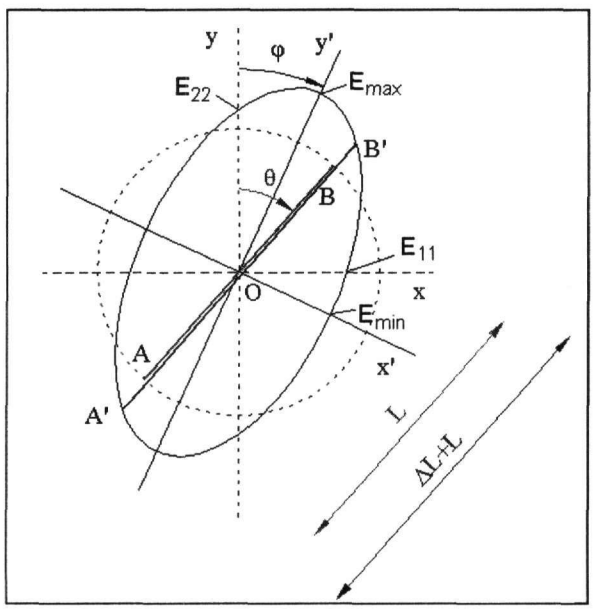

Figure 4. Geometric representation of our model, a circle (corresponding to a part of the earth's surface) deformed to an ellipse. All parameters for calculating the strain field based on the Frank's (1966) theory are shown.

Each observation of line length change contributes with one equation of this type, and finally a system of n linear equations is formed. In this system E_{11}, E_{22} and E_{12} are unknowns. Solving this system using standard least square techniques, E_{11}, E_{22} and E_{12} as well as their uncertainties, can be estimated. At a second step, the principal (maximum and minimum) strains and their directions are calculated based on the equations:

$$\varepsilon_{max} = \frac{E_{11} + E_{22}}{2} + \sqrt{\left(\frac{E_{11} - E_{22}}{2}\right)^2 + E_{12}^2} \qquad eq\ 2$$

$$\varepsilon_{min} = \frac{E_{11} + E_{22}}{2} - \sqrt{\left(\frac{E_{11} - E_{22}}{2}\right)^2 + E_{12}^2} \qquad eq\ 3$$

$$\tan\varphi = \frac{2 \cdot E_{12}}{E_{22} - E_{11}} \qquad eq\ 4$$

where φ is the azimuth of direction of maximum principal strain (ε_{max}).

3 ESTIMATION OF THE AVERAGE STRAIN IN A TUNNEL

The approach of Frank (1966) permits to estimate the average deformation (average strain tensor) of a horizontal area in the earth's surface assuming that this deformation is associated with insignificant vertical deformation (plane strain conditions). There are lines of evidence indicating that in most cases deformation of tunnel sections can also be described by plane strain conditions, i.e. that deformation is limited to a vertical plane, and deformation along the tunnel axis is a second-order effect (Hoek 2000; Leca et al. 2000).

Furthermore, it can be assumed that the deformation of the tunnels sections is uniform (i.e. parallel lines in the same section have the same strain) and monitoring data of at least a number of tunnels are not contaminated by systematic errors and blunders. Hence, the approach described above for horizontal surfaces can be adopted for the vertical surfaces of tunnel sections and their average strain can be computed, using the equations described above.

Schematically, this approach can be described as the computation of the parameters of an ellipse resulting from the deformation of a circle (i.e. of a tunnel section) of unit diameter (Fig. 5).

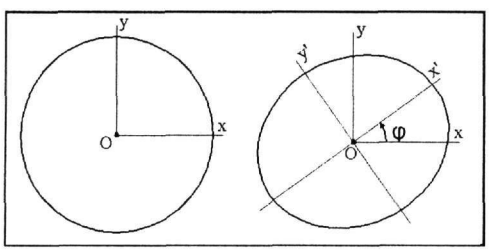

Figure 5. Due to strain, a circle of unit radius is transformed to an ellipse. Equations and techniques described above permit to calculate the length and orientation of the main axes of this ellipse.

4 A CASE STUDY

The approach described above was applied to the analysis of the deformation of a segment of the Acheloos Diversion Tunnel, western Thessaly, Greece. This tunnel was selected as a case study because it satisfies the requirements of the method explicitly analyzed above. In particular, the deformation of the tunnel sections is assumed uniform along long distances, the quality of measurements is high, and redundant measurements for a number of sections (see below) were available. This monitoring record covered a period of >400 days.

4.1 The Acheloos Diversion Tunnel, western Thessaly, Greece

The Acheloos River Diversion Tunnel, is designed to be 17.4 km long with an internal diameter after lining of least 6 m. Excavation is still active (May 2004) with a full face open shield TBM (construction from WIRTH) with an excavation diameter of 7.1m. Tunneling commences from water outlet station towards inlet with an upwards inclination of 0.3% mean value. During the first 3.5km upstream, tunneling advanced through high strength limestones, interchanges of cherts, marly cherts and cherty siltstones and members of the Pindos Flysch (silt-clay and sand-stones, Sfeikos & Marinos 2004).

However, along a distance of 30m, when the tunnel entered to a zone of flysch (siltstones

and sandstones) probably corresponding to a thrust zone (ch.16+250m to 16+280m, at ~400m overburden), observed displacements were about one order higher than in the adjacent limestone sections, despite the relatively stiff support (steel ribs HEB140/75cm, wire mess T140, 12cm shotcrete shell). Deformation continued for more than 12 months after excavation and led to cracking and detachment of shotcrete, additional contraction of ~6cm, floor heave and lateral displacement of preconstruction invert. The support measure lining was subsequently repaired (new steel ribs HEB140 and repairs to the shotcrete shell) and deformation was finally stabilized. No significant deformation to the adjacent sections was, however, observed.

Deformation monitoring of Acheloos Diversion Tunnel was based on measurements of distances across tunnel section with a tape extensometer of high accuracy (0.13mm/10m, Dunnicliff, 1993). Five pins were fixed at each control section and 6 different distances were measured (Fig.6). The complete set of measured distances for 8 different control sections covering a distance of more than 1.5km along the tunnel axis and ~400days were available for our study. In the following paragraph we analyze the estimation of the strain field in one of these sections (ch. 16+276m), located in the weak zone of increased deformation.

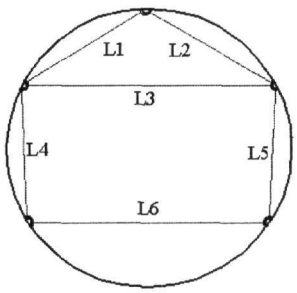

Figure 6. Drawing of a typical control section of Acheloos Diversion Tunnel. The 6 distances repeatedly measured with a convergence tape are marked L1 to L6.

4.2 Computation of the final strain tensor

The cumulative (final) deformation of the 6 control lines (for instance 0.0033 for line L1, corresponding to a total length change of 6.8mm along a distance of 2.086m), surveyed for a period of ~400days after section excavation, and the azimuth of each line (for instance 253° for line L1, 116° for line L2 etc.) were the input parameters to the equation for the strain tensor estimation (eq.1). One equation was written for each line; thus, the following system of 6 linear equations with 3 unknown parameters (strains E_{11}, E_{12} and E_{22}) was formulated as below:

$$0.0033 = E_{11} \cdot \sin^2(253^\circ) + E_{12} \cdot \sin(2 \cdot 253^\circ) + E_{22} \cdot \cos^2(253^\circ)$$

$$0.0136 = E_{11} \cdot \sin^2(116^\circ) + E_{12} \cdot \sin(2 \cdot 116^\circ) + E_{22} \cdot \cos^2(116^\circ)$$

$$0.0172 = E_{11} \cdot \sin^2(99^\circ) + E_{12} \cdot \sin(2 \cdot 99^\circ) + E_{22} \cdot \cos^2(99^\circ)$$

$$0.0007 = E_{11} \cdot \sin^2(201^\circ) + E_{12} \cdot \sin(2 \cdot 201^\circ) + E_{22} \cdot \cos^2(201^\circ)$$

$$0.0000 = E_{11} \cdot \sin^2(172^\circ) + E_{12} \cdot \sin(2 \cdot 172^\circ) + E_{22} \cdot \cos^2(172^\circ)$$

$$0.0150 = E_{11} \cdot \sin^2(94^\circ) + E_{12} \cdot \sin(2 \cdot 94^\circ) + E_{22} \cdot \cos^2(94^\circ)$$

Solving the above system on the basis of the least squares method and the Mathematica software, the following strain tensor parameters and their uncertainties were obtained:

E_{11} = 0.0105 ± 0.0023

E_{12} = -0.0054 ± 0.0034

E_{22} =-4.07*10^{-5} ± 0.0032

It is obvious that E_{22} (strain value at the vertical direction) is statistically not significant, in contrast to the E_{11} and E_{12} strain tensor components. The principal strain values were subsequently calculated from eqs. 2, 3 and 4: ε_{max} = 0.013, ε_{min} = 0 and φ = 0.4°. Finally, the deformed section was designed using AUTOCAD software (Fig.7).

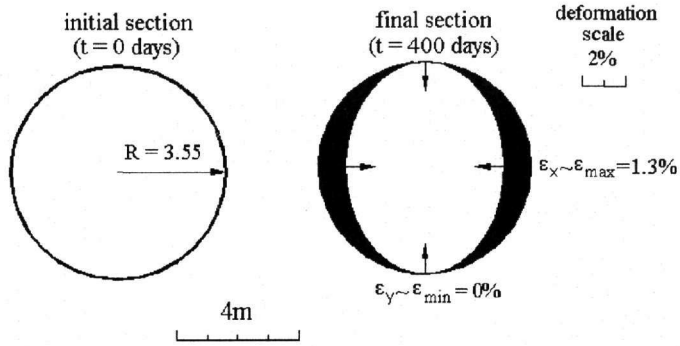

Figure 7. Schematic comparison of the initial and of the final (exaggerated) form of a representative section of Acheloos Diversion Tunnel (ch. 16+276m), 400 days after the excavation.

Similar calculations were made using deformation data collected at various times since the section excavation. This analysis revealed that the strain field of the study sections was gradually changing with time, as is schematically shown in figure 8, and that deformation was accumulating until the initially circular section was transformed to an ellipse.

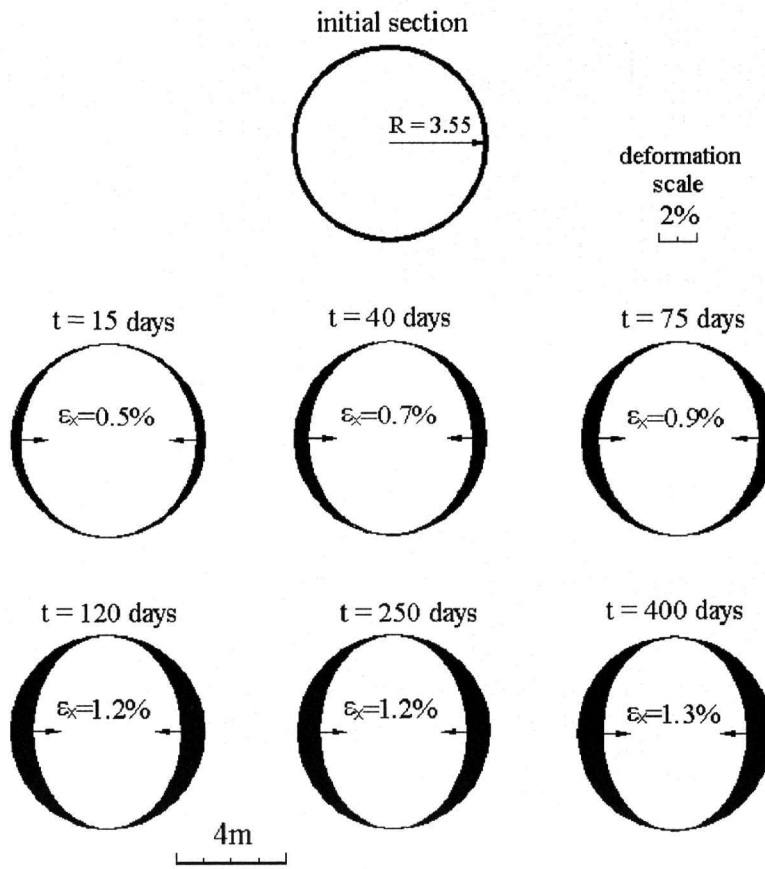

Figure 8. Progressive change of the section strain field along time. Horizontal strain (ε_x) accumulates gradually to 1.3% (corresponding to maximum strain), whereas vertical strain remains 0.

5 CONCLUSIONS

The Frank's (1966) methodology for calculating ground surface strains across several seismic regions on the basis of repeated geodetic measurements is adopted for the estimation of the average strain of tunnel sections during excavation. The analysis uses the deformation monitoring data, either geodetic or geotechnical (extensometers etc.), and estimates the strain tensor parameters by least squares calculations. The only requirements are first, uniform deformation across the section and second, measurements influenced by random errors only. Both these requirements are fulfilled by several tunnels cut through homogeneous ground conditions and following careful monitoring programs.

The application of this methodology on the Acheloos Diversion Tunnel data showed that the deformed section corresponds to an ellipse, with major axis at the vertical direction; the horizontal contraction reaches 1.3% after ~400 days after excavation but no vertical deformation is calculated. Furthermore, the calculation of the strain field parameters for several time periods after excavation reveals the kinematic response of the tunnel section to the excavation along time.

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