Tunnelling and Underground Space Technology 40 (2014) 141–150

Contents lists available at ScienceDirect

Tunnelling and Underground Space Technology

journal homepage: www.elsevier.com/locate/tust

# Monitoring tunneling induced ground displacements using distributed fiber-optic sensing

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ARTICLE INFO

*Article history:*
Received 16 May 2013
Received in revised form 24 September 2013
Accepted 26 September 2013
Available online 22 October 2013

*Keywords:*
Tunneling
Induced ground displacements
Gaussian curve
Modified Gaussian
Brillouin scattering
Rayleigh scattering
Volume loss
Pipe jacking
Monitoring
Fiber optics

ABSTRACT

Determination and monitoring of tunneling induced ground displacement is an important component in tunneling design and construction. In recent years several technologies for distributed strain measurement along fiber optics have been developed, namely the Brillouin Optical Time Domain Reflectometry (or Analysis) – BOTDR/A and the Rayleigh backscatter wavelength interferometry (OBR). This paper presents how these technologies could be used to monitor and define ground displacement models through an appropriate 2D and 3D optimization and signal analysis of information derived from a horizontally laid fiber above the tunnel. The suggested approach is evaluated in two field investigations, one involving excavation of a 3 m diameter tunnel by TBM at depth of 18 m, and the other installation of a 1 m diameter water main by pipe-jacking at depth of 6 m. Comparison between the results obtained by the different technologies shows that they are equally suitable for the suggest approach. The suggests approach allows reliable determination of the parameters involved in empirical ground displacement models, and allows field validation that the tunneling process lies within the design bounds. An interesting observation, supported by the analytical models, is that non-perpendicular alignment of the fiber, relatively to the tunnel line, results in a shift in the peak strain location as the tunnel advances. It was demonstrated that the rate of change in peak strain location, with tunnel advancement, can be used to obtain the settlement trough length parameter, without the need for complete evaluation of all other model parameters.



## 1. Introduction

Throughout the last decade a number of advanced fiber optic sensing technologies have matured and developed into commercial analyzers for temperature and strain measurements. Namely, the Brillouin scattering based technologies such as Yokogawa's Brillouin Optical Time Domain Refelectormetry – BOTDR AQ8603 and Omnisens' Stimulated BOTDR (named BOTDA, A for analysis) DITEST STA-R; and the Rayleigh scattering based technology such as the Luna's OBR 4600. These technologies allow for continuous (in space) measurement of strain and temperature along conventional telecommunication single mode fibers. The spatial resolution and maximal distance of the measurement varies between the technologies. While the BOTDR/A allows for long distance measurements, of up to 30 km, it is limited to a spatial resolution of roughly 1 m (with measurements taken every 10 cm). The OBR, on the other hand, has an extremely high spatial resolution (of less than 1 cm), but a shorter measurement distance of 2 km. It is expected that with time the capabilities of both technologies will be enhanced by implementation of more advanced sensing algorithms (e.g., Bao and Chen, 2012; Zadok et al., 2012).

The use of conventional optical fibers, together with the continuous (spatially) nature of the measurement, makes these technologies ideal for many civil engineering applications. Consequently, significant research effort has been invested in both methods of fiber optic installations and data interpretation for structural and geotechnical applications (e.g., Bastianini et al., 2005; Deif et al., 2010; Klar et al., 2006; Mohamad et al., 2007; Janmonta et al., 2008; Iten and Puzrin, 2009; Goldfeld and Klar, in press).

The fiber optic distributed sensing approach has also been applied for monitoring processes associated with tunneling. The most common use was the direct evaluation of the induced stressing and displacement in existing tunnels and pipelines due to the construction of a new tunnel (e.g., Vorster et al., 2006; Mohamad et al., 2010; Mohamad et al., 2011). In all of these applications the focus was on the evaluation of the existing structure, rather than on the excavation process of the new tunnel.

One of the applications in which the distributed sensing technology was used to actually evaluate tunneling activity was that of a smart underground fence for detecting and characterizing cross-border smuggling tunnels (Klar and Linker, 2010; Linker and Klar, 2013). In this application fibers were buried directly within the ground, and an advanced wavelet-based algorithm identified the tunnel.

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http://dx.doi.org/10.1016/j.tust.2013.09.011

This paper presents an engineering based approach for evaluating tunneling induced ground displacements using the signals provided by the fiber optic technology. The suggested approach aims at predicting fundamental greenfield parameters associated with the tunneling process, such as the volume loss and the inflection point (associated with the settlement trough). The approach is demonstrated through two different field experiments involving both large (3 m) and small (1 m) diameter tunnels. In addition existing relations of ground displacement models are evaluated and discussed.

Since many design processes are based on a greenfield displacement input (e.g., Vorster et al., 2005; Klar et al., 2008; Elkayam and Klar, 2010; Marshall et al., 2010; Wang et al., 2011; Zhang and Huang, 2012), the suggested approach could be used as a safety measure to ensure that the tunnel excavation process lies within the design bounds, simply by monitoring a fiber at a greenfield area in front of the structure of interest (e.g. pipeline, building, railway, etc.).

The paper is composed of three main sections, where the first section presents relations between greenfield displacement and horizontal strains within the fiber, the second section suggests evaluating the ground displacement parameters using optimization procedures, and the third section presents two field investigations in which the approach was applied.

## 2. Relations between ground displacement models and the longitudinal fiber strain

### 2.1. 2D and 3D ground displacement models

Several analytical and empirical models for predicting tunneling induced ground displacement exist. While in the analytical models (e.g., Sagaseta, 1988; Verruijt and Booker, 1996; Verruijt, 1997; Sagaseta, 1988; Bobet, 2001) the surface settlement profile results, implicitly, from the solution of the continuum governing equations (usually elasticity), in the empirical models (e.g., Peck, 1969; Attewell et al., 1986) the settlement profile is associated with a predefined shape function regulated by a few input parameters. The use of the empirical models is very common in engineering practice, since their profile shape functions are also used as an input for analytical solutions of many soil structure interaction problems (e.g., Attewell et al., 1986; Marshall et al., 2010; Zhang and Huang, 2012). The correct estimation of the parameters of the green field shape function may be crucial in the engineering evaluation of these interaction problems. For example, the normalized terms involved in the solution of the effect of tunneling on existing pipelines involve the use of the greenfield trough width $i_x$ raised up to power of 3 (where $i_x$ is the location of the settlement trough inflection point), and an inaccurate estimation of $i_x$ may lead to erroneous prediction of the expected bending moments in the pipeline.

The current work focuses on the empirical models, with the aim of evaluating their input parameters using fiber optics field measurements. The number of input parameters depends on the specific empirical model, and the current work focuses on three models: (1) the classical 2D Gaussian curve (Peck, 1969) representing a plane strain condition, (2) the 2D modified Gaussian curve (Vorster et al., 2005), and (3) the 3D model of Attewell et al. (1986). In principle, there is a significant difference between the interpretation of the measurement data when using 2D (plane strain conditions) or 3D models. Assuming that the tunnel line crosses a shallow buried optical-fiber, 2D models require that interpretation be made using measurements taken after the tunnel face has advanced significantly beyond the fiber (to result in a plane strain condition). This limitation does not apply to 3D models. These aspects are considered later on in Section 2.2.

The empirical equations of the above three models are as follows. The classical 2D curve:

$$
\begin{aligned}
s_v(x) &= s_{max}\exp\left(-\frac{1}{2}\frac{x^2}{i_x^2}\right)\\
s_h(x) &= -ns_{max}\frac{x}{\Delta z}\exp\left(-\frac{1}{2}\frac{x^2}{i_x^2}\right)
\end{aligned}
\tag{1}
$$

where $s_v$ and $s_h$ are the vertical and horizontal displacements at a transverse distance $x$ from the tunnel centerline, respectively, $n$ is a model parameter which relates to the focal point to which the displacement vectors point, $s_{max}$ is the maximum settlement (above the tunnel centerline), $i_x$ is the settlement trough width parameter (distance to the inflection point), and $\Delta z$ is the height difference between the tunnel centerline and the point of interest. Note that the relation between the horizontal and vertical displacement using the parameter $n$ follows (Attewell et al., 1986). The 2D modified Gaussian curve:

$$
\begin{aligned}
s_v(x) &= s_{max}\frac{q+1}{q+\exp\left(\xi\frac{x^2}{i_x^2}\right)}\\
s_v(x) &= -ns_{max}\frac{x}{\Delta z}\frac{q+1}{q+\exp\left(\xi\frac{x^2}{i_x^2}\right)}\\
q &= \exp(\xi)\frac{2\xi-1}{2\xi+1}
\end{aligned}
\tag{2}
$$

where $q$ (or $\xi$ interrelated through the third expression) is an additional parameter which controls the shape of the settlement trough (when $\xi = 1/2$, $q = 0$ and the equation degenerates into the classical error function). The 3D model, expressed as function of the local horizontal distance from the tunnel centerline ($\Delta x$), the longitudinal distance ahead from the tunnel face ($\Delta y$) and the height difference between the tunnel centerline and the point of interest is:

$$
\begin{aligned}
s_v(\Delta x,\Delta y) &= \frac{s_{max}}{2}\exp\left(-\frac{1}{2}\frac{\Delta x^2}{i_x^2}\right)\left(1-\mathrm{erf}\left(\frac{\Delta y}{\sqrt{2}i_y}\right)\right)\\
s_t(\Delta x,\Delta y) &= -n\frac{\Delta x}{\Delta z}s_v(\Delta x,\Delta y)\\
s_l(\Delta x,\Delta y) &= n\frac{i_y s_{max}}{\sqrt{2\pi}\Delta z}\exp\left(-\frac{1}{2}\frac{\Delta x^2}{i_x^2}\right)\exp\left(-\frac{1}{2}\frac{\Delta y^2}{i_y^2}\right)
\end{aligned}
\tag{3}
$$

where $s_t$ and $s_l$ are the horizontal ground displacements in the direction perpendicular and parallel to the tunnel centerline, respectively, erf is the error function ($\mathrm{erf}(z) = 2/\sqrt{\pi}\int_0^z e^{-t^2}dt$) and $i_x$ and $i_y$ are the settlement trough width and length parameters of the function. $i_x$ and $i_y$ are commonly assumed to be equal (e.g., Attewell et al., 1986; Dimmock and Mair, 2008), but since the proposed approach allows evaluation of their values, in the present work they are considered individually.

Fig. 1 illustrates the deformation pattern of the above three functions. The above three models are related, in a sense that the final settlement trough of the 3D model is identical to the classical 2D curve, and that the modified Gaussian curve degenerates into the classical curve when $q = 0$. Note that other '3 parameters' models (in addition to the modified Gaussian curve) could also be examined (e.g., Celestino et al., 2000). However, as was demonstrated by Marshall et al. (2012), once the '3 parameters' models are compared using the same basis they are equally suitable for predicting ground displacements.