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Probabilistic approach to assessing and monitoring settlements caused by tunneling

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ABSTRACT

Tunnel construction commonly causes deformations of the surrounding ground, which can endanger buildings and other structures located in the vicinity of the tunnel. The prediction of these deformations and damages to buildings is difficult, due to limited knowledge of geotechnical conditions and due to uncertainty in predicting the response of the structures to the settlements. This motivates the development of a probabilistic model for the prediction of tunneling-induced damage to buildings. We propose such a model, based on the classical Gaussian profiles for the approximation of the subsidence trough and the equivalent beam method for modeling the response of the building walls. In practice, settlements are commonly monitored through deformation measurements. To account for this, we present a Bayesian method for updating the predicted settlements when measurements are available. Finally, we show how maximum allowable settlements, which are used as threshold values for monitoring of the construction process, can be determined based on reliability-based criteria in combination with measurements. The proposed methodology is applied to a group of masonry buildings affected by the construction of the L9 metro line tunnel in Barcelona.

1. Introduction

Tunneling construction leads to ground subsidence, which can endanger buildings and infrastructure in the vicinity of the tunnel. Settlements caused by tunneling can be modeled using Gaussian profiles (Peck, 1969; Attewell and Woodman, 1982; Attewell et al., 1986). This simple model describes the geotechnical conditions by two parameters: the volume loss V_L and the trough width parameter K of the settlement trough. Once the settlement profile is determined, the resulting damages in buildings are commonly modeled by applying the equivalent beam method (Burland and Wroth, 1974; Boscardin and Cording, 1989). This method determines the maximum tensile strain in a particular building wall by modeling it as a linear elastic beam subjected to a given deflection ratio. This strain value is then compared with limiting strain values, which define different categories of damage to buildings, from negligible to very severe.

Prediction of damages is important as a basis for tunnel design, selection of the construction technology and for setting allowable limits on settlements. These allowable values of settlement are used in the construction phase for control purposes: if the measured settlement exceeds the allowable values, the construction is stopped and/or additional safety measures are taken. However, the prediction of damages to buildings caused by tunnel construction entails uncertainty due to (a) our limited knowledge of geotechnical conditions and simplified geotechnical models and (b) uncertainty on the response of structures subjected to differential settlements. This motivates the use of probabilistic approaches for the prediction of settlements and for determining allowable settlement values (Gong et al., 2014).

First attempts to the determination of allowable settlements for buildings were made by Skempton and MacDonald (1956), who defined allowable settlements according to evidence of existing data surveys of buildings. Settlement limits were determined for cases of panels in frame buildings and walls in load-bearing wall buildings. At present, the limits on allowable settlements are usually determined on a deterministic basis without consideration of uncertainty in the ground and building parameters. For example, Yoo and Kim (2003) proposed an approach for the determination

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of the maximum allowable volume loss in the construction of the Metro Subway Line 2 in Daegu (South Korea). The approach was based on a Gaussian profile of the settlement trough and the equivalent beam model. An iteration procedure was applied to identify the value of volume loss (and hence the allowable value of settlement) that would lead to damages below an acceptable level.

We propose a probabilistic model for the estimation of building damage due to tunneling, which is based on the Gaussian profile for the approximation of the subsidence trough and the equivalent beam method for modeling the response of the building walls (Section 2). The proposed methodology allows taking into account the uncertainties associated with the main model parameters, namely the volume loss V_L, the trough width parameter of the settlement profile K, the ratio of the Young's modulus to the shear modulus of the building and the model errors.

Based on the probabilistic model, we propose a novel approach for determining the allowable settlement on a reliability basis (Section 3). We demonstrate how the probabilistic model can be updated based on measurements using Bayesian analysis. This allows the computation of the conditional probability of damages given settlement measurements. The allowable settlement is then defined as the maximum measured settlement, for which the conditional probability of damage to a building wall is acceptably low. The approach was first introduced in Camós et al. (2013), here it is extended to account for the fact that the settlement depends on the actual phase of construction, i.e. on the distance of the tunnel heading from the point of measurement.

The proposed methodology is applied to a case study of masonry buildings affected by the construction of the L9 metro line in Barcelona (Section 4). A parametric study is included to analyze the influence of the different model parameters on the estimation of allowable settlements.

2. Probabilistic model of building damage due to tunneling

A typical tunneling situation is depicted in Figs. 1 and 2, with a building wall of length l_{build}, with its reference point $\hat{A}$ located at a distance d_{orig} from the origin of coordinates and aligned θ degrees with respect to the tunnel transverse plane (Camós and Molins, 2015). The depth of the tunnel axis and the tunnel diameter are z_0 and d respectively. Note that the analysis of an entire building should include all exterior walls. However, from now on we will refer to *building damage* as the damage occurring only in a particular wall, without considering the contribution of the other walls. Alignments counterclockwise with respect to the x-axis are positive ($\theta > 0$). The y axis follows the tunnel longitudinal axis, whereas the x axis corresponds to a transverse plane to the tunnel. The origin of coordinates is set to the intersection of the longitudinal axes of the tunnel and of the building wall. This implies that the coordinate system is a different one for each considered building (wall). The tunnel face is located at coordinate y_s and it advances towards $y = -\infty$, following the criteria set by Attewell et al. (1986).

2.1. Modeling of ground settlement – Gaussian profiles

Gaussian profiles of tunneling-induced settlements consist of a Gaussian probability density function describing the shape of settlements in the transverse direction (x-axis) and a Gaussian cumulative distribution function describing it in the longitudinal direction (y-axis). An example of a Gaussian profile is shown in Fig. 3.

The settlement in [mm] at a certain position with coordinates x, y, z in [m] is calculated by (Peck, 1969; Attewell and Woodman, 1982; O'Reilly and New, 1982):

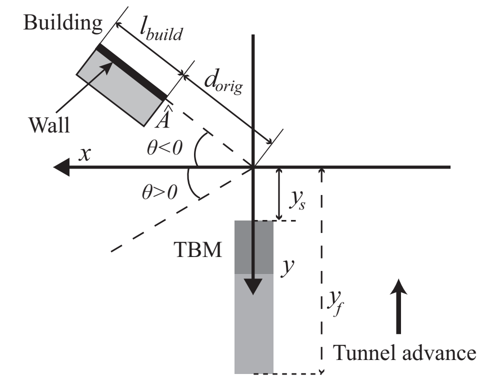

Fig. 1. Tunnel and building positions (from Camós and Molins, 2015).

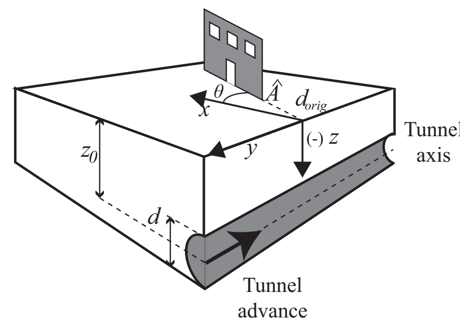

Fig. 2. 3D view of tunnel and building wall positions.

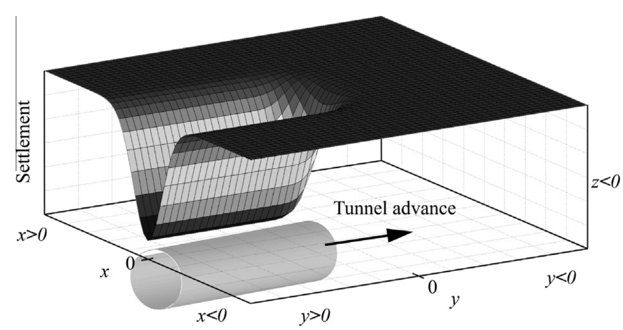

Fig. 3. Settlement trough produced by tunnel excavation in the transverse (x) and longitudinal (y) directions. The origin of the coordinate system is set relative to the position of the analyzed building wall.

$$S(x, y, z, d, y_s, y_0, y_f, z_0, V_L, K_x, K_y) = -1000 \cdot S_{max} \cdot \exp\left[-\frac{x^2}{2 \cdot K_x^2 \cdot (z_0 - z)^2}\right] \cdot \left[\Phi\left(\frac{y - (y_s + y_0)}{K_y \cdot (z_0 - z)}\right) - \Phi\left(\frac{y - y_f}{K_y \cdot (z_0 - z)}\right)\right] \quad (1)$$

where S_{max} is the absolute value of maximum settlement far behind the tunnel face, where the deformations are fully developed. It is calculated as:

$$S_{max} = \frac{V_L \cdot \pi \cdot d^2}{\sqrt{2\pi} \cdot K_x \cdot (z_0 - z) \cdot 4} \quad (2)$$

d and z_0 are given in meters. z_0 is a positive magnitude. y_s represents the position of the tunnel face as shown in Fig. 1. y_0 is the horizontal shift of the longitudinal settlement profile with respect to the tunnel face. y_f is the distance of the tunnel portal. In the