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3D analytical prediction of building damage due to ground subsidence produced by tunneling ☆

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ABSTRACT

Tunnel construction entails the generation of ground settlements, which can endanger the adjacent buildings. The prediction of damages in buildings is usually based on the classical Gaussian profiles for the approximation of the subsidence trough and the equivalent beam method for modeling the response of building walls. Current available expressions refer to walls aligned transversally with respect to the tunnel axis, which usually represents the worst-case scenario. However, approximations must be done for other building alignments, since no analytical expressions are available for these cases. We propose a novel equation for the determination of the horizontal ground strain, which departs from the equations of the classical Gaussian settlement profiles. The novel formulation allows the application of the equivalent beam method in 3D and the modeling of the tunnel advance. The results show significant variations of the estimated damage depending on the wall position with respect to the tunnel axis. The paper reviews also certain relevant aspects of building damage predictions, such as the influence area of settlements and the possible contribution of ground horizontal strain to damage reduction. A parametric analysis is further performed to create a non-linear regression model that allows direct estimation of the maximum tensile strain in a building wall according to input values of geological conditions and wall and tunnel geometries.

1. Introduction

1.1. Background

Design of urban tunnels requires the prediction of possible damages in adjacent buildings produced by tunneling subsidence. The use of Finite Element Models is appropriate for the estimation of damages, including the location and width of crack patterns (Giardina et al., 2013). However, primary assessments of the response of buildings to settlements can be done with the equivalent beam method (Burland and Wroth, 1974; Boscardin and Cording, 1989), which is widely used in tunneling engineering. This method models a building wall as a weightless linear elastic beam subjected to a given ground settlement profile. Strains in the beam are generated (a) due to the deflection when conforming to the settlement profile and (b) due to the ground horizontal strain generated on the base of the beam. The distribution of strains along the beam depends on the mode of deformation, which comprises a combination of bending and shear. For this reason, two extreme modes are typically considered in order to ascertain which is the most critical: pure bending and pure shear. Maximum tensile strains in the beam due to pure bending (ε_{br}) and pure shear (ε_{dr}) deformations are given by the following expressions derived from the elastic beam theory:

$$\varepsilon_{br} = (\varepsilon_{bmax} + \varepsilon_h) \quad (1)$$

$$\varepsilon_{dr} = \varepsilon_h\left(1 - \frac{E}{4G}\right) + \sqrt{\frac{\varepsilon_h^2}{16}\left(\frac{E}{G}\right)^2 + \varepsilon_{dmax}^2} \quad (2)$$

where E/G is the ratio between the Young and shear moduli of the wall material, ε_{bmax} and ε_{dmax} are the maximum strains due to the deflection of the beam in pure bending and pure shear modes of deformation (Section 4) and ε_h is the value of horizontal ground strain on the base of the beam, which depends on the shape of the settlement trough and on the location of the wall (Fig. 1). This location is defined by the proximity and the alignment with respect to the tunnel axis (Section 2). The maximum tensile strain ε_{max} corresponds to the highest value between ε_{br} and ε_{dr} along the beam.

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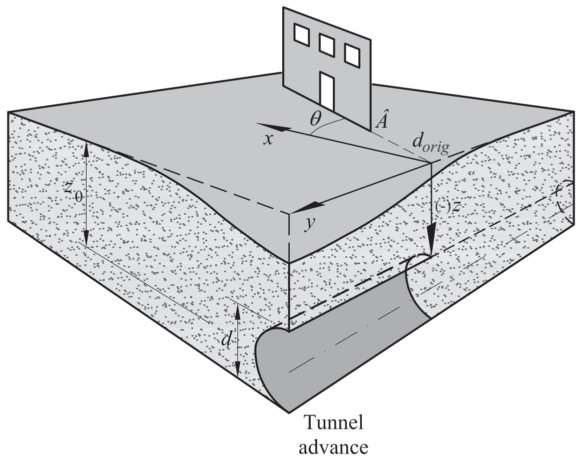

Fig. 1. 3D settlement trough above an advancing tunnel.

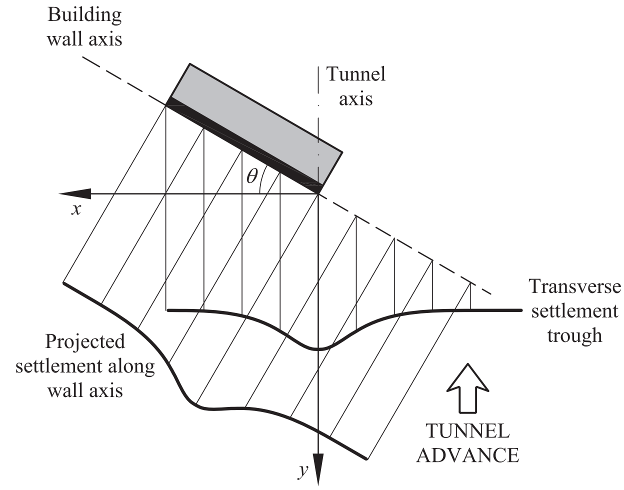

Fig. 2. Projection of settlement profile in case of a rotated building respect to x-direction.

Based on ε_{max}, the approach of Burland et al. (1977) is used in this paper for classification of the damage magnitudes (Section 4).

The determination of ε_{max} represents a 3D problem that depends on (a) the ground conditions, (b) the building geometry, (c) the tunnel geometry, (d) the building position with respect to the tunnel axis, (e) the location of the tunnel face and (f) the construction technology. Nevertheless, equivalent beam analyses are usually simplified and performed in 2D. For example, in case of buildings aligned transverse to the tunnel axis (x-direction), data evidence has shown that the shape of the settlement profile S can be closely approximated to a Gaussian probability density distribution (Peck, 1969). The settlement profile in the longitudinal direction (y-direction) is usually described by a Gaussian cumulative distribution function (Attewell and Woodman, 1982). Settlement profiles in both directions are depicted in Fig. 1.

Expressions of ground horizontal movements in the transverse $U_x(x)$ and longitudinal $U_y(y)$ directions with respect to the tunnel axis were given by O'Reilly and New (1982) by assuming that ground particles move towards the tunnel axis. Horizontal ground strain ε_h in the transverse $\varepsilon_{h,xx}(x)$ and longitudinal $\varepsilon_{h,yy}(y)$ directions are directly given by derivation of $U_x(x)$ and $U_y(y)$:

$$\varepsilon_{h,xx}(x) = \frac{dU_x(x)}{dx} \tag{3}$$

$$\varepsilon_{h,yy}(y) = \frac{dU_y(y)}{dy} \tag{4}$$

Buildings walls aligned transversally and longitudinally with respect to the tunnel axis are statistically representative, since many urban tunnels follow the tracks of avenues or streets. However, there are a significant number of buildings randomly aligned with respect to tunnel axes, in particular when using a Tunnel Boring Machine (TBM). The damage assessment in these cases is usually simplified by projecting the transverse or the longitudinal (whichever is the closest) settlement profile along the axis of the rotated wall, as shown in Fig. 2 (Kappen, 2012; Camós et al., 2014). However, this practice can become unrealistic for alignments far from the transverse or longitudinal cases. Therefore, the determination of ε_h and the posterior damage assessments using this practice may be inaccurate.

The models of Peck (1969), Attewell and Woodman (1982) and O'Reilly and New (1982) can be extended to obtain 3D expressions for the settlement trough, $S(x,y,z)$, the ground horizontal displacements, $U_x(x,y,z)$ and $U_y(x,y,z)$ and the ground horizontal strains, $\varepsilon_{h,xx}(x,y,z)$ and $\varepsilon_{h,yy}(x,y,z)$ (see Section 2). However, no equation has been found in the literature to determine the resultant value of ε_h in a particular wall alignment. Therefore, accurate estimations of ε_h can only be achieved with the use of numerical simulation and hence, the complete analytical assessment of building damage cannot be performed. Moreover, numerical simulation is commonly avoided in practice due to the required computation resources and modeling expertise (Giardina et al., 2012).

1.2. Objective and approach

The present paper proposes a novel equation for the exact determination of ε_h in a particular wall alignment by applying a change of basis to the infinitesimal ground strain tensor (Section 2). The new equation departs from the equations of Peck (1969), Attewell and Woodman (1982) and O'Reilly and New (1982), which assume that settlement troughs produced by tunneling construction are Gaussian-shaped. The proposed equation is used to show the influence of the ground conditions and the tunnel geometry in the values of ε_h (Section 3). The paper furthermore reviews certain relevant aspects of building damage predictions with the equivalent beam method in 3D, such as the influence area of settlements and the possible contribution of ground strain to damage reduction. The influence of the tunnel face location and the position of the building wall in the damage assessment is also shown by means of a parametric analysis (Section 4). The resulting data is used to create a non-linear regression model that allows the direct estimation of the maximum tensile strain ε_{max} in a building wall according to input parameters of the geological conditions and the wall and tunnel geometries (Section 5).

2. Development of a novel equation for the ground horizontal strain ε_h in 3D

2.1. Description of the building wall position

The next sections describe the development of a novel equation for the determination of the resultant ground strain ε_h in a particular wall alignment θ with respect to the tunnel axis. For this reason, the notation for the description of the building wall position is given, first for a general case (Section 2.1.1) and then for the particular case of building walls parallel to tunnel axis (Section 2.1.2).

2.1.1. General case

A typical tunneling situation with a building wall of length l_{build} is depicted in Fig. 3. The y-axis follows the tunnel longitudinal axis,