Structure interaction effects on tunneling induced settlements

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ABSTRACT: Tunnels are increasingly being constructed in densely built urban environments in which there is a pressing need for accurate design tools able to predict ground movements and their influence on existing structures. The investigations in this paper are concerned both with the discussion of different models to quantify ground’s subsidence and the damage induced to buildings. For this purpose, the instrumentation data of three tunnels bored in the city of Madrid have been processed to compare “green field” values with the corresponding settlement of buildings along the tunnel route. The interaction effects have been analyzed in terms of the building situation in respect of the settlement trough and of the structure type. Finally, three-dimensional finite difference models have been used to simulate the coupled effect of the ground movements on the building strains, therefore providing a theoretical check of the measurements.

1 SCOPE OF THIS STUDY

The progress of the excavation of a tunnel induces a transitory three-dimensional deformation field that is highly dependent of the construction method and the rheological behaviour of the ground.

The feasibility of the development of underground infrastructures below densely built environments relies upon the tolerance of existing structures to the tunnel-induced ground movements, as they can suffer a degree of damage ranging from minor aesthetical impact to the ruin of the buildings, passing through different levels of functional affection.

It is therefore important to develop analytical tools able to predict the degree of damage induced by the tunnel, which help the designer to choose between either preventive or remedial measures with a reasonable confidence.

2 METHOD OF ANALYSIS

Three are the problems inherent to the estimation of potential damage to buildings:

(a) assessment of the ground movements induced by the tunnel excavation
(b) tolerable deformation of the structure
(c) mechanism of interaction between the structure and the ground movements.

2.1 Ground movements

The two-dimensional simplification of the deformation field has been widely studied in the technical literature. The models, representing the settlement profile of the cross section far behind the tunnel face to avoid transitory effects, have been traditionally classified as semiempirical (for example, Peck, 1969; Sagaseta and Oteo, 1974), analytical (such as Sagaseta, 1987; Verruijt and Booker, 1996; Loganathan and Poulos, 1998; González and Sagaseta, 2001) or numerical. Of them, the latter have the highest predictive potential (allowing to take into account difficulties such as ground heterogeneity, material constitutive laws, geometry and construction staging), though their inherent complexity requires necessary adjustments for which the semiempirical and the analytical models are of invaluable aid. In this sense, the three-dimensional modelisation has proven a decisive factor to reproduce the tunnel subsidences, as will be shown below. However, for the sake of simplicity, Peck’s (1969) semiempirical formulation will also be employed in this investigation as it continues to furnish accurate settlements profiles in “green field” conditions far behind the tunnel face. This approach has also the advantage of the benefit of the huge data base available in the technical literature for the parameter’s assessment.

2.2 Allowable structure deformation

Although many authors or codes of practice still tend to assess the serviceability limits in terms of a limiting value of the movement of the foundation of the building (for example, Bjerrum, 1963; Ciria, 1981; CTE, 2003), the pioneering work carried out by Burland and Wroth (1974), successfully adapted by Mair, Taylor and Burland (1996) in their “equivalent beam
methodology” has shown to be the most useful for the designer as it correlates the degree of damage of the structure with a quantitative parameter (maximum tensile strain of a model beam) which can take into account many structural aspects such as the stiffness of the building (either flexural and in shear), the typology of the foundation, the different behaviour in sagging or hogging modes of deformation, etc. For these reasons, the latter method has been adopted in this investigation using the authors’ recommendations for the input of ground settlements and horizontal movements in the equivalents beam model.

2.3 Ground structure interaction

Measured settlement profiles of buildings and numerical model results suggest that the buildings exhibit less curvature than the adjacent greenfield troughs. In such cases, the assessment procedures of the maximum tensile strain of the equivalent beam in terms of greenfield site ground movements may yield conservative results.

In their original applications, the methodology assumed that buildings follow the same settlement profile as would occur in “green field” conditions, namely their stiffness is neglected as they are supposed to deform in the shape of the Gaussian settlement trough as predicted by Peck’s (1969) semiempirical model. However, parametric studies carried out by Potts and Addenbrooke (1997) using finite element analyses, simulating the building as a beam with different stiffnesses (either axial and flexural) have shown that buildings accentuate or flatten the curvature of the settlement profile, depending on different factors such as the mode of deformation (sagging or hogging), the relative stiffness or the relative position of tunnel and building. The modification factors for deflection ratio obtained by Potts and Addenbrooke (1997) are shown in figure 1, and have been used in this investigation to introduce the building interaction effects in the equivalent beam analysis.

This modification factors indicate the values by which one should multiply the greenfield values of deflection ratio to obtain those to be imposed on the structure. A modification factor of 1 means that the building behaves perfectly flexibly while a modification factor of 0 means that the building has a perfectly rigid behaviour.

2.4 Stiffness of the structure

As can be seen from figure 1, the modification factor for deflection ratio depends on the relative eccentricity e/B of the tunnel and the relative stiffness in bending, defined as:

\[ \rho^* = \frac{EI}{E_s H^4} \]

where H is half width of the beam and E_s the soil stiffness. For a structure with n storeys, Potts and Addenbrooke (1997) recommend to obtain the bending stiffness with the following equation:

\[ (E_c I)_{rig} = E_c \sum_{i=1}^{n+1} (I_{slab + A_{slab}} d^2) \]

where d is the vertical distance from the structure’s neutral axis to the individual slab’s neutral axis. However, equation (1) implicitly assumes that the columns of the building are infinitely rigid, grossly overestimating the stiffness of the structure. Using a three-dimensional slab and column elastic analysis to obtain the real stiffness \((E_c I)_{real}\) of the building, figure 2 compares the values of \(\rho^*\) obtained under both assumptions of infinitely rigid columns and real flexible columns. It can be seen that the real behaviour of the building corresponds to a \(\rho^*\) factor 10^2 to 10^4 times lower depending on the number of spans and the number of storeys.
This correction of the assessment of the bending stiffness of the building has been adopted throughout this investigation for the purpose of estimating the modification factors of Potts and Addenbrooke (1997).

3 CASE STUDIES

3.1 Measured settlements

Three case studies have been analysed using the aforementioned methodology. The three tunnels were bored under urban areas in the centre and the periphery of the city of Madrid, in materials that geologically pertain to the miocene detritic basin constituted by medium dense to dense silty sands with occasional layers of clayey sands. All three tunnels were excavated and supported in 2 stages using the traditional Madrid method, therefore they have a similar shape of the cross section (see figure 3), although with different excavated sizes: 49 m² for the single track subway tunnel, 78 m² for the two lane road tunnel and 125 m² for the three lane road tunnel. Settlements were measured in different sections along the tunnels routes, either in “green field” conditions (see figure 4) and below existing buildings (see figure 5). A Gaussian curve was fitted to the “green field” settlement points which allowed to obtain the troughs’ volumes as a percentage of the excavated area. Figure 6 shows these values as a function of the tunnel overburden in Miocene material. The measured points lie near the lower limit of the range of values proposed by Oteo (2000), indicating a good workmanship in construction.

3.2 Behaviour of the buildings

A total of 26 buildings were surveyed during the tunnels’ construction and their settlements were compared to the “green field” settlements in an equivalent situation of tunnel depth and geotechnical conditions. Figures 7 and 8 show an example of such comparison for buildings respectively in hogging and sagging mode of deformation. This comparison enables to obtain in each case the modification factors of the deflection ratio. The backanalyzed values of the modification factors are shown in figure 9, together with the parametric curves proposed by Potts and Addenbrooke.
Although there is a wide scatter between the measured points and the theoretical curves, some conclusions can be drawn:

(a) buildings in sagging tend to behave less stiff than the parametric model, yielding higher modification factors

(b) buildings in the hogging mode tend to follow more closely the parametric model, except for some particular cases of structures of load bearing walls (represented by the farthest points) which, due to brittle failure, behave in a less stiff way than it corresponds to their $\rho^*$ value.

4 NUMERICAL MODEL

A three-dimensional finite difference model was run to simulate the tunnel construction below one of the buildings in hogging mode in which good agreement was found between the theoretical and measured modification factors. The constitutive law for the ground was elastoplastic and the excavation process was modeled by imposing a ground loss that resulted in a “green field” settlement similar to that measured in a control section. Figure 10 shows the settlement of the coupled analysis (building and ground) at the building section, which is in good agreement with the measured values.

In this model, the tensile strains of the building (shown in figure 11) yielded a maximum value of 0.046% which was very close to the result of the equivalent beam analysis using the modification factors of Potts and Addenbrooke (1997).
Figure 10. Comparison of settlement computed and measured below building.

Figure 11. Distribution of tensile strains in bearing walls due to the tunnel excavation.

5 CONCLUSIONS

The equivalent beam analysis has been used to estimate the potential damage to buildings in three case studies of tunnels in Madrid area, allowing to conclude that:

- The interaction effects measured in the sagging mode of deformation show a less stiff behaviour than predicted.
- For buildings in hogging mode, there is a closer agreement with the predictions.
- The maximum tensile strain obtained from the equivalent beam analysis (which serves to assess the potential degree of damage) agrees closely to that obtained from three-dimensional finite difference analysis.

REFERENCES