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The influence of an existing surface structure on the ground movements due to tunnelling

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ABSTRACT: The results of a parametric study have been used to quantify the influence of an existing structure on the ground movements due to tunnelling. Modification factors are obtained which can be applied to building damage parameters calculated from ground movements obtained from design equations which assume greenfield conditions (i.e. no surface structure). These factors provide a simple and convenient way of accounting for the stiffness of any surface structure when assessing the likely damage caused by tunnelling beneath it.

1. INTRODUCTION

The assessment of the influence of tunnelling on buildings and other structures has become an important and costly environmental issue. For example a large proportion of the petitions against the Jubilee Line Extension in London were settlement related. There is therefore, and has been for some time, a pressing need for research on the performance of structures subjected to tunnelling induced settlements.

Current design practice depends on empirical methods for the prediction of tunnelling induced ground movements. The methods are based on historical data from greenfield sites (e.g. Peck, 1969; O'Reilly and New, 1982). If the effect of ground movements on a surface structure is to be assessed, then the building is assumed to be infinitely flexible, and to follow the greenfield settlement profile. The translations, rotations, strains and deformations so predicted are then compared with limiting criteria to estimate the likely damage to the building (Burland and Wroth, 1974; Boscardin and Cording, 1989).

In this paper it is shown how this approach, based on a greenfield settlement profile, and making no allowance for the stiffness of the structure, can be improved to account more accurately for urban environments where existing surface structures modify the ground movements.

2. PARAMETRIC STUDY

The geometry of the problem under investigation is shown in Figure 1. The excavated tunnel diameter was fixed at D=4.146m and the depth from the soil surface to the tunnel axis, Z, was either 20m or 34m. These values are typical for a London Underground running tunnel. A beam of width, B, resting on the ground surface with its centre at an offset distance, e, from the tunnel centre line was used to represent the effect of a surface structure. The main variables considered in the parametric study were the axial and bending stiffness EA and EI (where E is the Young's modulus, A the cross sectional area and I the second moment of area of the beam) along with the beam width, B, and its eccentricity with respect to the tunnel centre line, e.

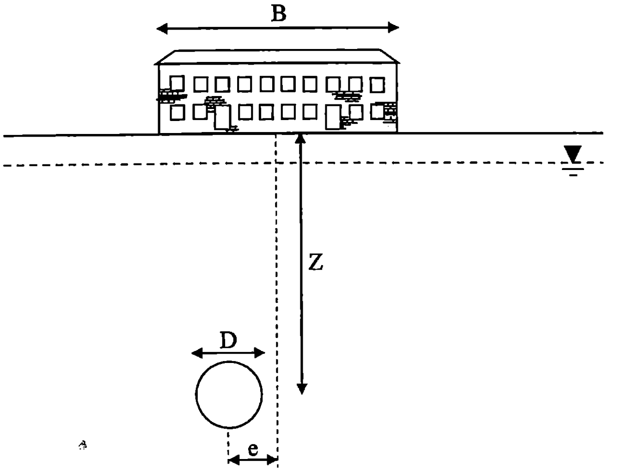


Figure 1: Problem geometry

The soil profile was assumed to be London Clay and was represented by a nonlinear elastic plastic constitutive model. The model described by Jardine et al (1986) was used to represent the nonlinear elastic pre-yield behaviour, and a Mohr Coulomb yield surface and plastic potential were used to model the plastic behaviour. The initial stress state in the ground was assumed to be controlled by a saturated bulk unit weight of 20kN/m^3, a hydrostatic pore water profile with a water table located 2m below ground surface and a Coefficient of Earth Pressure at Rest, K_o=1.5. Only a short term response was investigated and therefore the soil was assumed to behave undrained.

The surface beam used to represent an overlying structure was assumed to be elastic and its interface with the soil to be rough.

A total of 100 finite element analyses have been performed in which the depth of tunnel, the width and eccentricity of the surface beam and the axial and bending stiffness of the beam were varied. For further information the reader is referred to Potts and Addenbrooke (1996).

3. RELATIVE STIFFNESS PARAMETERS

To account for the stiffness of both the beam (structure) and the soil the following two measures of relative stiffness are introduced. The relative bending stiffness, ρ^*, and relative axial stiffness, α^* are defined as;

$$\rho^* = \frac{E.I}{E_s.H^4} \; ; \qquad \alpha^* = \frac{E.A}{E_s.H} \qquad (1)$$

where H is half the width of the beam (=B/2) and E_s is a representative soil stiffness. The expression for ρ^* is similar to that used by Fraser & Wardle (1976) and Potts and Bond (1994) and that for α^* is similar to that used by Boscardin & Cording (1989). It should be noted that for the present investigation, which involves plane strain conditions, α^* becomes dimensionless while ρ^* has dimensions of m^{-1}. The value of E_s adopted in the present work is the secant stiffness that would be obtained at 0.01% axial strain in a triaxial compression test performed on a sample retrieved from a depth of Z/2. This was chosen as it is a measure that could be obtained from a site investigation (Jardine et al, 1985).

4. GROUND SURFACE SETTLEMENTS

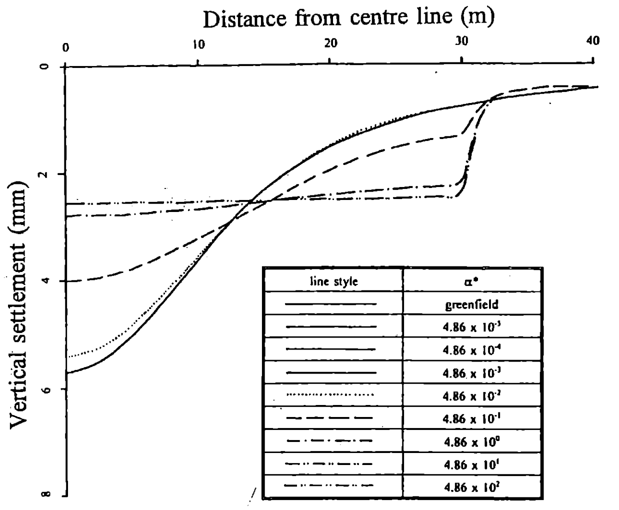
Surface settlement troughs from analyses of a 20m deep tunnel excavated beneath beams 60m wide with a zero eccentricity are given in Figure 2. Also shown for comparison is the numerically predicted greenfield settlement trough. In Figure 2a the profiles are for beams with a constant bending stiffness, ρ^*=0.518, but varying axial stiffness. It is evident that the greater the axial stiffness the greater the modification to the greenfield settlement. Figure 2b shows profiles for beams with a constant axial stiffness, α^*=48.6, but varying bending stiffness. Here it is evident that the stiffer the beam in terms of flexural rigidity, the greater the modification to the greenfield settlement. It is interesting to note that for the beams with very low bending stiffness the maximum settlements are greater than those from the greenfield analysis. These figures clearly show that both the axial and bending stiffness affect the settlement trough. Both figures also show that the structure only influences the settlements over a limited extent beyond its edge. The greenfield settlement curve is recovered within a horizontal distance equal to 15% of the beam width. For the stiffer structures the rate of change of settlement in this region is severe. The settlement troughs are similar in shape to those observed when tunnelling under Mansion House in London, (Frischmann et al, 1994) and beneath structures in Frankfurt (Breth & Chambosse, 1975).

5. BUILDING DAMAGE PARAMETERS

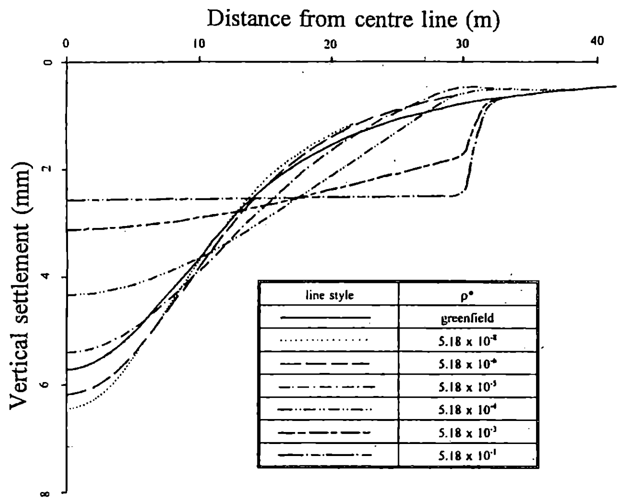
The building damage parameters adopted are deflection ratio and horizontal strain, (Boscardin and Cording, 1989, Burland, 1995). Deflection ratios for both sagging, DR_{sag}, and hogging, DR_{hog}, are defined, see Figure 3. If a point of inflection of the surface settlement trough occurs below the beam then it separates the zones of sagging and hogging. In the analysis this point was determined by interrogating the surface settlement troughs to locate the point at which the rate of change of slope of the trough changed sign. The horizontal strain, ε_h, is obtained directly from the computer output and is the maximum horizontal strain of the neutral axis of the beam and therefore of the structure the beam represents. By referring the strain to the neutral axis any effects of bending are eliminated.

When presenting the results from analyses with a surface structure comparisons will be made with greenfield predictions. It is therefore convenient to define the following modification factors for deflection ratio;

$$M^{DR_{sag}} = \frac{DR_{sag}}{DR^g_{sag}} ; \quad M^{DR_{hog}} = \frac{DR_{hog}}{DR^g_{hog}} \qquad (2)$$



(a) Effect of α^* for $\rho^*=0.518$



(b) Effect of ρ^* for $\alpha^*=48.6$

Figure 2: Surface settlement troughs for Z=20m, B=60m, e=0

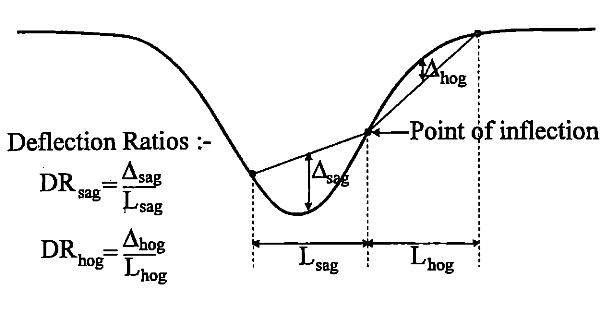


Figure 3: Definition of deflection ratios

where DR^g_{sag} and DR^g_{hog} are the deflection ratios for that portion of the greenfield settlement trough which lies directly beneath the structure. The modification factors for the maximum compressive and tensile horizontal strains are defined as;

$$M^{\varepsilon_{hc}} = \frac{\varepsilon_{hc}}{\varepsilon^g_{hc}}; \qquad M^{\varepsilon_{ht}} = \frac{\varepsilon_{ht}}{\varepsilon^g_{ht}} \qquad (3)$$

where ε^g_{hc} and ε^g_{ht} are the maximum horizontal compressive and tensile strains of the ground surface for that portion of the greenfield settlement trough which lies directly beneath the structure.

6. DESIGN RECOMMENDATIONS

A design approach is proposed here which aims to predict the likely damage to an existing surface structure located above a new tunnelling operation. The approach is based on the results of the parametric study, Potts and Addenbrooke (1996), and the established methods for greenfield ground movement prediction and building damage category assessment.

In outline, the greenfield surface settlement and horizontal ground movements are established from the geometry of the tunnelling problem (its depth and diameter) and the assumed volume loss during construction without reference to any surface structure. The position of the existing surface structure is then considered. Over the region of the ground surface beneath the structure the settlement and horizontal movements are used to calculate the maximum hogging and sagging deflection ratios, and the maximum compressive and tensile strains. These are the greenfield values of the building damage parameters. The bending and axial stiffness of the structure relative to the soil stiffness is calculated. As a first estimate the engineer could consider the contribution to stiffness of the foundation alone, before considering the independent or coupled contributions to bending and axial stiffness of slabs, beams, columns and load bearing walls. Design curves, based on the numerical analyses presented by Potts and Addenbrooke (1996), are then employed to obtain modification factors for sagging and hogging deflection ratio, and compressive and tensile horizontal strain which correspond to the relative axial and bending stiffness calculated. These modification factors are then applied to the previously calculated greenfield values of deflection ratio and horizontal strain. The newly obtained combinations of modified deflection ratio and horizontal strain imposed on the structure (in the sagging and hogging regions of the settlement trough) are used to estimate the likely building damage category and classification.

The key steps in this approach are now considered in more detail.

(i) Greenfield Ground Movement Predictions

In design it is common to assume that the transverse ground surface settlement trough caused by tunnel construction is given by a normal Gaussian distribution curve of the form;

$$S = S_{max}.e^{\left(\frac{-x^2}{2.i^2}\right)} \qquad (4)$$

where S is the surface settlement at a horizontal distance, x, away from the tunnel centre line, S_{max} is the surface settlement above the tunnel centre line and i is the horizontal distance from the centre line of the tunnel to the point of inflection of the settlement trough. The volume of the settlement trough given by equation 4 is;

$$V_s = (2\pi)^{0.5}.i.S_{max} \ \ per\ unit\ length \qquad (5)$$

Excavation for a tunnel in clay is likely to take place relatively quickly and therefore there is unlikely to be any volume change of the clay. This implies that the volume of the surface settlement trough will be equal to the difference between the volume of soil excavated and the theoretical volume of the tunnel. The volume loss, V_l, can therefore be written as;

$$V_l = \frac{4.V_s}{\pi.D^2} \qquad (6)$$

Combining equations 4 to 6 gives the following expression for the surface settlement trough;

$$S = \frac{0.313\ V_l\ D^2}{i}\ e^{\left(\frac{-x^2}{2i^2}\right)} \qquad (7)$$

The associated horizontal ground movements can be found by assuming that the resultant vectors of ground displacement are directed towards the tunnel axis. This gives:

$$h = \frac{x.S}{Z} \qquad (8)$$

For these equations to be used it is necessary to establish values of V_l and i. Various empirical relationships are available which relate i to the tunnel diameter D and its depth below ground level Z. One such relationship is that given by Rankin (1988) and takes the form;

$$i = 0.5Z \qquad (9)$$

For a given tunnel geometry it is therefore only necessary to specify the volume loss, V_l, for the ground surface movements to be calculated. The volume loss depends on the ground conditions and the type of construction method used to excavate the tunnel.

(ii) Greenfield Building Damage Parameters

The profiles of settlement and horizontal ground movement which lie directly beneath the position of the existing surface structure must be isolated from the entire greenfield prediction. That is the portion of the greenfield settlement trough that is located between the x coordinates of the two ends of the surface structure must be extracted. If this contains the point of inflection, then this is taken as defining the point of transition from sagging deformation to hogging deformation. The maximum values of sagging and hogging deflection ratio are then calculated, see Figure 3. If the structure does not span the point of inflection of the greenfield curve then only a sagging or hogging mode of deformation is appropriate.

The horizontal strains at the ground surface can be found by differentiating equation 8 with respect to x, giving:

$$\varepsilon^g{}_h = \frac{0.313\ V_l\ D^2}{i\ Z}\ [1-(\frac{x}{i})^2]\ e^{\left(\frac{-x^2}{2i^2}\right)} \qquad (10)$$

It should be noted that the point of inflection of the settlement trough divides the regions of compressive and tensile horizontal strain; in the sagging region ($x<i$) these strains are compressive whereas in the hogging region ($x>i$) they are tensile. This equation can be used to evaluate the maximum compressive and tensile strains that occur at the location of the surface structure.

Depending on whether the structure spans the point of inflection of the greenfield settlement trough, up to four greenfield damage parameters can be established at this stage.

(iii) Relative Bending and Axial Stiffness

The relative bending and axial stiffness are calculated from Equation 1.

(iv) Modification Factors

The design curves given in Figures 4 and 5 are used to establish the modification factors for deflection ratio (hogging and/or sagging) and horizontal strain (compression and/or tension). The position of the structure relative to the centre line of the proposed tunnel divided by the width of the structure defines the eccentricity ratio e/B. Modification factors can then be read off the appropriate design curve at the position of the calculated relative stiffness.

The design curves in Figures 4 and 5 are based on the results of the parametric study, Potts and Addenbrooke (1996). They are valid for likely values of α^* (>0.5). The curves have been selected to give conservative values of the modification factors.

(v) Building Damage Assessment

The greenfield values of deflection ratio and horizontal strain are multiplied by the respective modification factors to obtain those likely to be imposed on the structure:

$$DR_{sag} = M^{DR_{sag}}.DR^{g}_{sag}; \quad DR_{hog} = M^{DR_{hog}}.DR^{g}_{hog}$$

and

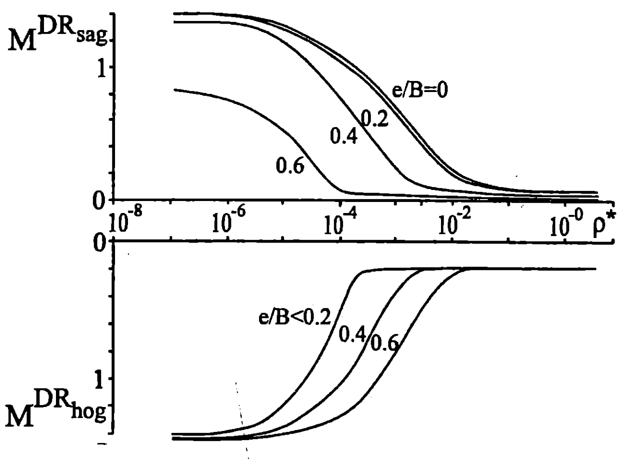


Figure 4: Modification factors for deflection ratio

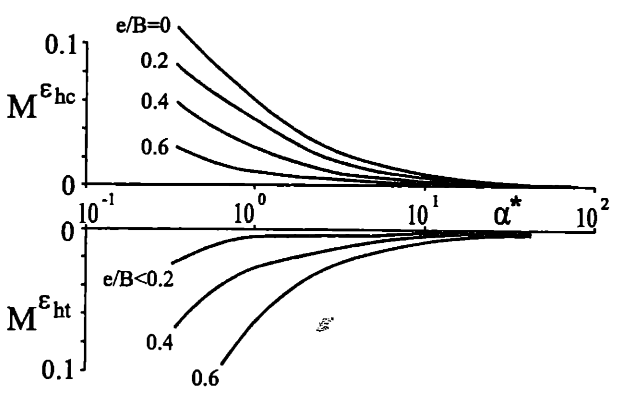


Figure 5: Modification factors for horizontal strain

$$\varepsilon_{hc} = M^{\varepsilon_{hc}}.\varepsilon^{g}_{hc}; \quad \varepsilon_{ht} = M^{\varepsilon_{ht}}.\varepsilon^{g}_{ht}$$

The combinations of sagging deflection ratio and compressive strain, and hogging deflection ratio and tensile strain can then be input into damage category charts such as that shown in Figure 6 (after Burland, 1995) to quantify the likely damage to the surface structure.

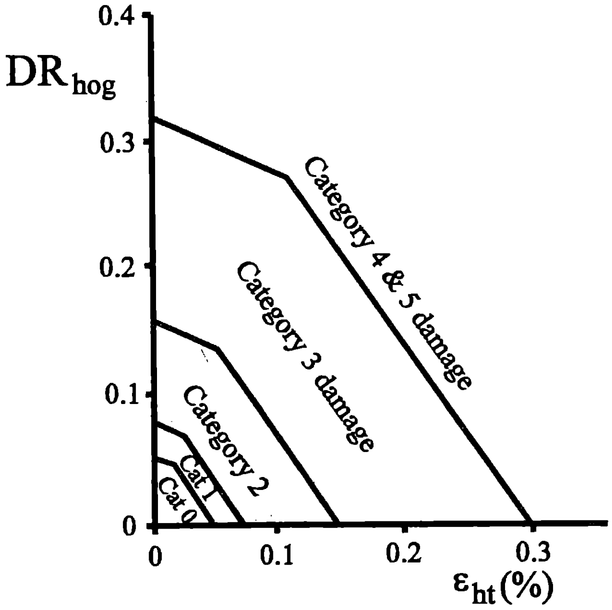


Figure 6: Relationship between damage category, deflection ratio and horizontal tensile strain for hogging (after Burland, 1995)

7. CONCLUSION

This paper has considered the influence of an existing surface structure on ground movements due to tunnelling. The results show that both the axial and bending stiffness of the structure will influence the ground surface movements and that these movements can be very different to those for a greenfield site (no surface structure). The presence of a surface structure usually has the effect of reducing the ground surface movements compared to the greenfield scenario. However if the structure has a low bending stiffness but a high axial stiffness then the surface settlements can be greater than those when no structure is present. At first sight this may seem to be a surprising result but it arises because the structure imposes a restriction on lateral surface movements. Just beyond the edge of the structure high gradients of ground movement can be induced. These could have severe implications for any adjacent services.

The results of a parametric study involving some 100 nonlinear finite element analyses have been used to construct design charts which can be introduced into the building damage assessment process. These curves enable the engineer to predict more accurately the likely damage to an existing structure resulting from tunnelling beneath it, by taking account of the soil/structure relative stiffness in both bending and lateral straining. The two stiffness parameters which have been introduced are the relative bending stiffness, ρ^*, and relative axial stiffness, α^*. The design curves give values of modification factors for deflection ratio and for horizontal strain. These indicate by how much the structure modifies the greenfield predictions of the relevant damage parameter. For example the results show that for likely values of relative axial stiffness, horizontal strains are not expected to exceed 10% of those calculated for a greenfield situation.

The numerical parametric study on which the design curves are based included a wide range of ρ^* from 5.18×10^{-8} to 5.18×10^{-1} and a recommended likely range of $\alpha^* > 0.5$. The analysis of soil/structure problems falling outside of these ranges will therefore require careful consideration of the applicability of the design curves. When an assessment indicates a damage category giving cause for concern, and in the case of especially sensitive structures, individual and more detailed analysis will be required, possibly including site specific numerical analysis.

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