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Ground movement estimation for underground box structures: Movements at corners

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ABSTRACT: When assessing the feasibility of underground construction works impact assessment is usually undertaken in the first instance employing empirical means for the determination of excavation-induced ground movements as part of the widely-accepted 3-stage procedure for potential impact assessment. Ground movements generated by the excavation of boxes and shafts are predicted using an empirical approach validated by data from case studies of similar excavations. Vertical and horizontal ground movements are estimated on the basis of conservative greenfield assumptions. For box excavations, ground movement depends on the depth of the excavation and support system stiffness. The values for settlement at the wall and the extent of the settlement trough are expressed as functions of the support system stiffness and the excavation depth. One of the key limitations of the current approaches is the estimation of ground movements around the corners of box excavations. The increased stiffness evident at the corners of box structures should result in reduced excavation-induced ground movement behind the embedded retaining walls in these zones; field measurements support this assertion, the observations of wall deformations and ground movements at the corners of box structures being lower than elsewhere within the footprint of the box. However, this beneficial effect is largely ignored in the initial phases of the impact assessment process; the assumption that the ground movements are constant around corners is commonly made. A methodology for incorporating the reduction in ground movement evident behind the corners of box structures is presented in this paper. The use of this methodology in conjunction with other complementary empirical methods allows for more informed decision-making and early discussion with affected Third Parties whose approval will be sought as part of project implementation.

1 INTRODUCTION

When assessing the feasibility of underground construction works impact assessment is usually undertaken in the first instance employing empirical means for the determination of excavation-induced ground movements as part of the widely-accepted 3-stage procedure for potential impact assessment (Mair et al., 1996). In this procedure an increased level of rigour is applied at each stage of the assessment process.

Initially, ground movements generated by the excavation of boxes and shafts are predicted using empirical approaches validated by data from case studies of similar excavations. Vertical and horizontal ground movements are estimated on the basis of conservative greenfield assumptions.

In the UK such empirical ground movement estimation procedures are largely based on the case histories of box and shaft excavations in stiff clays presented in CIRIA C580; most of the data available relate to excavations within London Clay.

One of the key limitations of the current approaches for box excavations is the estimation of ground movements around the corners of such structures. The increased stiffness evident at the corners of box structures should result in reduced excavation-induced ground movement behind the embedded retaining walls in these zones; field measurements support this assertion (Burland and Hancock, 1977), the observations of wall deformation and ground movement at the corners of box structures being lower than elsewhere adjacent to the footprint of the box. However, this beneficial effect is largely ignored in the initial phases of the impact assessment process; the assumption that the ground movements are constant around corners is commonly made.

Much work has been undertaken investigating the differences between plane strain, axisymmetric and three-dimensional (3D) predictions of the ground movements induced by box excavation (for example Zdravkovic et al., 2005). Some of this work has also considered the excavation-induced ground movements at the corners of boxes (for example Ou and Shiau, 1998 and Fuentes and Devriendt, 2010). A method for determining the excavation-induced ground movements around the corners of boxes has been proposed by London Underground Limited (LUL, 2009) based on experience gained during the construction of the High Speed 1 railway line in the UK.

2 GROUND MOVEMENT DUE TO BOX CONSTRUCTION

For boxes, the ground movement induced by excavation is considered to be dependent upon the depth of the excavation and support system stiffness. The geometry of the box footprint can also be important. The deformation profile induced by a box excavation generally assumes either a spandrel or concave shape depending upon the nature of the deflected profile of the retaining wall.

The spandrel deformation profile (Figure 1) occurs where the magnitude of the initial wall deflection is greater than during subsequent stages of excavation; it can also occur where the retaining wall displays a cantilever-type of deflection profile. In such deformation profiles the maximum surface settlement occurs very close to the wall.

As shown in Figure 2 the concave deformation profile occurs where the retaining walls of the box are restrained during the initial stages of excavation; it can also occur when the magnitude of the initial wall deflection is less than during subsequent stages of excavation to depth or there is additional cantilever-type wall deflection during these latter stages of excavation. In contrast to the spandrel type of deformation profile, the maximum surface settlement occurs for concave profiles at a distance away from the supported wall.

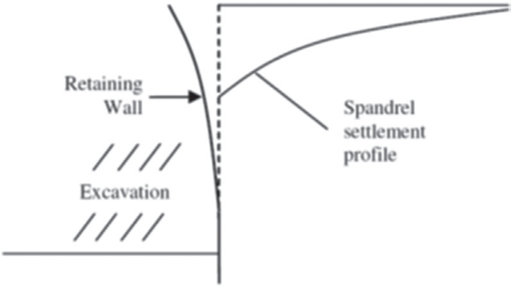


Figure 1. Spandrel type of retaining wall deflection profile.

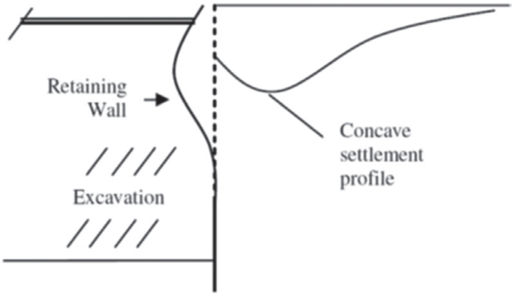


Figure 2. Concave type of retaining wall deflection profile.

In empirical formulations for estimating the ground movements induced by box excavation, the settlement trough is commonly described by the hogging zone of the inverted normal probability distribution (Gaussian) curve adopted for tunnels with the equivalent tunnel centreline inset from the box wall by a distance equal to the distance to the point of inflection of the ground surface settlement profile (GCG, 2004). An equation of the following form is used in such approaches to calculate the ground surface settlements anticipated from box excavation, assuming a variation of settlement from a maximum at the wall of the box to a minimum at a distance W from the wall.

$$S_v = \delta_v e^{\left[\frac{1}{2}-\frac{1}{2}\left(1+\frac{1.5y}{W}\right)^2\right]} \tag{1}$$

where:

S_v = the settlement due to the box construction [mm];

δ_v = the settlement at the wall face of the box [mm];

y = the distance from the outer wall of the box [m], and

W = the extent of the settlement trough [m].

The values for settlement at the wall (δ_v) and the extent of the settlement trough (W) are expressed as functions of the support system stiffness, i.e. 'high stiffness', being top down or multi-prop, and 'low stiffness', being cantilever or single prop solutions, and the excavation depth (Z).

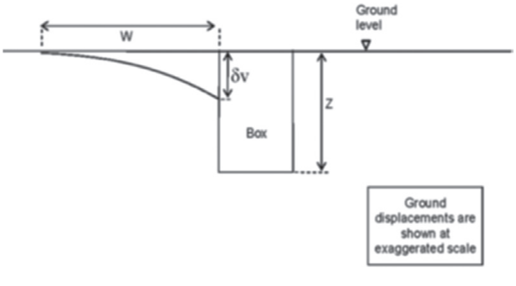


Figure 3. Surface settlement profile due to box excavation.

Figure 3 illustrates the assumed ground surface settlement profile and input parameters for modelling box excavations in this manner.

The corresponding horizontal movement is defined by the following equation:

$$S_h = s\left(\frac{\delta_h}{\delta_v}\right)\left(1+\frac{1.5y}{W}\right) \tag{2}$$

where

S_h = horizontal movement due to the box/shaft construction [mm]

s = settlement at a distance y from the outer face of the box [mm]

δ_h = horizontal movement at the outer face of the wall [mm], and

δ_v = settlement at the outer face of the wall [mm]

Whilst this approach provides an accurate representation for the spandrel type of wall deflection profile it is not suitable for the concave type of wall deflection profile. This paper is concerned only with the concave type of deformation profile; this profile is the one most likely to be encountered for box construction in congested urban environments.

As shown in Figure 4, Hsieh and Ou (1998) proposed a tri-linear curve to describe the vertical ground surface movement resulting from a concave deformation profile. In this method the surface settlement at the wall is assumed to be equal to half the maximum surface settlement; the maximum surface settlement is assumed to occur at a distance of half the excavation depth from the wall. The surface settlement reduces to about 10% of the maximum at a distance of about twice the excavation depth away from the wall; at a distance of about four times the excavation depth away from the wall the surface settlement is negligible.

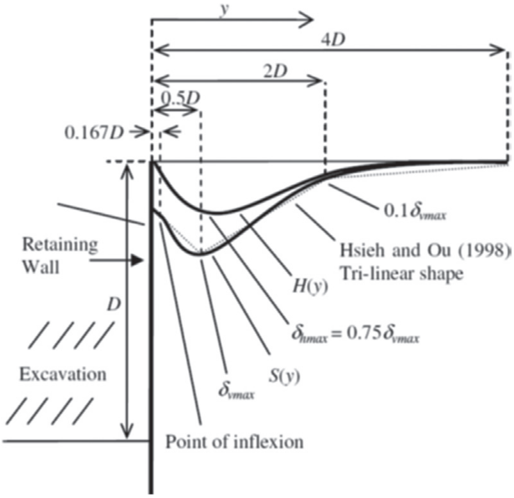


Figure 4. Hsieh and Ou tri-linear shape for the concave settlement profile.

The corresponding vertical ground surface movement profile can be described approximately through the adoption of a normal (Gaussian) distribution curve as in the prediction of ground surface movement due to the excavation of a tunnel. In contrast to the conventional approach where the centreline of the equivalent tunnel is located through the centre of the box footprint, in this approach the location of the equivalent tunnel is move to the edge of the box footprint.

However, it is not possible to fit a single Gaussian curve through all the points defined by Hsieh and Ou (1998). The curve is split into two parts: the first part of the curve covers the zone $0 \le y < 0.5D$ with the second part of the curve covering the zone $0.5D \le y \le 4D$, where y is the distance from the edge of the embedded retaining wall. Both parts of the curve are adjusted through factors to fit the tri-linear shape of the deformed profile.

Hsieh and Ou (1998) did not explicitly define the corresponding horizontal movement profile but they did indicate that, in general, the maximum ground surface settlement is between 0.5 and 0.75 of the maximum lateral wall deflection.

In formulating the horizontal movement profile it has been assumed that the maximum horizontal movement is equal to 0.75 of the maximum ground surface settlement; the horizontal movement at the wall is also assumed to be zero.

$$H(y) = \kappa(y/D)S(y) \tag{3}$$

where $\kappa = 0.387$.

A limitation of the methods described above is that corner effects are excluded.

3 MOVEMENT AROUND THE CORNERS OF BOX EXCAVATIONS

In impact assessment work it is important to realistically estimate how the corners of an excavation will influence the distribution of the settlement. In general, the corners of an excavation tend to restrict movement (Burland and Hancock, 1977); however, the movements from walls at re-entrant corners may superimpose to give larger movements than for a straight wall.

An approach, the *walls method*, has been developed to enable the modelling of individual walls that can be used to create a box rather than defining boxes and their associated walls, thus addressing the issue of corner restraint, where a concave deformation profile is anticipated, i.e. a multi-propped excavation. Typically when modelling a box excavation it consists of all the wall elements that make up that box, whereas in the *walls method* the box is broken up into individual elements with subsequent superposition of settlement. In allowing for superposition of settlement in closed corners and natural end effects more realistic movements are obtained, which are comparable with published case histories.

The *walls method* combines the transverse settlement profile for box excavation-induced ground movement after Hsieh and Ou (1998), as described in Section 2, with the corresponding forward trough associated with tunnel excavation. A concave curve is used that approximates to the shape proposed by Hsieh and Ou (1998), and is described by the formula:

$$S_v = \delta_v e^{\left(\frac{-0.5}{\sigma(x)^2}\right)(x-0.5)^2} \tag{4}$$

where

δ_v = the maximum settlement occurring a distance z/2 from the wall;

z = the excavation depth for the particular wall [m];

$\sigma(x) = 0.425 + 0.55(\phi(x) - 0.5)$;

$\phi(x)$ = the cumulative normal distribution function.

Transversely, the method employs an asymmetrical Gaussian curve (actually comprising three separate Gaussian curves for the various sections of the concave curve including a 'fictitious' section within the box) produced through the incorporation of an equivalent tunnel in the model, the centre of which is located a distance z/2 from the wall and an invert depth equal to the excavation depth of the box. On the wall side of the tunnel centerline, a value for the horizontal offset to the point of inflexion of the Gaussian curve, i, of approximately 0.425z is assumed; on the other, box side of the tunnel an i value of 0.7z is assumed These values were determined through a process of trial and error in order to obtain the best fit to the Gaussian curve. This creates a settlement profile very similar to the concave shape after Hsieh and Ou (1998). The horizontal movements are modelled in the same way as for the concave curve for boxes and open excavation.

A comparison has been made between the measured surface settlements from the House of Commons Car Park, New Palace Yard, Westminster (after Burland and Hancock, 1977) and those generated for this box excavation geometry using the walls method. The underground car park at the House of Commons comprises an approximately 50 m by 66 m box in plan, about 18.5 m deep. The walls of the box comprise reinforced concrete diaphragm walls which were strutted at all stages of excavation and construction by the permanent reinforced concrete floors of the car park, i.e. a top-down construction methodology was adopted. The works were comprehensively instrumented and it represents one of the few case histories where the movements around the corner of a box have been captured.

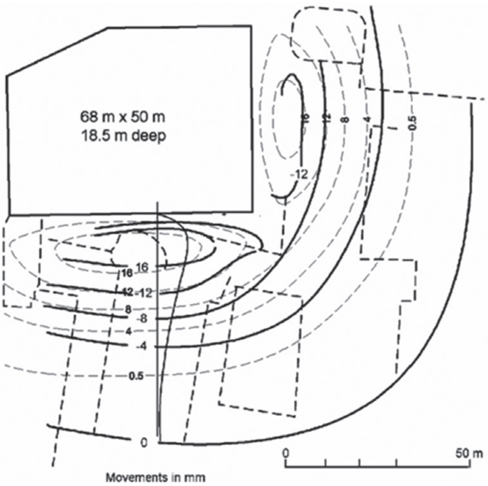


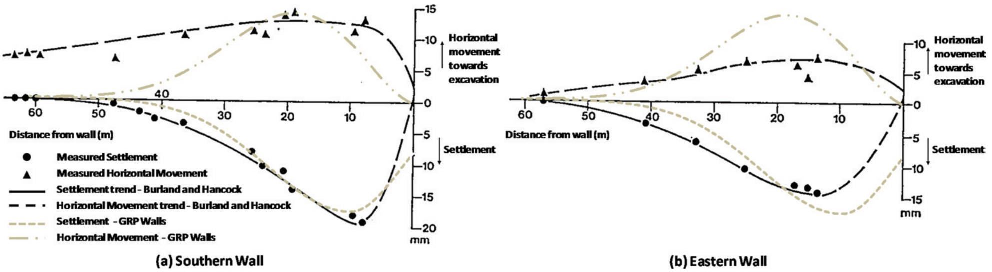
Figure 5. Ground surface settlement contours at New Palace Yard—observed and predicted.

As shown in Figure 5 there is generally good agreement between the observed movements on completion of box excavation and the Class C1 predictions (Lambe, 1973); the observed movements are represented by the solid lines in the figure. In the predictions a value for δ_v/Z of 0.1% has been assumed.

The corresponding vertical and horizontal ground movement profiles through the southern and eastern walls of the House of Commons Car Park box on completion of box excavation are shown in Figure 6. The profiles for the southern wall presented in Figure 6a show relatively good agreement between observed and predicted movements. For the eastern wall profiles given in Figure 6b the predicted movements overestimate the observed movements somewhat.

4 DISCUSSION

The benefits in terms of ground movement estimation in considering the stiffening effect of the corners of boxes as presented in the walls method in this paper has been implemented into Stage 2 of the potential impact assessment process. In Stage 3 of the impact assessment process the benefit of



(a) Southern Wall

(b) Eastern Wall

Figure 6. Observed and predicted vertical and horizontal movements at the end of box excavation – (a) Southern Wall, (b) Eastern Wall, New Palace Yard.

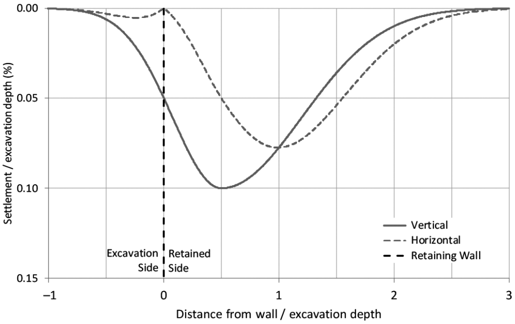


Figure 7. Normalised ground surface settlement due to box excavation using the *Walls Method*.

considering corner effects should be considered through numerical analysis parametric studies.

The use of this methodology in conjunction with other complementary empirical methods as part of the widely-accepted 3-stage procedure for potential impact assessment (Mair et al., 1996) allows for more informed decision-making and early discussion with affected Third Parties whose approval will be sought as part of project implementation.

A key advantage of the *walls method* is that it avoids steps in the movement/strain profiles around the corner. It also provides the opportunity to study the movements/strains around re-entrant corners. However, a drawback with the *walls method* is that 'fictitious' settlement on the excavation side of the wall can be generated. Figure 7 shows the settlement profile normalised with depth; ground movement is generated on both sides of the retaining wall being considered. For wide excavations this has little effect, but for narrow excavations additional settlement will be predicted. This can be allowed for by the designer by only including the walls in the assessment model that directly impact on the asset being assessed.

Although the method is straightforward to implement, either via spreadsheets or simple programs, the authors acknowledge that the method requires further calibration, particularly against cases studies for excavation in ground conditions other than stiff clay, before more definitive conclusions can be reached. However, initial results are encouraging.

5 CONCLUSIONS

In the initial stages of the widely-accepted 3-stage procedure for potential impact assessment empirical means validated by appropriate case history data are usually employed in the determination of excavation-induced ground movements. Vertical and horizontal ground movements are estimated on the basis of conservative greenfield assumptions.

One of the key limitations of the current approaches is the estimation of ground movements around the corners of box excavations. The increased stiffness evident at the corners of box structures should result in reduced excavation-induced ground movement behind the embedded retaining walls in these zones; field measurements support this assertion, the observations of wall deformations and ground movements at the corners of box structures being lower than elsewhere within the footprint of the box. This beneficial effect is largely ignored in the initial phases of the impact assessment process; the assumption that the ground movements are constant around corners is commonly made.

A methodology for incorporating the reduction in ground movement evident behind the corners of box structures in empirical ground movement estimations has been presented in this paper; the movements determined using this approach for the New Palace Yard case history (Burland and Hancock, 1977) have been shown to be in good agreement with the observed movements.

The use of this methodology in conjunction with other complementary empirical methods as part of the widely-accepted 3-stage procedure for potential impact assessment (Mair et al., 1996) allows for more informed decision-making and early discussion with affected Third Parties whose approval will be sought as part of project implementation.

Although these initial results are encouraging, it is acknowledged that the method requires further calibration before more definitive conclusions can be reached.

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