

Empirical prediction of horizontal movements induced by tunnelling in fine-grained soils

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Abstract

Available evidence indicates that the focal depth of displacement vectors along the ground surface decreases with the transverse distance from the tunnel centre-line. Based on field and centrifuge observations, this paper presents a new empirical method in which the focal depth is a function of the transverse offset and, possibly, the tunnel volume loss. The comparison with experimental data from centrifuge experiments and case histories confirms the reliability of the proposed method, in terms of both surface horizontal displacements and strains. In particular, the predicted horizontal displacement profiles, both in terms of maximum value and extension, are in better agreement with the available experimental evidence than those obtained using the empirical and analytical methods currently adopted in design. Finally, an operational way to obtain the complete horizontal displacement field at the surface, near-surface, and at depths down to the tunnel crown is suggested and the importance of carrying out field monitoring for surface and subsurface horizontal displacements is highlighted.

Notation

D	tunnel diameter
H	depth below ground surface of focus of surface displacement vectors
h	normalised depth of focus of surface displacement vectors
h^*	average normalised depth of focus of surface displacement vectors within $x \pm i$
$h_{\max}$	maximum normalised depth of focus of surface displacement vectors
i	transverse distance between tunnel centre-line and point of inflection of settlement trough
K	settlement trough width parameter
u	horizontal ground movement in x direction
V_L	tunnelling volume loss
w	ground settlement
$w_{\max}$	maximum ground settlement at given depth z
x	transverse distance from tunnel centre-line
z	depth below ground level
z_t	depth of tunnel axis
ρ	relative ovalisation

1 Introduction

The excavation of new tunnels results in ground movements affecting surface and buried infrastructure. For risk assessments, engineers need to estimate the magnitude and distribution of greenfield displacements (Mair and Taylor 1997). In particular, existing near-surface assets such as, e.g., masonry buildings on unreinforced strip footings as well as bridges and frames on separate footings may be critically affected by the pattern of shallow horizontal movements (Mair et al. 1996). For tunnels excavated in fine-grained soils, settlements can increase with time due to the dissipation of tunnelling-induced excess pore water pressures and the change in the hydraulic conditions at the tunnel internal boundary, where pore pressures are equal to zero. However, past studies (e.g. O'Reilly et al. 1991; Bowers et al. 1996; Soga et al. 2017) found that, in the long term, the build-up of horizontal displacements and strains during consolidation are much smaller than those induced by short-term tunnel excavation and that further building damage is unlikely to occur. Therefore, in this paper, focus is placed on short-term, undrained movements only, also considering that the dearth of monitoring data on long-term tunneling-induced horizontal displacements would not support the derivation of empirical relationships. Starting from observed displacements near the ground surface, an empirical method is proposed for an improved estimate of short-term tunnelling-induced horizontal greenfield movements in fine-grained soils, by considering the variation of the focal depth of the displacement field with transverse distance from the tunnel axis. Finally, an operational approach for the estimate of near-surface movements from the interpolation of two empirical approaches is evaluated.

2 Background

The observed short-term transverse greenfield settlements w caused by tunnelling in fine-grained soils are empirically well-described, both at the surface and at depth, by a Gaussian curve:

$$w = w_{\max} \exp\left(-\frac{x^2}{2i^2}\right) \quad w_{\max} = \sqrt{\frac{\pi}{32}} \frac{V_L D^2}{i} \quad (1)$$

where $w_{\max}$ is the maximum settlement at the tunnel axis at any given depth z , x is the transverse distance from the tunnel axis, V_L is the volume loss, D is the tunnel diameter and i is the distance of the inflection point of the settlement trough from the tunnel axis. To use Equation 1 for design predictions, the values of the numerical parameters defining, e.g. the expected trough width at surface and its variation with depth, must be assigned based on the available experimental evidence collected for similar ground conditions and construction techniques. While the measurement of tunnelling-induced vertical displacements at surface is

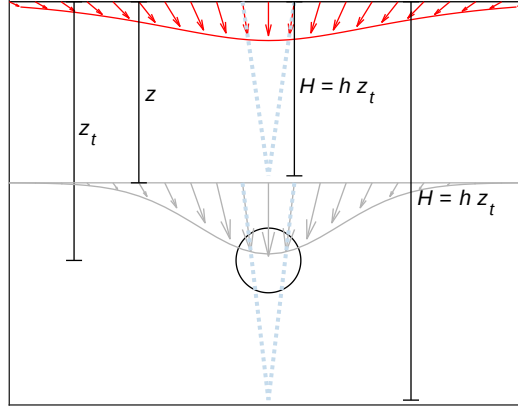


Fig. 1. Depth of focus of tunnelling-induced displacements for surface and subsurface horizon

routinely carried out, well-documented field observations of horizontal ground movements and, more generally, of displacements at depth are not very common, and therefore their empirical prediction is based on somewhat arbitrary assumptions. In fine-grained soils, it can be reasonably assumed that V_L is constant with depth, whereas i , and hence $w_{\max}$, are generally taken to be functions of depth. Empirical formulas for horizontal ground movements u are less well established. As shown in Figure 1, assuming that the greenfield displacement vectors at any depth z are directed towards a common focus located along the centre-line at a depth H , the horizontal displacement u of a point at depth z and distance x from the tunnel axis is:

$$u = -\frac{x}{H-z}w = -\frac{x}{h z_t - z}w \quad (2)$$

where z_t is the tunnel depth and $h = H/z_t$ is the normalised depth of the focus. O'Reilly and New (1982) proposed that, for tunnelling in clays, displacement vectors converge towards the tunnel centre, i.e. $h = 1$. For this to be valid under constant volume conditions, the trough width parameter $K = i/(z_t - z)$ has to be constant with depth (Mair and Taylor 1997). However, using field and centrifuge data, Mair et al. (1993) proposed that the variation of the subsurface trough width parameter K may be expressed as:

$$K = \frac{0.175 + 0.325(1 - \frac{z}{z_t})}{1 - \frac{z}{z_t}} \quad (3)$$

Grant and Taylor (2000) showed that, if a unique focal point exists at any depth z , to satisfy undrained conditions, this must be at the intersection between the vertical line through the tunnel axis and the tangent to the profile of trough width i with depth. Moreover, their experimental observations indicated that the distribution of i with depth z is nonlinear close to the surface and linear at greater depths, and that the depth of the focus varies

with distance from the tunnel axis at shallow depths. In particular, from centrifuge measurements, [Grant and Taylor \(2000\)](#) concluded that, at depths $z/z_t \geq 0.2$, Equations (1)-(3) predict w and u well, with a constant vector focus located at a depth of $H = 1.54z_t$, i.e. $h = 1.54$. On the other hand, at shallower depths ($z/z_t < 0.2$), the focal depth H is above the tunnel axis (i.e. $h < 1$). Interestingly, the analytical methods of [Loganathan and Poulos \(1998\)](#) and [González and Sagaseta \(2001\)](#) which are frequently used in research and practice for predicting undrained tunnelling-induced ground movements give a displacement field with a constant value of $h = 1$ across horizons at any depth.

Currently, w and u at the surface are often predicted assuming $K = 0.5$ and $h = 1$ with Equations (1)-(3). However, Equation 2 with $h = 1$ and constant with x leads to profiles of horizontal displacement u that are narrower than field evidence suggests, as will be discussed later. This design approach is inconsistent with case histories and centrifuge data that clearly indicate a reduction of h with x , with the focus of the vector of displacements shifting upwards as the transverse distance from the centre-line increases ([Grant and Taylor 2000](#); [Wan et al. 2017a](#)). [Lin et al. \(2024\)](#) back-analysed the field observations reported by [Deane and Bassett \(1995\)](#) and [Wan et al. \(2017b\)](#) and proposed an expression for H as a function of depth z . However, no attempt was made to differentiate between the different tunnel depths in the case histories or to address the variation of H with offset distance x .

To address the shortcomings of adopting a depth of the focus of displacement vectors constant with depth and with the transverse distance from the tunnel axis, the depth of focus close to the ground surface are studied in this paper.

3 Case histories studied

This section presents the dataset used for the proposed empirical method. Table 1 summarises case histories and experimental results of tunnels excavated in clay, along with empirically or analytically calculated focal depths.

Five case histories were considered for excavations in fine-grained soils. [Deane and Bassett \(1995\)](#) documented, for the Heathrow Express project, monitoring data at a station tunnel of 9 m width which was used as a trial tunnel. The stratigraphy consisted of 2 m of made ground, 2-4 m of Terrace Gravels and at least 45 m of London Clay. The tunnel was excavated using NATM. Three excavation phases were explored: (i) two side headings followed by removal of central core, (ii) one full side heading followed by enlargement and (iii) top heading and bench approach. The monitoring data from the last (Type 3) construction sequence were considered in this study, as symmetric construction makes straightforward data interpretation. For horizontal displacements, only readings recorded by inclinometers located at four distinct locations were reported. [Nyren et al. \(2001\)](#) monitored twin running tunnels for the Jubilee Line Extension (JLE) constructed at St James's

Park, where the westbound tunnel passed below the instrumented greenfield section 8.5 months before the eastbound tunnel. Excavation was carried out by an open-face tunnel boring machine (TBM) with a mechanical excavation arm in stiff London Clay. The soil above the tunnel axis consisted of 13 m of made ground, sands and gravels, underlain by 11.5 to 22 m of London Clay. Ground surface settlement measurements were made by precision levelling using standard BRE monitoring plug and total station using reflective prisms. Horizontal surface movements were measured using both a micrometer stick and total stations. Withers (2001) documented a case history for the JLE tunnels that were excavated using earth pressure balance TBMs at the Southwark Park area. The site consisted of 6.7 m of made ground, sands and gravels, underlain by 13.7 m of the Lambeth Group deposits. In this case, the tunnel invert was in silty fine and medium sand. Settlements were measured using precision levelling and horizontal displacement through micrometer sticks, as in St James's Park. In the instrumented area, the westbound tunnel was constructed before the eastbound tunnel. The short-term ground settlement caused by the westbound tunnel excavation was deducted from the total settlement to infer the net settlement due to the eastbound tunnel alone. Wan et al. (2017a) measured movements at Hyde Park during the construction of Crossrail (now Elizabeth Line). There were 4.6 m of made ground and Terrace Gravels, underlain by about 57 m of London Clay. Earth pressure balance TBMs were used. Vertical and horizontal displacements were measured by precision levelling, total stations and micrometer sticks. Finally, settlements and horizontal movements were measured at a greenfield site east of the Porta Metronia station in Rome during the construction of Line C of the Rome Metro ("the AMA site") (Losacco and Viggiani 2020). The site consists of 17-28 m of gravelly and sandy made ground overlying layers of alluvial deposits comprising of silty sands, sandy silts and clayey silts, through which the tunnels were constructed.

Centrifuge tests by Loganathan (1999) and Grant and Taylor (2000) were carried out to measure subsurface deformation patterns from tunnel volume losses in overconsolidated kaolin clay, using plane strain model tunnels consisting of flexible linings supported by silicone oil and compressed air. Loganathan et al. (2000) performed three tests for cover-to-diameter ratios between 2 and 3; surface settlements troughs and lateral movements induced by $V_L = 0.88\%$ at an offset of approximately one tunnel diameter were considered (the influence of piles at the measurement plane was neglected). Grant and Taylor (2000) modelled a tunnel excavation in overconsolidated kaolinite clay, with measurements at $V_L = 5\%$ considered in this paper.

Table 1. Tunnelling case histories, centrifuge tests, and prediction methods reviewed

Case	Tunnel data		Surface settlement			Average	Reference
	D (m)	z_t (m)	$w_{\max}^*$ (mm)	V_L^* (%)	i^* (m)	focus h^* within $\pm i$	
FIELD MEASUREMENTS							
Heathrow Trial Tunnel §	8.74	19.25	39.3	1.3	7.11	0.85	Deane and Bassett (1995)
St James's Park (JLE †)	4.85	31	20.0	3.3	12.09	0.64	Nyren et al. (2001)
St James's Park (JLE ‡)	4.85	20.5	22.9	2.6	8.51	0.55	Nyren et al. (2001)
Southwark Park (JLE †)	4.85	20.4	3.7	0.42	8.34	0.64	Withers (2001)
Southwark Park (JLE ‡)	4.85	20.4	3.6	0.48	9.91	0.49	Withers (2001)
Hyde Park (Crossrail †)	7.1	34.54	5.4	0.44	13.38	0.52	Wan et al. (2017a)
Hyde Park (Crossrail ‡)	7.1	34.54	10.2	0.82	12.89	0.63	Wan et al. (2017a)
AMA site (Rome Metro Line C)	6.7	26.05	3.9	0.3	10.81	0.57	Losacco and Viggiani (2020)
CENTRIFUGE TESTS							
UWA, Australia	6	15	15.7	0.88	6.35	0.81	Loganathan et al. (2000)
City University, UK	5	15	88	5.0	5.3	0.78	Grant and Taylor (2000)
EMPIRICAL / SEMI-ANALYTICAL SOLUTIONS						Value of h for all x	
O'Reilly and New (1982)						1	
Taylor (1995); Mair and Taylor (1997)						1.54	
Loganathan and Poulos (1998)						1	
González and Sagaseta (2001)						1	
Notes:							
* From fitted Gaussian settlement trough, † Westbound tunnel drive, ‡ Eastbound tunnel drive							
§ NATM tunnel width = 9 m							

4 Empirical study

4.1 Proposed method

To demonstrate that near-surface displacement focal depth decreases with distance from the tunnel axis x , Figure 2 shows the measured focal depth of selected case histories normalised by the tunnel depth $h = H/z_t$. Results all indicate that the surface displacement vectors along near-surface horizons do not point towards a single point. Instead, the focal depth of displacement vectors is deepest near the tunnel centre-line, and it decreases beyond the distance of the inflection point of the settlement trough ($x = \pm i$). It becomes shallower still, as the transverse distance from the tunnel axis increases, tending nearly towards the surface beyond $x = \pm 4i$. The differences between field monitoring results of focal depth may be partly due to variations in soil properties and, as addressed later, the magnitude of the tunnelling volume loss.

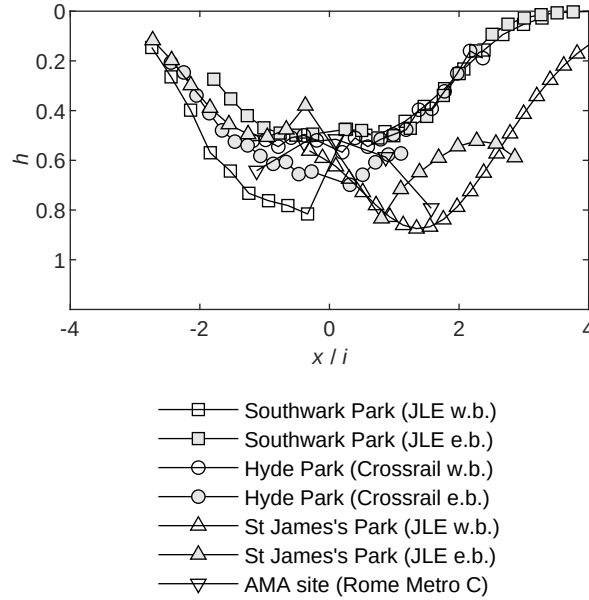


Fig. 2. Depth of focus of measured tunnelling-induced surface displacements

It is interesting that advanced numerical modelling of tunnelling-induced displacements (e.g. Addenbrooke and Potts 2001; Kovacevic et al. 2001; Venturi and Viggiani 2003; Losacco and Viggiani 2019) also indicates that, near the surface, the depth of the focal point of displacements is shallower than the tunnel axis with $h = H/z_t$ of about 0.6 within $x = \pm i$. This numerical focal depth is associated with different tunnelling scenarios: namely, Addenbrooke and Potts (2001) simulated in 2D the JLE TBM at St James's Park for a target $V_L = 3.4\%$, considering for the London Clay an elastic - perfectly plastic constitutive model with stiffness degradation; Kovacevic et al. (2001) predicted numerically ground movements for the JLE construction at Southwark Park for three different values of volume loss: $V_L = 0.5\%$, 1.2% and 2.0% ; finally, Venturi and Viggiani (2003) and

Losacco and Viggiani (2019) carried out 3D numerical analyses of TBM excavation accounting for face support pressure and the reduction of support pressure at the tail-skin of the TBM shield.

Next, the magnitude and shape of the near-surface distribution of focal depth are addressed by analysing the field measurements. In all cases, when processing data from the measurements collected, minor adjustments were made to offset the data such that the maximum vertical movement and zero horizontal movement coincides with the centre-line of the respective tunnels. Figure 3a shows h^* , the average value of h within $x = \pm i$, plotted against the volume loss on a logarithmic scale; the average value h^* was used to avoid the sensitivity of h close to $x = 0$ as a result of the near-zero horizontal displacement u . The data in Figure 3a are admittedly rather scattered: the values of h^* from the field are in the range 0.5–0.63 when $V_L < 1\%$ where there are continuous measurements across the horizon; there appears to be a gradual increase in h^* with $V_L \geq 1\%$ in the range 0.5–0.8 when the focal depth was measured at discrete transverse locations in several cases. Figure 3b shows the ratio h/h^* against the normalised offset x/i ; the shape of the relative reduction in the focal depth along the surface horizon is qualitatively similar to a Gaussian distribution.

By interpreting the measurements in Figures 3a and 3b, a novel empirical method for the prediction of surface horizontal displacements is proposed based on the assumptions that the distribution of focal depth $h/h_{\max}$ along the horizon is shaped like a modified Gaussian curve that best-fits h/h^* (which captures the observation that the greater the offset, the shallower is the focal depth), while the centre-line value of the empirical model $h_{\max}$ is taken as either an average or a semilogarithmic fit of h^* with the volume loss. This is shown in Equations (4) and (5).

$$h_{\max} = m_h \log [V_L] + q_h \quad (4)$$

$$\frac{h}{h_{\max}} = \frac{n}{(n-1) + \exp \left[\alpha \frac{x^2}{(Li)^2} \right]} \quad n = e^{\alpha \frac{2\alpha-1}{2\alpha+1}} + 1 \quad (5)$$

where m_h and q_h are the coefficients of the trendline of $h_{\max}$ with V_L , L is the ratio between the inflection offset in the $h/h_{\max}$ distribution and the inflection offset i of the w distribution, and α is a shape parameter.

Figures 3a–3b show the parameters best fitting the benchmark datasets using Equations (4) and (5); only field and experimental data were considered. Figure 3a shows both a logarithmic fit between $h_{\max}$ and V_L as well as single constant value of $h_{\max}$ fitted for all V_L . The only data that lie notably outside the 95% confidence intervals are the NATM-induced lateral movement reported by Deane and Bassett (1995) and the centrifuge results of Loganathan et al. (2000), both of which only involved horizontal displacement data at discrete offset distances from the tunnel axis and could therefore be potentially less representative. More importantly, although the semilogarithmic fit $h_{\max} = 0.15 \log[V_L] + 0.66$ indicates a moderate increase of the centre-line depth of the focal point $h_{\max}$ with volume loss, because of the significant scatter, the data may be equally well interpreted

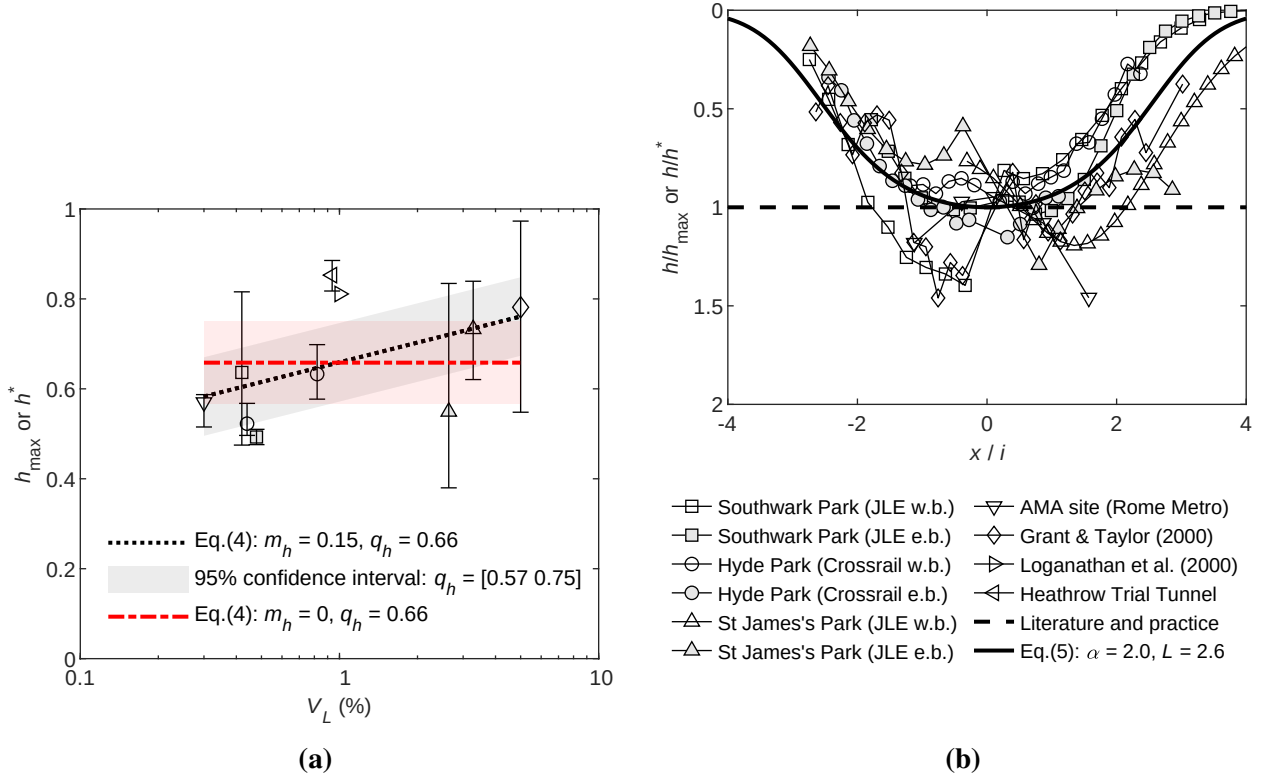


Fig. 3. Calibration of empirical model at ground surface: (a) $h_{\max}$ fitted within $x = \pm i$ for cases in Table 1; (b) $h/h_{\max}$ along surface horizon for selected cases

using a constant value of $h_{\max} = 0.66$. Next, the coefficients of the expression $h/h_{\max}$ were determined using Equation 4 for $h_{\max}$ and experimental or field results; from this, $L = 2.6$ and $\alpha = 2.0$ were obtained. Thus, the proposed empirical model adopts Equations (4)-(5) with parameters $m_h = 0.15$ or 0 , $q_h = 0.66$, $L = 2.6$ and $\alpha = 2.0$. To evaluate the practical implications of the regression parameters, the validation of the empirical method against the measured displacement data and its sensitivity to the input parameters are later analysed.

To validate the approach, Figure 4 illustrates the application of the *proposed* empirical model to several case histories: the ratio of u/w is obtained from Equations (4)-(5) with coefficients from Figure 3, while best-fitted Gaussian profiles of settlements w are used (Equations 1-2, width parameter K reported in each subplot). It follows that in the proposed method $h = f(x, i, V_L)$ or $h = f(x, i)$, depending on the fitting method used, where i is the inflection point offset of the settlement trough. Also, this figure compares the proposed approach with the *traditional* approach which adopts $h = 1$ for surface movements. The proposed expressions match satisfactorily field and experimental measurements of u over a wide range of tunnel volume loss ($V_L = 0.4$ – 5%) while overcoming the two key limitations associated with assuming near-surface focal depth at the tunnel axis ($h = 1$): viz., the under-estimation of the maximum u across the horizon and a greater fidelity of the extent of the u profile (i.e. the tunnelling-induced influence zone). Practically, the differences in horizontal movements u between empirical models with $h = f(x, i)$ and $h = f(x, i, V_L)$ are negligible. Therefore, for the sake of

obtaining a displacement field whose shape is independent of the volume loss, it is suggested that the use of the constant fit model $h = f(x, i)$ with $h_{\max} = 0.66$, $\alpha = 2$ and $L = 2.6$ can be used. A sensitivity study of these three parameters along with the trough width parameter K is later presented.

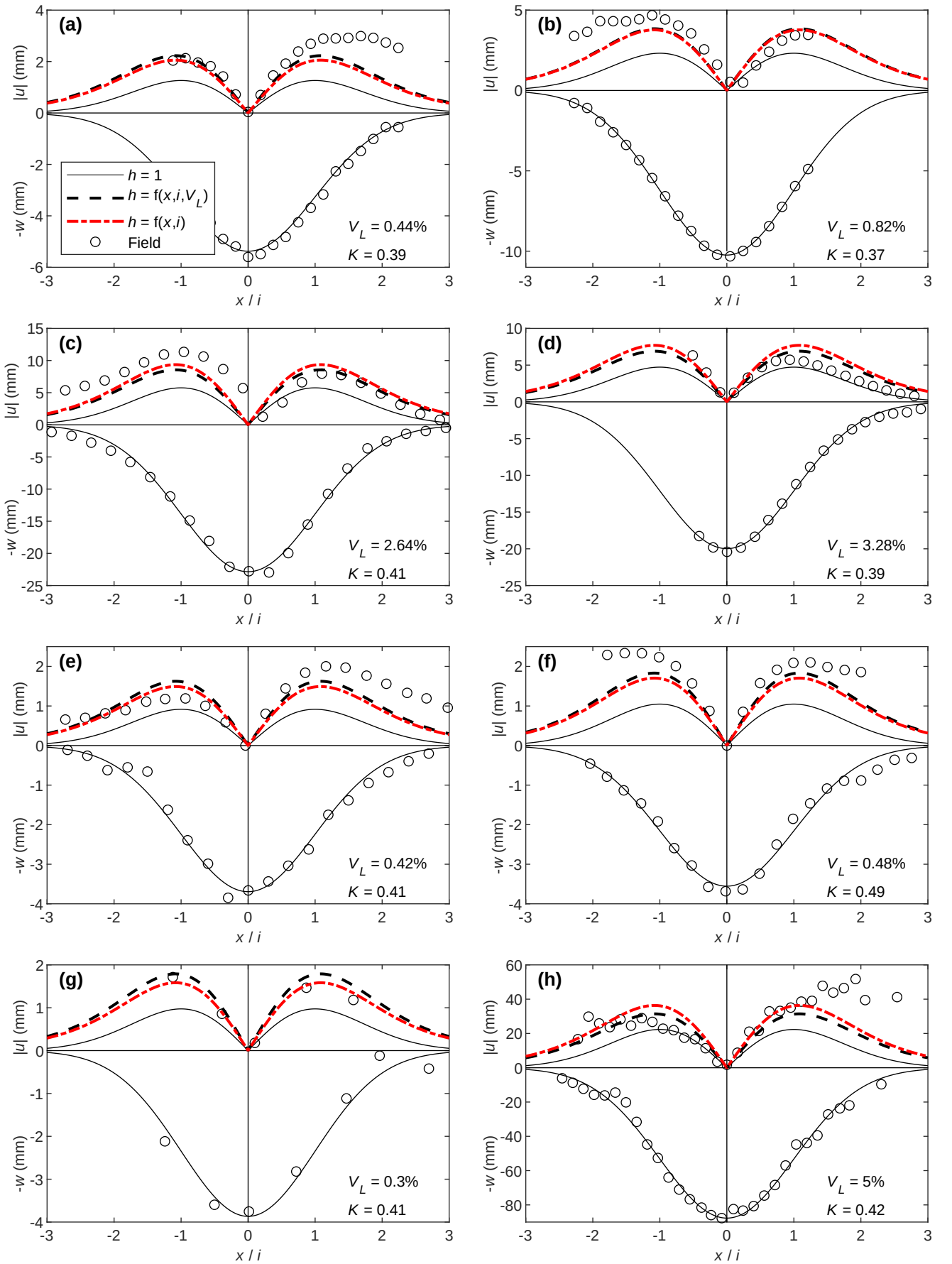


Fig. 4. Comparison of predicted and measured greenfield horizontal ground surface movements: (a) Hyde Park (Crossrail w.b.); (b) Hyde Park (Crossrail e.b.); (c) St James's Park (JLE e.b.); (d) St James's Park (JLE w.b.); (e) Southwark Park (JLE w.b.); (f) Southwark Park (JLE e.b.); (g) AMA site (Rome Metro); (h) [Grant and Taylor \(2000\)](#) centrifuge

4.2 Comparison with analytical methods

In the context of risk assessments, it is of interest to compare the proposed prediction method with analytical estimates (although seldom adopted when studying embedded foundations or buried structures) and traditional empirical distribution ($h = 1$).

For the tunnelling configurations involved in the JLE tunnel drives at St James's Park and Southwark Park, Figure 5 compares the field displacements u and w against the predictions from the traditional empirical method, analytical solutions of Loganathan and Poulos (1998) and González and Sagaseta (2001), as well the empirical approach proposed in the present study. In Figure 5, a trough width $K = 0.48$ obtained from the Jones (2010) expression was used in the empirical method. González and Sagaseta (2001) back-analysed a relative ovalisation ρ (which controls the distribution of displacements) between 0.7 and 1.0 for tunnelling cases in London Clay and Bangkok Clays; in this study, $\rho = 1$ was considered appropriate as it gives near-surface u and w consistent with the semi-analytical approach of Loganathan and Poulos (1998). Also, given that the ground tensile strain is often critical to the serviceability of buildings, Figure 6 reports horizontal strain profiles for the JLE eastbound tunnel.

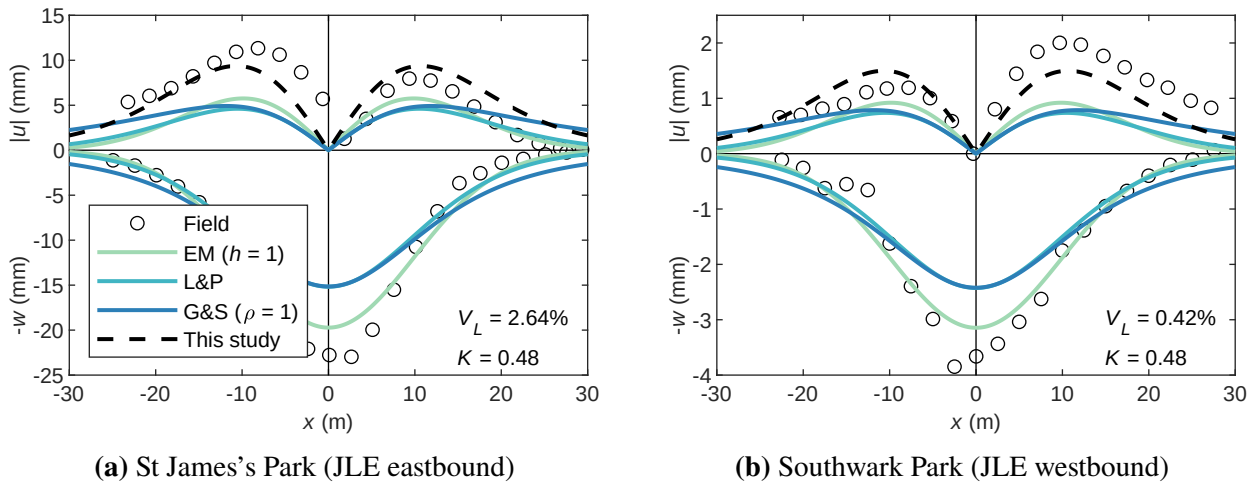


Fig. 5. Comparison of greenfield ground movement predictions

In Figure 5, although the shape of the horizontal displacement profile calculated from $h = 1$ is similar to the measured displacement profile, both the magnitude and extent of the displacements are considerably under-predicted. Similarly, both analytical methods predict wider settlement troughs that underestimate central settlements near the centre-line while the prediction of u is somewhat similar to the traditional empirical method with $h = 1$, particularly for Loganathan and Poulos (1998). On the other hand, the proposed empirical approach provides more realistic horizontal movements near the tunnel centre-line, while all other methods predict horizontal movements that are only approximately half of the measured values at the two JLE reference greenfield sites. Finally, the reliability of the proposed method is confirmed by a reasonable prediction of

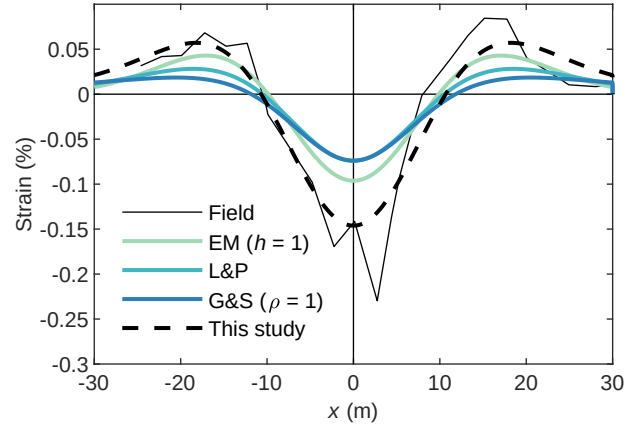


Fig. 6. Horizontal ground strain during JLE eastbound tunnel drive at St James's Park

measured maximum compressive strain directly above the tunnel and tensile strain extension in Figure 6. Although field results are inevitably imperfect, e.g. measurements on both sides of the tunnel axis were not perfectly symmetric, it is nevertheless clear from this comparison that either the traditional empirical approach with $h = 1$ or the semi-empirical methods under-predict the maximum horizontal compressive and tensile strain while giving an influence zone which is potentially too narrow.

5 Interpolation method for near-surface movements

Thus far this study has focused on surface movements. However, there is often the need to estimate near-surface u between $z/z_t = 0$ and 0.2 . To enable this, an *interpolation method* for empirical focal distances is tested that interpolates between (i) the above proposed method of calculating $h = f(x, i, V_L)$ at the surface ($z/z_t = 0$) and (ii) with the empirical approach of [Grant and Taylor \(2000\)](#) for subsurface movements ($h = 1.54$) when $z/z_t \geq 0.2$ (for all x and V_L). The case history of Crossrail by [Wan et al. \(2017b\)](#) is used for illustration, given the availability of distributed subsurface measurements. Figure 7 compares field measurements of the subsurface u detected along verticals by tilt sensors at Hyde Park and empirical predictions. Field measurements confirm the applicability of assuming $h = 1.54$ below a depth of about $0.2z_t$, as suggested by centrifuge tests from [Grant and Taylor \(2000\)](#). Also, in the range $z/z_t = 0-0.2$, the proposed interpolation method reasonably predicts subsurface horizontal displacements and outperforms $h = 1$, which underestimates surface horizontal movements.

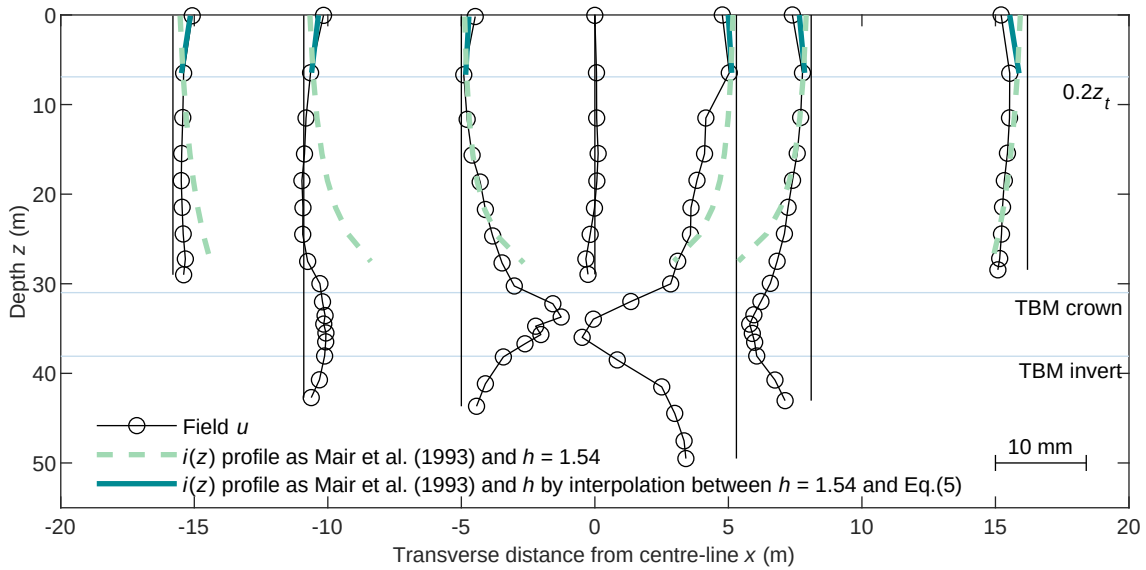


Fig. 7. Subsurface horizontal movements during Crossrail westbound tunnel drive at Hyde Park (field measurements after [Wan et al. 2017b](#))

6 Sensitivity study and discussion on settlement trough width

To investigate the sensitivity of the horizontal displacements predicted by $h = f(x, i)$ to variations in the empirical coefficients $h_{\max}$, α , L , the Crossrail westbound tunnel at Hyde Park was chosen for a parametric study. The empirical coefficients q_h , α , and L were varied, one at the time, within their respective 95% confidence intervals. The horizontal displacements u were obtained using the field value of $K = 0.39$. The sensitivity study in Figure 8a–8c shows the following: (i) the effect of L (ranging from 2.43 to 2.72) on the predicted horizontal displacements is limited; (ii) α (from 1.12 to 2.85) controls the tail of the horizontal displacement plot, with the proposed best-fit value $\alpha = 2.0$ corresponding to an extent of the zone of influence for the horizontal displacements of about $\pm 4i$, which is larger than the commonly assumed zone of influence of vertical displacements of $\pm(2.5 \text{ to } 3.0) i$; (iii) parameter $h_{\max}$ (from 0.57 to 0.75) affects mostly the maximum value of the computed horizontal displacement but not the pattern in any significant way.

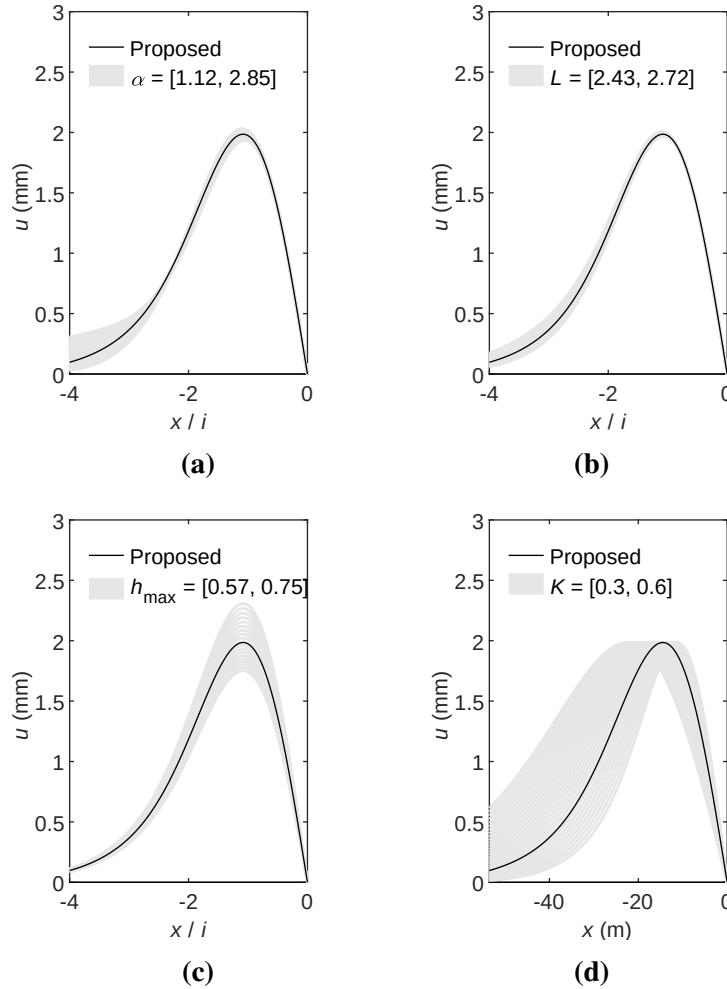


Fig. 8. Sensitivity of the empirical model for variation in : (a) α , (b) L , (c) $h_{\max}$, and (d) K

Considering that the empirical method $h = f(x, i)$ infers horizontal displacements from the settlement trough, it is important to accurately estimate the trough width parameter K (see Figure 4). The trough width

parameter $K = 0.5$ at the surface has been widely adopted for deriving the tunnelling-induced surface settlement profile in clays. However, K is less than 0.5 for recent case histories including deeper tunnel (see Table 1). Figure 9 compares trough width parameters associated with standard Gaussian curves reported by O'Reilly and New (1982) and Mair and Taylor (1997), the case studies considered in this paper, and also the empirical expression proposed by Jones (2010) calibrated including the Thames Water Ring Main Extension (TWRM) dataset. This figure shows that surface trough widths $K < 0.5$ were observed for $z_t > 20$ m, consistently with Jones (2010)'s suggestion that K is between 0.35 and 0.49 for z_t between 35 m and 20 m. The surface value of K has also been suggested to decrease with the tunnel depth (Peck 1969; Cording and Hansmire 1975) and K can be as large as 0.6-0.7 in soft clays (e.g. Ribacchi 1993; Mair and Taylor 1997).

Using the Crossrail westbound tunnel at Hyde Park as a hypothetical design problem, Figure 8d illustrates the significant impact of the trough width parameter K on the shape of u , by varying K in the range 0.3–0.6 while fixing $h_{\max} = 0.66$, $\alpha = 2.0$, $L = 2.6$, and $V_L = 0.44\%$. This demonstrates that the trough width K and volume loss V_L are the key design parameters, even more so than the empirical parameters proposed in this study.

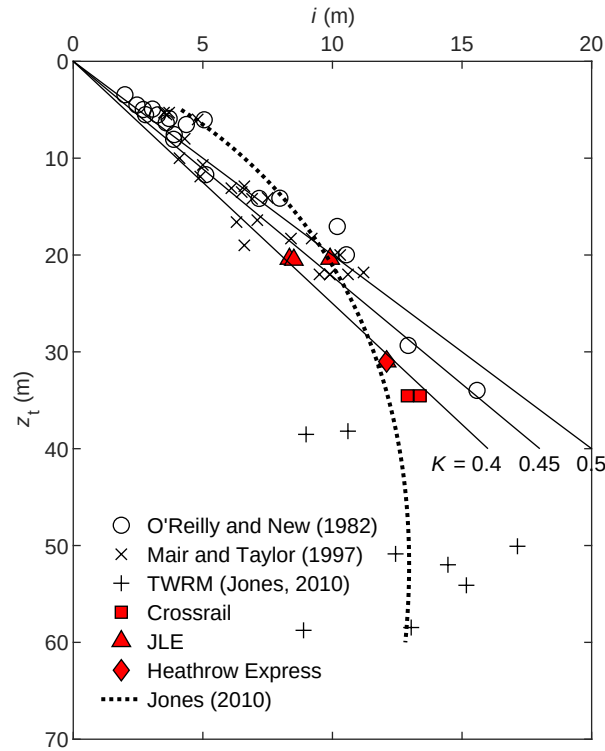


Fig. 9. Surface settlement trough width

7 Conclusion

It was confirmed that currently available empirical methods, which assume that the focus of the surface displacement vectors is at a constant location at or below the tunnel centre, and analytical approaches often under-predict the maximum surface horizontal displacements as well as the extent of the tunnelling influence zone in terms of horizontal displacements or strains.

There is a general lack of field measurements of horizontal tunnelling-induced movement. Nevertheless, a review of case histories of tunnel excavations in fine-grained soils demonstrated that, at the ground surface, the vector focus is located above the tunnel centre and its depth becomes shallower with increasing transverse distance from the tunnel centre-line. Considering this observation, a novel empirical method for which the variation in the normalised focal depth is given as a function of the transverse offset along the surface was proposed using a modified Gaussian function. The maximum depth of the vector focus, located at the tunnel centre-line, can be approximately taken as 0.66 times the tunnel depth. This proposed empirical approach was shown to achieve better estimates of the distribution of horizontal tunnelling-induced surface displacements and the resulting compressive and tensile ground strain for impact assessment purposes, than existing empirical and analytical methods. However, in this approach, horizontal movements would depend on the settlement predictions; thus the appropriate selection of the settlement trough width parameter for tunnelling in clays has also been discussed. For forward prediction purposes, designers are advised to consider the sensitivity of the displacement field to the empirical parameters proposed, as shown in the confidence interval in Figure 3a, and particularly the uncertainties associated with the determination of V_L and i , which control both the shape and magnitude of horizontal movements.

Until more detailed field or numerical results become available, to estimate near-surface movements (between surface and a depth level of about 20% the tunnel axis depth), it is suggested to interpolate linearly the focal depth from the proposed method at the surface and a focal depth of $z = 1.54z_t$ at 20% the tunnel axis depth, given that the reliability of using $h = 1.54$ at greater depth values has been widely accepted. Through this approach, the horizontal subsurface displacement profiles at Hyde Park was reasonably reproduced.

In future work, the subsurface variation of the focal depth both in the vertical and horizontal directions may be studied, possibly leading to the refinement of the proposed model. For this purpose, it is key that high-quality monitoring of surface displacements across a complete transverse cross-section, including at larger offsets from the tunnel axis, should be conducted to assess whether horizontal movements indeed have an extent of the zone of influence as large as predicted by the empirical model.

Competing interests

The authors declare there are no competing interests.

Data availability

Data generated or analysed during this study are provided in full within the published article.

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