

Research Article

Quantitative Evaluation of Ground Movements Caused by Grouting during Shield Tunnelling in Clay

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Grouting has been deemed as one of the most effective measures for mitigation of ground movements during tunnel construction in soft soil. Notwithstanding that, a reliable measure to quantitatively evaluate the grouting-induced ground movements during shield tunnelling in soft soil has not yet been developed. This paper presents a simple method capable of quantitatively estimating the ground movements associated with grouting for tunnel-boring operations where the grouting parameters and soil properties are taken into consideration. The grouting process is simplified as the expansion of a cylindrical cavity with a uniform radial stress applied at soil-grout interface in a half plane, and the analytical solution proposed by Verruijt is introduced for determining the ground movements by the expansion of the cylindrical cavity. The proposed method is verified with a case history undertaken in London Clay. The results obtained suggest that this procedure would be helpful in managing the grouting parameters adopted in upcoming soft ground tunnelling project and mitigating the environmental impacts on nearby properties.

1. Introduction

The shield tunnelling method has been widely used to construct underground structures in urban areas for more than 40 years [1–16]. During shield tunnelling, grouting is generally adopted for mitigation of soil settlement due to ground loss [17–20]. Many successful applications of grouting in clay have been reported by published literatures [21–28]. However, in the grouting process, due to the injection of pressurized grout, it will bring the additional loads on the surroundings (such as tunnel linings and ground) and be likely to cause the ground displacements, which can lead to adverse effects on existing building foundations or utilities [29–32]. Therefore, it is of great concern to estimate the magnitude of expected ground displacements before tunnel construction [33]. At present, there are only a few

investigations relating to the grouting-induced response during shield tunnelling [34–38]. Komiya et al. [34] investigated the effectiveness of grouting to reduce surface settlements caused by shield tunnelling in clayey soil based on the laboratory tests and a field case history. Bezuijen et al. [35] studied the distribution of grout pressure by performing the field testing in the construction of the Sophia Rail Tunnel. Zhang et al. [36] proposed a nondestructive testing method to evaluate the quality of the grouting treatment during shield tunnelling using ground penetrating radar (GPR). Farrell [37] reported a case history to mitigate the tunneling-induced settlement by the use of compensation grouting in London. Ye et al. [38] developed a half-spherical surface diffusion model to describe the infiltration effect of grouting during shield tunnelling. However, it is difficult to find out an available method to quantitatively evaluate the

ground movements caused by grouting during shield tunnelling.

The objective of this paper is to develop an approach that is capable of estimating the ground movements induced by grouting during tunnel construction in soft soil by taking into account the grouting parameters (grout pressure and volume) and soil properties, based upon the expansion theory of a cylindrical cavity in a half plane. The proposed method was applied to analyse a case history undertaken in London Clay for demonstrating its applicability.

2. Simplification of Grouting Process of Shield Tunnelling in Soft Soil

During shield tunneling, the annular gap can generally be formed between the erected tunnel lining and the excavated ground due to the smaller extrados of tunnel lining than the shield. The annular gap needs to be soon backfilled with grout not only to stabilize the tunnel linings but also to mitigate the movements of surrounding soil. Figures 1(a) and 1(b) present the longitudinal and transverse views of the grout injection into the annular gap around tunnel lining, respectively. It can be seen from Figure 1 that the grout is injected through the pipes into the shield tail gap with a designed grouting pressure (p_g) soon after installing the tunnel lining. Since the grouting process associated with the injection of pressurized grout into the annular gap can result in the additional loads on the surrounding soil and tunnel lining, the ground movements are thus expected. Grouting is a dynamic process, and for the sake of simplicity, this study assumed that the ground movements caused by grouting during shield tunnelling in soft soil are equal to those induced by the expansion of a cylindrical cavity (r_{sg}) with uniform radial stress (p_{um}) in a half plane, as indicated in Figure 1(c).

Verruijt [39] developed an analytical solution for calculating the deformations by expansion of a circular cavity with uniform radial stress in a half plane, and in this study, Verruijt's solution was adopted to determine the ground movements caused by grouting during shield tunneling in soft soil. The physical meaning of the radius of circular cavity and the uniform radial stress can be interpreted as the radius of the soil-grout interface (r_{sg} is related to the diameter of tunnel lining and grout volume) and the uniform pressure at the soil-grout interface (p_{um} is related to the grout pressure), respectively.

3. Ground Displacement Caused by Grouting of Shield Tunnelling in Soft Soil

Verruijt [39] proposed a method for calculating the ground movements for the case of a uniform stress applied at the cavity boundary in a half plane using the complex variable function. Figure 2 shows the parameters needed for calculating the ground movements for the aforesaid case.

The equations for calculating the ground movements proposed by Verruijt [39] are shown as follows:

$$S_{xA} = \text{Re} \left\{ \frac{1+v}{E} \left[(3-4\nu)f(Z) - Z\overline{f'(Z)} - \overline{\omega(Z)} \right] \right\}, \quad (1)$$

$$S_{yA} = \text{Im} \left\{ \frac{1+v}{E} \left[(3-4\nu)f(Z) - Z\overline{f'(Z)} - \overline{\omega(Z)} \right] \right\}, \quad (2)$$

where Re and Im mean taking the real and imaginary parts, respectively; S_{xA} = the displacement of point A in x direction; S_{yA} = the displacement of point A in y direction; ν = Poisson's ratio; E = Young's modulus; x and y are coordinate values of point A in x direction and y direction, respectively, as shown in Figure 2; $Z = x + iy$; $f(Z)$ and $\omega(Z)$ are the analytic functions and can be determined from the following equation:

$$f(Z) = \eta \left[-2i(1+\Lambda^2) + 2i \frac{Z(1+\Lambda^2) + iH_t(1-\Lambda^2)}{Z(1+\Lambda^2) - iH_t(1-\Lambda^2)} + 2i\Lambda^2 \frac{Z(1+\Lambda^2) - iH_t(1-\Lambda^2)}{Z(1+\Lambda^2) + iH_t(1-\Lambda^2)} \right], \quad (3)$$

$$\omega(Z) = \eta \left\{ -3i(1+\Lambda^2) + 2i\Lambda^2 \frac{Z(1+\Lambda^2) + iH_t(1-\Lambda^2)}{Z(1+\Lambda^2) - iH_t(1-\Lambda^2)} + i \left[\frac{Z(1+\Lambda^2) + iH_t(1-\Lambda^2)}{Z(1+\Lambda^2) - iH_t(1-\Lambda^2)} \right]^2 + 2i \frac{Z(1+\Lambda^2) - iH_t(1-\Lambda^2)}{Z(1+\Lambda^2) + iH_t(1-\Lambda^2)} + i\Lambda^2 \left[\frac{Z(1+\Lambda^2) - iH_t(1-\Lambda^2)}{Z(1+\Lambda^2) + iH_t(1-\Lambda^2)} \right]^2 \right\}, \quad (4)$$

$$f'(Z) = \eta \left\{ \frac{4H_t(1-\Lambda^2)(1+\Lambda^2)}{[Z(1+\Lambda^2) - iH_t(1-\Lambda^2)]^2} - \frac{4\Lambda^2 H_t(1-\Lambda^2)(1+\Lambda^2)}{[Z(1+\Lambda^2) + iH_t(1-\Lambda^2)]^2} \right\}, \quad (5)$$

$$\eta = \frac{\Lambda^2 p_{um} H_t}{(1-\Lambda^2)(1-\Lambda^4)}, \quad (6)$$

$$\Lambda = \frac{H_t - \sqrt{H_t^2 - r_{sg}^2}}{r_{sg}}, \quad (7)$$

where H_t = the distance from the tunnel centre to the boundary of half plane; p_{um} = the uniform pressure at the soil-grout interface, which is related to the grout pressure (p_g); η = a parameter defined by p_{um} , H_t and r_{sg} ; Λ = a parameter defined by H_t and r_{sg} ; r_{sg} = the radius of the soil-grout interface, which can be estimated under equivalent volume conditions:

$$r_{sg} = \sqrt{\frac{D_{out}^2}{4} + \frac{V_L}{\pi}}, \quad (8)$$

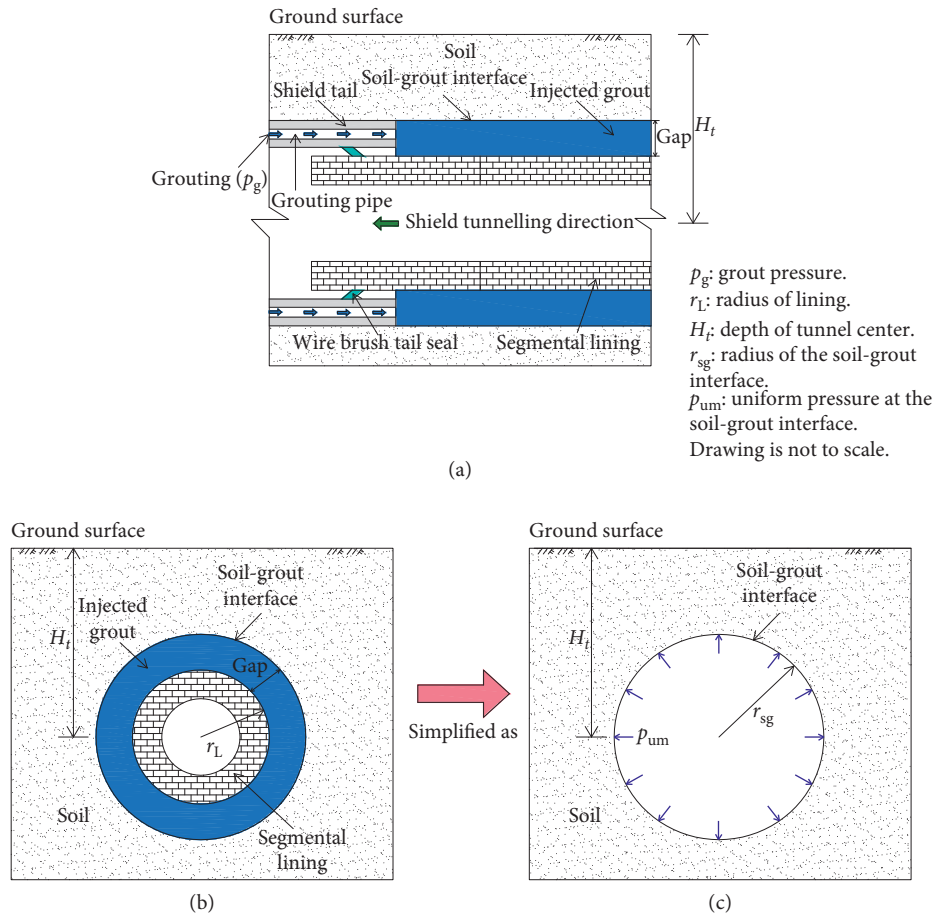


FIGURE 1: Schematic illustration of ground movements induced by expansion of a cylindrical cavity: (a) longitudinal and (b) transverse views of the grout injection into the annular gap surrounding; (c) expansion of a cylindrical cavity with uniform radial stress in a half-plane.

where D_{out} = the outer diameters of the ring and V_L = the grout volume per unit length.

4. Analysis of Case History

Wan et al. [23] presented a case study on the ground deformation response to the construction of crossrail tunnels in London Clay using earth pressure balance machines (EPBMs). Figure 3 presents the subsoil profiles for the worksite where two geological strata, that are, superficial deposits and London Clay, are identified. The thicknesses of the superficial deposits is measured to be 6 m, and it comprises a thin layer of made ground underlain by a series of river terrace deposits [40].

As shown in Figure 3, the unit weight of the superficial deposits averages 18 kN/m^3 . Avgerinos et al. [40] indicated that the modulus of elasticity for the superficial deposits is measured at 10.0 MPa . The successive London Clay at the depths varying from 6.0 to 59.9 m below the ground surface consisted of three units, that are, B2, A3, and A2, and the unit weight of London Clay averages 20 kN/m^3 . Gasparre et al. [41, 42] indicated that Young's modulus for London Clay is measured to be 132 MPa . The axis of crossrail tunnels is some 34.5 m below the surface. The extrados of the tunnel rings measured at 6.8 m, and the width of each tunnel ring is

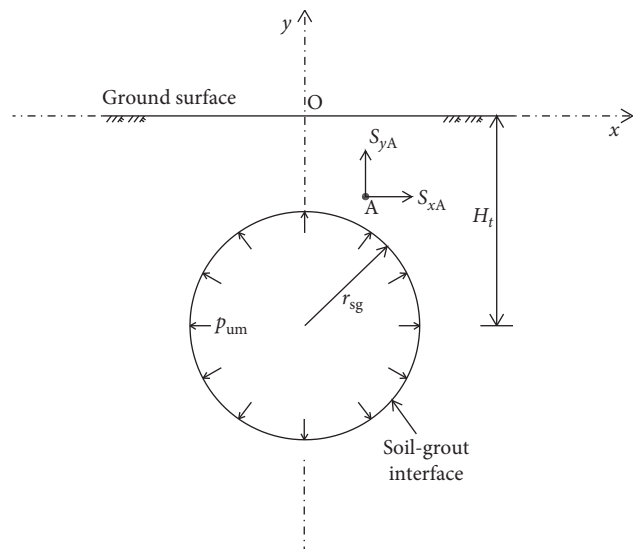


FIGURE 2: Parameters needed for calculating the ground displacement in case of a uniform stress applied at the cavity boundary (soil-grout interface).

1600 mm. Additionally, this case history recorded both the grouting pressure (p_g) and the volume of injected grout (V_L), as shown in Figures 4 and 5. The grouting pressure varied

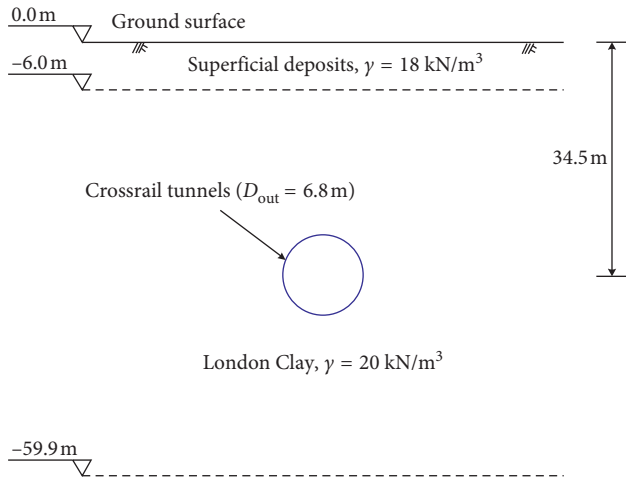


FIGURE 3: Geotechnical conditions and cross-sectional view of the tunnel layout in the case history. γ , unit weight (created based on [23]).

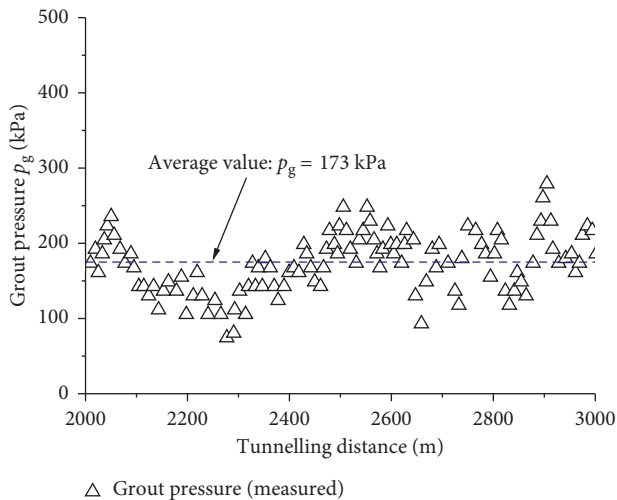


FIGURE 4: Grout pressure recorded in the case history (created based on [23]).

from 74 to 279 kPa, with an average value of 173.1 kPa. The volume of injected grout was within the range of 2.74–3.47 m^3/m , and the associated average value was measured at 3.12 m^3/m .

By use of equation (8), the value of $r_{sg} = 3.54$ m can be obtained. According to the soil stratum thickness, the weighted average value of Young's modulus is calculated as follows: $(10 \text{ MPa} \times 6 \text{ m} + 132 \text{ MPa} \times 53.9 \text{ m})/59.9 \text{ m} = 119.8 \text{ MPa}$. As discussed previously, the value of the uniform pressure acting at the soil-grout interface (p_{um}) is an unknown parameter which is related to the grouting pressure (p_g) and cannot be determined in a straightforward manner. Thus, this study chooses five values, i.e., $p_{um} = 0.2p_g, 0.4p_g, 0.6p_g, 0.8p_g,$ and $1.0p_g$, for the uniform pressure at the soil-grout interface for the calculation of ground movements. Since the vertical displacement of ground surface has been deemed as the major concern in tunnelling practice, it is primarily considered in this study. For the presented case history, the vertical displacement

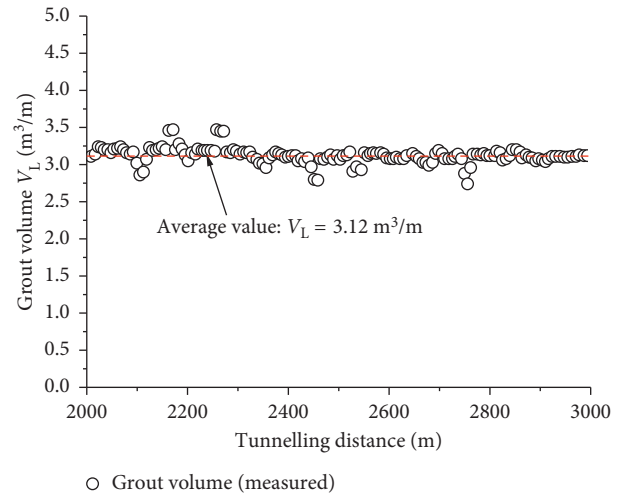


FIGURE 5: Grout volume recorded in the case history (created based on [23]).

of ground surface can be calculated by substituting the weighted average value of Young's modulus E , the value of r_{sg} , and the five different values of p_{um} into equations (1)~(7). Table 1 shows the parameters used in the analysis. The coordinate values of x and y and the variations of the vertical displacement of ground surface against the chosen p_{um}/p_g ratios can be obtained with the parameters. The described procedure is briefed in Figure 6.

Figure 7 presents the variation in the calculated vertical displacement of ground surface against the horizontal distance to the tunnel centre for the chosen five values of the uniform pressure. It can be seen from Figure 7 that the calculated vertical displacement against the various distances to the tunnel centre was increased with the increasing grouting pressure and that for the same grouting pressure, the calculated vertical displacement possessed a maximum value at the tunnel centre and was descended with the increasing distance to the tunnel centre. The maximum vertical displacement ($S_{y,max}$) against the chosen five values of p_{um} was calculated to be 0.41 mm, 0.81 mm, 1.22 mm, 1.63 mm, and 2.04 mm, respectively.

Grouting is a complex procedure to simultaneously fill the annular gap formed between the erected tunnel lining and the excavated tunnel bore during the shield tunnelling process. The vertical displacement of ground surface (S_y) is generally consisted of two components: one is the displacement caused by ground loss during shield tunnel construction, and the other is the displacement due to the cavity expansion of injection of pressurized grout. However, in situ constraints and other reasons cause some difficulty in distinguishing the two components. The described procedure briefed in Figure 6 demonstrates how the vertical displacement of ground surface (S_y) induced by grouting can be calculated using equations (1)~(7). Considering the p_{um}/p_g ratios being equal to 0.2, 0.4, 0.6, 0.8, and 1.0, the associated $S_{y,max}$ (maximum vertical displacement) values of 0.41 mm, 0.83 mm, 1.22 mm, 1.63 mm, and 2.04 mm were calculated. The $S_{y,max}$ values were then normalised with its maximum value (Δw_{max}) of 10.4 mm incurred in the shield

TABLE 1: Parameters used in the analysis.

E	ν	V_L	H_t	D_{out}	r_{sg}	p_g	p_{um}
119.8 MPa	0.3	3.12 m ³ /m	34.5 m	6.8 m	3.54 m	173.1 kPa	$0.2p_g = 34.6$ kPa $0.4p_g = 69.2$ kPa $0.6p_g = 103.8$ kPa $0.8p_g = 138.4$ kPa $1.0p_g = 173.1$ kPa

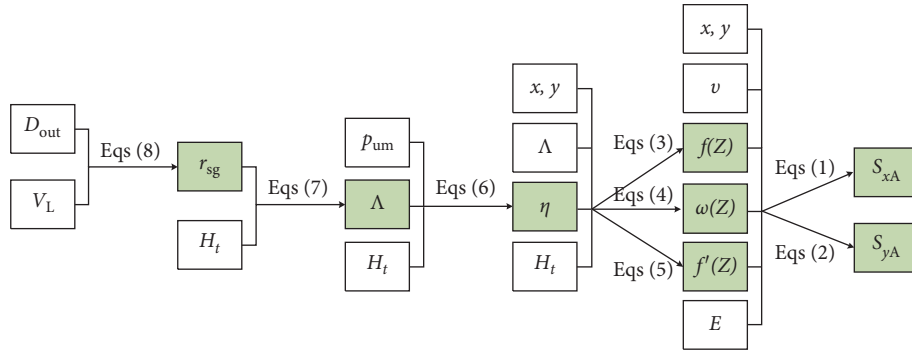
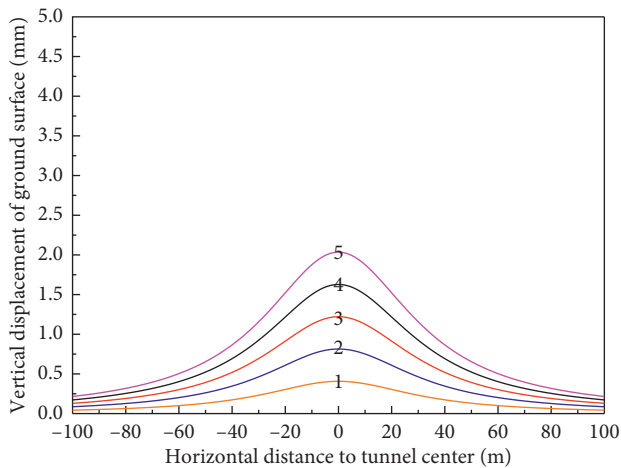


FIGURE 6: Flow chart for calculating the vertical displacement of ground surface.



- 1: $p_{um} = 0.2p_g$
- 2: $p_{um} = 0.4p_g$
- 3: $p_{um} = 0.6p_g$
- 4: $p_{um} = 0.8p_g$
- 5: $p_{um} = 1.0p_g$

FIGURE 7: Variation of calculated vertical displacement of ground surface with the horizontal distance to the tunnel centre for different five different values of the uniform pressure at the soil-grout interface.

tunnelling process in London Clay [23], as shown in Figure 8. Figure 8 not only clarified the normalised vertical displacement of ground surface ($S_{y,max}/\Delta w_{max}$) versus the p_{um}/p_g ratio relationship in the presented case history but also distinguished the $S_{y,max}$ value from the Δw_{max} value.

As can be seen, the normalised ground heave was increased linearly with the increasing pressure ratio and can be expressed using the equation $S_{y,max}/\Delta w_{max} = 0.19 p_{um}/p_g$. Bezuijen et al. [35] reported that the value of p_{um}/p_g was typically 0.64–1.0 with reference to field measurements of grouting pressure in tunnel-boring operations. During the

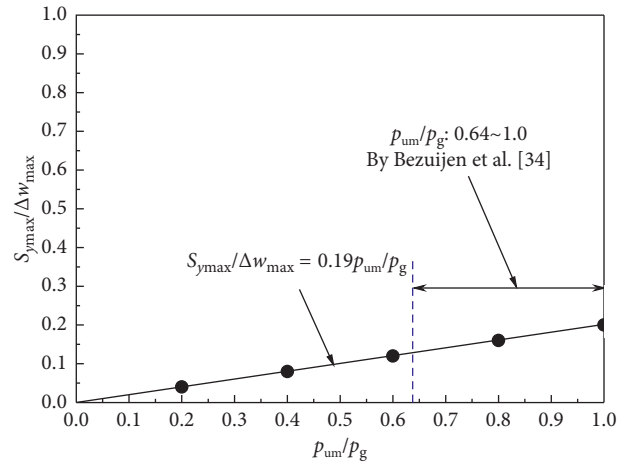


FIGURE 8: Normalized vertical displacement of ground surface versus the ratio of uniform pressure acting at the soil-grout interface to grouting pressure.

shield tunnelling process, the pressurised grout is injected into the annular gap formed between the erected tunnel lining and the excavated tunnel bore, and the distribution of the grout injected may be affected by the gravity and its rheology. It is often seen that the grout injected is distributed in an arbitrary manner, particularly for the tunnel invert. Secondary grout injection may be required to deal with the said problem preventing formation of cavity behind tunnel lining and further cracking of tunnel lining due to stress concentration resulting from the cavity behind.

In addition to the reasons above, ground heterogeneous nature and ordering of grout injection are also involved in the distribution of injected grout. Thus, the actual pressure distribution at the soil-grout interface cannot be uniform. This is deemed as the main cause to lead to the p_{um}/p_g ratio typically 0.64–1.0. In the event where the values of p_{um} for

the analysed case history were chosen to be $0.64p_g \sim 1.0p_g$, the vertical displacement of ground surface due to grouting could reach 12~19% of the maximum vertical displacement induced by shield tunnelling in soft soil. The results obtained from this study would be helpful in managing the grouting parameters adopted for upcoming tunnelling project and mitigating the environmental impacts on adjoining properties.

5. Conclusions

Grouting is a complex procedure to simultaneously fill the annular gap formed between the erected tunnel lining and the excavated tunnel bore during shield tunnelling process. It is of great importance to evaluate the ground movements caused by grouting during shield tunnelling in clay. This paper described a simple procedure for calculating the grouting-induced ground movements during shield tunnelling in soft soil using the expansion theory of a cylindrical cavity where the grouting parameters (grouting pressure and volume of injected grout) and the soil properties are taken into consideration. The grouting process is simplified as the expansion of a cylindrical cavity with a uniform radial stress at soil-grout interface in a half plane. The proposed method was verified with a case history of London Clay. The results obtained suggest that this procedure would be very helpful in managing the grouting parameters adopted for upcoming soft ground tunnelling project and mitigating the environmental impacts on adjoining properties.

Data Availability

The data used to support the findings of this research work are included within the article.

Conflicts of Interest

The authors declare no conflicts of interest.

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