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Twist deformation of buildings from ground movements due to skewed-tunnel excavation

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ABSTRACT: Substantial ground settlements from tunnel excavation near existing buildings may result in building distortion and increase the risk of structural damage. Current studies on building-tunnel interaction are usually limited to the plane-strain analyses that neglect the out-of-plane deformation behaviour of a structure. When tunnels are orientated (skewed) to the building, additional three-dimensional deformation such as out-of-plane ground movements and building twist may lead to further building straining. Estimation of the twist is not always straightforward as the building stiffness modifies the greenfield displacements induced by tunnelling. In this paper, the results of a three-dimensional numerical parametric study on the influence of existing surface structure on the twist deformation are presented. The buildings are represented by elastic shell elements where their in-plane geometries, stiffnesses, and rotation angles with respect to the tunnel axis are varied. The results show that in most of the cases, presence of the building reduce the global twist deformation in comparison to those of greenfield condition, except in the case of low building stiffness, and when the tunnel is excavated with skew angle less than 30° relative to the existing buildings.

1 INTRODUCTION

The construction of tunnels in urban area can induce ground displacements which distort and, in severe cases, damage overlying buildings and services. In addition, assessment of building damage due to excavation-induced ground displacement has always been a major concern so much so there exist thus for several approaches, for convenience of tunnel engineers, to carry out this task. The common semi-analytical method relates the building damage to the two-dimensional (2D) greenfield components of movement (Burland & Wroth 1974, Boscardin & Cording 1989, Finno et al. 2005). Namazi & Mohamad (2013) have recently extended this approach to include three-dimensional (3D) component of the movement. However, this method is still conservative and suitable only for preliminary damage assessment since it does not consider the effects of building stiffness on the ground movements. Besides, it is generally known that the presence of surface building alters the shape of settlement trough (Breth & Chambosse 1974, Frischmann et al. 1994).

In 1997, Potts and Addenbrooke presented a relative stiffness approach to quantify the effects of building stiffness on the 2D ground movements. Whilst this method has been used in engineering practice (Mair & Taylor 2001, Mair 2003, Dimmock & Mair 2008), 3D analyses on the behaviour of building are still rare in the literature. Case records showed that when a building oriented at a significant skew to the axis of tunnel, measurable 3D building deformation called twisting occurred (Geilen & Taylor 2001a, b, Withers 2001, Standing et al. 2003). The damage recorded in these cases ascribed to the twisting deformation of the structures. The twist is defined as the rate of change between two deformation slopes on the planes with the same normal as one moves in the perpendicular direction to these planes. Figure 1 shows the definition of global twist, θ_{ab} in the building with length b, width a, assuming linearly varying corners settlements (S_1, S_2, S_3 and S_4).

In terms of symmetric 3D analysis, Franzius et al. (2006) examined the effects of building geometry and tunnel depth on the twist behaviour of building that is aligned perpendicular to the axis of tunnel. In such setting, the twist deformation occurs temporarily during the tunnel excavation work. More general forms of permanent building twist would most likely take place when the positions of building are skewed to tunnel axis.

The present paper investigates the twist behaviour of buildings with various skew angles with respect to the tunnel axis using fully 3D numerical analysis. Effects of buildings with different geometries and stiffnesses are explored for each tunnel orientation. For convenience, the final twist deformations are expressed as fraction of those obtained in the greefield

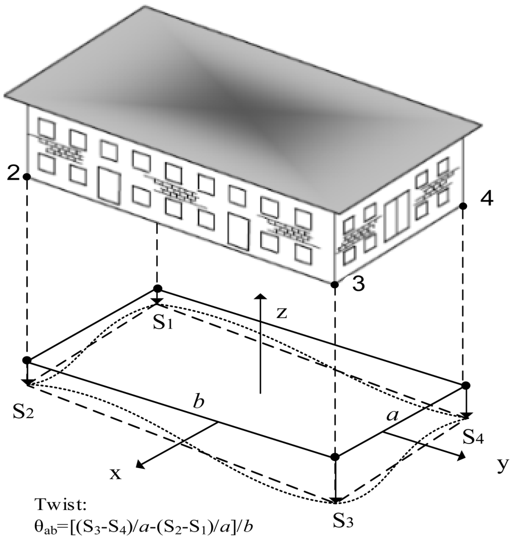

Figure 1. Twist deformation of building.

conditions and are defined as twist modification factors. The modification factor shows that how much the greenfield twist is modified in different building scenario. The tunnel engineer may anticipate the building twist by multiplying of the greenfield twist with the modification factor.

2 DETAILS OF NUMERICAL ANALYSIS

A hypothetical tunnel excavation in homogenous and stiff London Clay was modelled, adopting the Finite Element (FE) program, ABAQUS (ABAQUS, 2010) employing a 3D mesh as shown in Figure 2. The tunnel has a constant diameter of 4.1 m and is located 20 m beneath an existing building. These values are typical for running tunnels in the London underground system. The model domain was 150 m wide, 50 m high and 150 m long.

The London Clay was described by elastic-perfectly plastic behaviour. The elastic part (pre-yield) was treated as isotropic and non-linear, following description given by Jardine et al. (1986). In this model, the normalized bulk and shear moduli of elasticity against mean effective stress are not constant but vary in a reducing manner with the increases in volumetric and shear strains, respectively. In the plastic part (post yield), the Mohr-Coulomb yield surface was employed for the models. The Mohr-Coulomb plastic parameters of cohesion, $c = 5$ kPa friction angle, $\varphi = 25°$, and dilation angle, $\psi = 12.5°$ considered for the soil in this study.

The numerical simulation of tunnel and building was carried out in a step-by-step manner. The primary steps include establishment of the initial stress condition, simulation of the building and then the modelling of tunnel construction. The initial horizontal and vertical stresses in the ground were controlled

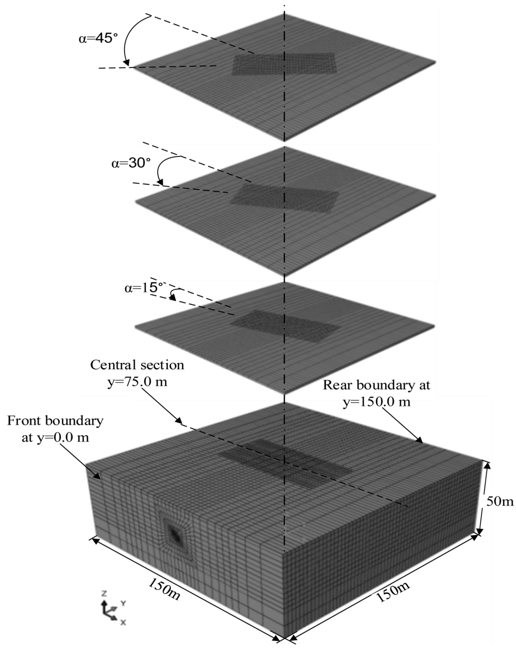

Figure 2. Full 3D finite element mesh of tunnel beneath skewed buildings.

Table 1. Material properties of tunnel lining.

Thickness [m]	Young's modulus [kN/m^2]	Poisson's ratio
0.2	28×10^6	0.15

by the assumed bulk unit weight of 20 kN/m^3, pore water pressure profile with a water table at the ground surface, and coefficient of earth pressure at rest, $K_0 = 0.5$.

The simulation of tunnel construction was conducted in two stages: removing soil element (excavation) and left unsupported (similar to an open-face excavation) till the desired volume loss is reached and finally the installation of the lining element. Simulation of tunnel construction was performed continually by repeating in sequence the soil elements removal and lining activation. A total of 62 steps were simulated for each model.

The tunnel lining was modelled with elastic shell element (Schroeder, 2003). The material parameters for the lining are summarised in Table 1.

The building on the soil surface was represented by weightless elastic shell elements. To simulate different numbers of building storey, the equivalent Young's modulus and thickness for the elastic shell model were calculated from the following equation and used as input parameters in the numerical model.

$$t_{eq} = \sqrt{12(EI)_{bu}/(EA)_{bu}} \tag{1}$$

$$E_{eq} = (EA)_{bu}/bt_{eq} \tag{2}$$

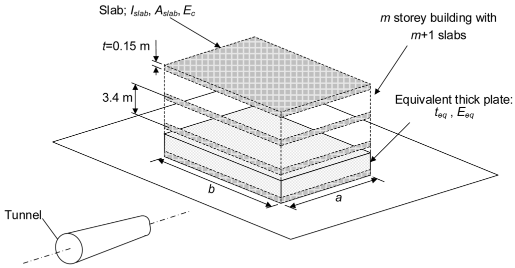

Figure 3. Excavation of tunnel under *m* stories building and equivalent thick plate.

Table 2. Finite Element input parameters for shell element.

Number of storey	Young's modulus E_{eq} [kN/m^2]	Thickness t_{eq} [m]
1	1.17e–6	5.9
2	1.05e6	13.19
3	1.03e6	20.09

where b = length of building; $(EA)_{bu}$ = axial stiffness of building; $(EI)_{bu}$ = bending stiffness of the building. The $(EA)_{bu}$, and $(EI)_{bu}$ can be calculated using the parallel axis theorem (Timoshenko, 1957). Assuming a concrete frame building with m stories, $m+1$ slabs (Figure 3):

$$(EA)_{bu} = (m+1)(E_cA)_{slab} \tag{3}$$

$$(EI)_{bu} = E_c \sum_{1}^{m+1} (I_{slab} + A_{slab} H_m^2) \tag{4}$$

where E_c = Young's modulus of the slabs, t_{slab} = thickness of the slabs, A_{slab} = area of the slabs; I_{slab} = second moment area of the slabs; H_m = the vertical distance from the structure's neutral axis to the individual slab's neutral axis. The building stiffness values are summarised in Table 2.

3 DEVELOPMENT OF SETTLEMENT AT BUILDING CORNERS

It is generally agreed that the shape of the surface settlement transverse to the axis of tunnel approximates closely to a normal Gaussian distribution curve in the greenfield condition (Peck, 1969). The settlement is maximum above the tunnel axis but decreases with an increase in the horizontal distance from the tunnel axis. Clearly, the presence of buildings alters the shape of this settlement curve. To analyse this interaction problem, the development of settlement below the building during excavation of tunnel is presented in the following.

Figure 4 shows settlement contours below the 71 m × 35 m building with its axis rotated 45° from the tunnel axis. The settlement contours are represented

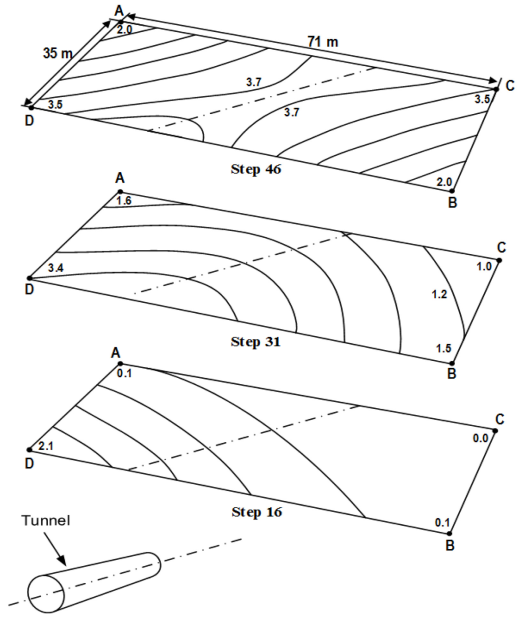

Figure 4. Development of settlement contour under 71 m × 35 m building with an angle of skew, $\alpha = 45°$ (Units of contours are given in mm).

for three different tunnel construction stages: (i) when the tunnel face reaches the front facade (step 16), tunnel face is under the building centre (step 31) and the tunnel face just passes the rear facade (step 46). As the tunnel face approaches the building, the structure rotates about edges AC and BC and causes increase in settlement at corner D to the maximum value of 2.1 mm (see Figure 4). When the tunnel is excavated under the building, the structure leans inward to the tunnel axis. By passing the tunnel beneath the structure, the building rotates around edges AD and BD in such a manner that the settlement at corner C increases to the same value of corner D. At this point, the settlement in the opposite corners of A and B are also equal. The differential settlements on the edges of building are consequently the same but in opposite sign which lead to an increase in the building twist. The building settlement after tunnelling completion is maximum above the tunnel axis and decline corresponding to increment in the horizontal distance from the axis in the same manner as the greenfield condition.

4 NUMERICAL RESULTS OF PARAMETRIC STUDY

So far, it is evident as shown and discussed in Section 3 that tunnelling skew angle influences the settlement field of building substantially. This section on the other hand explores intensity of such effect when parameters of buildings are varied. The parametric study was performed using three different in-plane building geometries: 71 m × 35 m, 62 m × 20 m and 40 m × 10 m. These represent the major building geometries exist along Jubilee Line Extension (JLE) project in London. For each building size, the stiffnesses of the buildings were varied to values equivalent of 1, 3 and 5 storeys. The tunnel was excavated in four orientations beneath the existing building: perpendicular and with skew angles of 15°, 30° and 45° relative to the perpendicular (see Figure 2). The twist results obtained from excavation of the tunnel beneath the building with different scenario are compared and discussed in the following sections.

4.1 *Influence of building stiffness on the global twist*

The settlements at the corners of the building are used to calculate the global twist (Figure 1). This global twist is resultant of different values of the surface settlement at the building corners, which are located in the different longitudinal and transverse settlement troughs. The influence of the building stiffness on twist is shown in Figure 5 for the 71 m × 35 m building, which is skewed 45° to the tunnel axis. The tunnel face encounters building at y = 37.5 m, passes beneath building centre line at y = 75 m and from y = 112.5 m beyond the building. The twist is plotted against the position of tunnel face for the building case and corresponding greenfield conditions. In general, the twist develops in such way that it increases gradually when the tunnel face approaches the building, but then decreases slightly when the building is encountered and increases again after passing the buildings centreline.

By advancing the tunnel towards the building, the settlement of the building at point D increases significantly than the rest which leads to an increase in twist. The progress of tunnel from the front facade of building onward has caused the surface settlement at point B to increase faster than point D, inducing negative twist which decreases the global twist. After the tunnel passes the centre point, the rear facade of the building rotates in the clockwise direction and causes the positive twist that increases the global twist again. The global twist reaches the maximum value after the tunnel passes the building. The twist remains approximately constant when tunnelling is carried out beyond the buildings rear facade.

The influence of the structure's stiffness on the global twist is clearly recognised in Figure 5. It is straightforward to see that building with the lowest stiffness gives the highest twist deformation. In comparison, one storey building produces the highest twist of $1.6 \times 10^{-7}\,\mathrm{m}^{-1}$ which is close to the maximum twist of $1.7 \times 10^{-6}\,\mathrm{m}^{-1}$ given by the greenfield condition. The twists for the greenfield conditions are obtained by adopting the same building size. Decreasing the stiffness also causes the twist to reach the peak value at a slightly slower rate. For instance in one-storey building, the maximum twist is reached when the tunnel face is positioned at y = 115 m whereas for five-storey building, the maximum twist is obtained at y = 107.5 m.

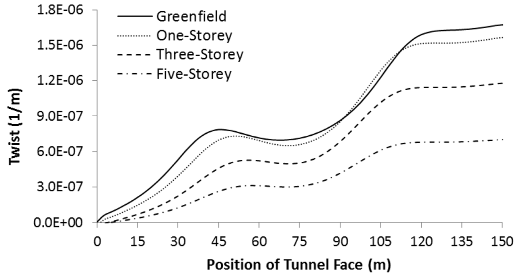

Figure 5. Global twist against position of tunnel face in presence of building (B) and greenfield (GF) condition at 45° skew angle.

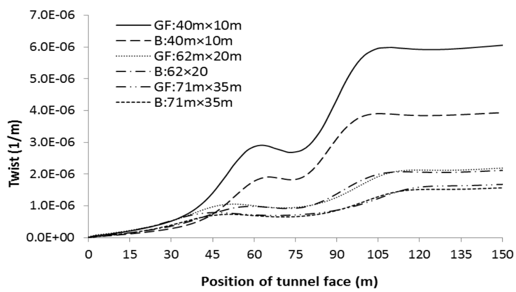

Figure 6. Global twist against position of tunnel face in presence of building (B) and greenfield (GF) condition at 45° skew angle for different in-plane geometries.

To compare the twists in the building case with the greenfield condition, the modification factor, M_θ is calculated for each case. The modification factor is defined as the ratio of the maximum building twist to the maximum twist in the corresponding greenfield condition after the tunnelling is completed. The five-storey structure only gives a modification factor of $M_\theta = 0.42$. This value increases to 0.70 for the three-storey building. The modification factor for one-storey building is maximum around 0.94.

4.2 *Influence of building geometry on global twist*

Figure 6 compares the influence of in-plane geometries on the global twist. The figure compares the increment of twist against tunnel face position for 71 m × 35 m, 62 m × 20 m and 40 m × 10 m geometries when the tunnelling axis is askew 45° to a one-storey building. As the tunnel face approaches the building, the twist rises sharply in the smallest building. Twist reaches a constant value when the tunnel face passes the buildings at a distance of 5D, where D is the diameter of tunnel, from the rear boundary of building. The graph reveals that the largest building (71 m × 35 m) develops the least amount of twist. The 62 m × 20 m structure with higher twist value lies closer to 71 m × 35 m building results. As larger structure extends further away from the tunnel centreline, the differential settlements between the building corners are relatively less.

In the case of greenfield condition, similar to building cases, the largest geometry (71 m × 35 m) also develops the smallest global twist. The 40 m × 10 m geometry produces a final twist deformation of $6.05 \times 10^{-6}\,m^{-1}$ whereas that of 71 m × 35 m develops a permanent twist deformation of $1.67 \times 10^{-6}\,m^{-1}$.

It is interesting to note that the relative twist due to reduction in building size is less when corresponding to those greenfield values. This leads to a reduction of M_θ for the small geometry. M_θ for one-storey 45° skewed building with geometry 71 m × 35 m is 0.94 which reduces to 0.92 for 62 m × 20 m building and further down to 0.63 for that of 40 m × 10 m.

4.3 *Effects of skew angle on global twist*

Figure 7 shows the development of twist of building with various orientations during the tunnelling process beneath the structure, focusing solely on three-storey building with 71 m × 35 m dimensions. The structures do not have eccentricity with respect to the tunnel axis. Four different skew angles 0°, 15°, 30°, and 45° with respect to X-axis were analysed (see Figure 2). The analysis for the case of $45° < \alpha \leq 90°$ are not considered in this study since the twist in a building with a skew angle relative to X-axis is the same as that in a building with equivalent rotation relative to the tunnel axis where its length and width are mutually replaced. For instance, the twist deformation in 71 m × 35 m building with 15° skew angle with respect to X-axis is equal to that in 35 m × 71 m building which is rotated 75° with respect to X-axis (or 15° with respect to the tunnel axis).

In Figure 7, twist deformation induced by tunnel excavation for the perpendicular building is approximately zero. In this case, the settlement contours are relatively symmetrical and parallel to tunnel axis which leads to negligible permanent twist in the building. By increasing of the skew angle the twist increases. The maximum twists are two and four times that without skew angle when the skew angle is rotated from 30° to 45°. The changes in the building-tunnel orientation cause significant differential settlement between the edges of the building and consequence increase of the twist.

In the case of 45° skew angle, the maximum permanent twist in building is less than that of greenfield, from which the twist modification factor is $M_\theta = 0.7$. In contrast, the resultant modification factor is greater than unity when skew angle is 15°, implying that the presence of the building causes greater twist than the greenfield conditions.

5 VARIATION OF TWIST MODIFICATION

In the following, a set of twist modification factors, M_θ was obtained for a total of 48 3D FE analyses for buildings with various sizes, shell stiffnesses and tunnel excavation angles. The results of twist modification factor are summarized in Table 3. The results from perpendicular tunneling are not reported as the twist is negligible in comparison to other cases. It is evident that, the greater building stiffness (due to higher number of floors) and skew angle, the greater modification, while the greater building geometry the smaller modification to the greenfield twist displacement. It is interesting to note that the modification factors are greater than unity for flexible buildings with skew angle lower than 30°, indicating that the presence of structure causes greater twist deformation. Such observation has been reported in terms of deflection ratio in the flexible buildings by Potts and Addenbrooke (1997), Franzius et al. (2006), and Farrell and Mair (2012). This is likely a result of the influence of horizontal shear stress acting at the base of the building which enhances the distortion.

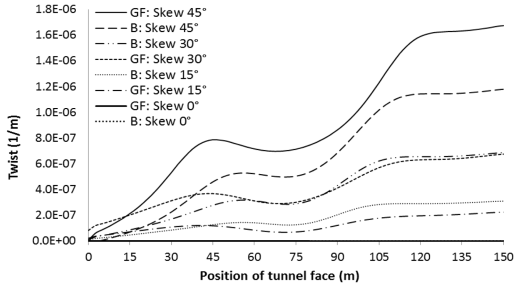

Figure 7. Development of global twist in the greenfield condition (GF) and presence of three-storey buildings for different skew angles.

Table 3. Modification factor of twist for different building scenarios.

Building geometry	Storey	Skew (°) 15	30	45
40 m × 10 m	1	1.04	1.04	0.63
	3	0.45	0.46	0.31
	5	0.34	0.29	0.19
62 m × 20 m	1	1.37	1.26	0.92
	3	0.99	0.82	0.55
	5	0.64	0.49	0.31
71 m × 35 m	1	1.63	1.27	0.94
	3	1.38	1.02	0.70
	5	0.82	0.60	0.42

6 CONCLUSION

This study analysed the influence of tunnelling on twist related displacement of an existing surface structure. The results of a full 3D parametric study involving 48 FE analyses have been presented. In these analyses, the tunnel was excavated with different skew angles relative to the surface building. The building was modelled with linear elastic shell elements with different in-plane dimensions and stiffnesses whereas the soil was modelled using non-linear elastic and perfectly plastic Mohr-Coulomb material description.

The results showed that the presence of the building affects the twist deformation and in most of the cases had a reduction effect in comparison to those of greenfield condition. Increase in building stiffness (due to increasing number of floors), and larger in-plane geometry as well as decrease in building skew angle increase the modification to the twist. An exception case was observed when the tunnel is excavated with skew angle less than 30° relative to the existing buildings with low stiffness, where the twists can be greater than those when no structure is at present.

It is important to note that the current results are only applicable for the London Clay or for the soil with the same stiffness behaviour. Nonetheless, further analyses can be carried out utilising the present methodology to predict the building twist for other soil conditions.

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