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A cantilever approach to estimate bending stiffness of buildings affected by tunnelling

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ABSTRACT

The evaluation of the effect of tunnel construction on buildings is a problem being faced by engineers around the world. Building bending stiffness is an important parameter in tunnel-soil-structure interaction analyses. The construction of a new tunnel influences an existing building via induced ground movements, and the existence of a building also affects ground displacements due to tunnelling via its stiffness and weight. The magnitude of the effect depends on the properties of the building and foundation as well as the complex soil-structure interactions that occur. In this paper, an approach is proposed in which the building response to tunnelling is related to the bending of a cantilever beam and empirical-type relationships are developed to predict building bending stiffness. This approach is relevant to cases where the building is perpendicular to the tunnel axis and its nearest edge does not overlap more than half of the tunnel cross-section. Rigorous finite element analyses are used to evaluate the response of buildings to ground displacements and expressions are provided which relate three-dimensional building bending stiffness to a simple beam theory expression. The results show that lower storeys have a proportionally higher stiffness effect than higher storeys. In addition, the parameters that affect the global behaviour of the building, such as component stiffness and geometry, are studied. The suggested approach provides a relatively quick and easy way of accurately evaluating building bending stiffness for use within tunnel-soil-structure interaction analyses.

1. Introduction

The popularity of tunnel construction within urban areas for provision of transport and other essential infrastructure is increasing. Tunnel construction inevitability causes ground movements which can have detrimental effects on nearby structures and buried infrastructure. The analysis of tunnelling induced displacements and tunnel-structure interaction has received considerable attention by the research community (e.g. Mair and Taylor, 1997; Mair, 2013). The focus of this paper relates to the effect of tunnelling on buildings. Research in this area has included field investigations (Boscardin and Cording, 1989; Dimmock and Mair, 2008; Farrell et al., 2014), experimental studies, including geotechnical centrifuge tests at elevated gravity (Farrell and Mair, 2012; Giardina et al., 2012; Farrell et al., 2014), numerical analyses (Potts and Addenbrooke, 1997; Mroueh and Shahrour, 2003; Franzius et al., 2006; Pickhaver et al., 2010; Maleki et al., 2011; Mirhabibi and Soroush, 2013; Fargnoli et al., 2015), and the development of analysis methods for evaluating building deformations (Rankin, 1988; Attewell et al., 1986; Franza et al., 2017).

The level of complexity of the tunnel-building interaction analyses varies considerably. In the simplest form, it is assumed that the building deforms according to greenfield displacements (Rankin, 1988). However, in reality the building influences the resulting soil movements due to its stiffness (Potts and Addenbrooke, 1997; Mair and Taylor, 1997) and weight (Liu et al., 2001; Mroueh and Shahrour, 2003; Franzius et al., 2004; Giardina et al., 2015).

This paper deals specifically with how building stiffness can be evaluated; this stiffness value can then be used to inform analyses of tunnel-building interaction. Several researchers have investigated the effect of structural stiffness on tunnelling- or excavation-induced ground movements, such as Potts and Addenbrooke (1997), Franzius et al. (2006), Dimmock and Mair (2008), Goh and Mair (2014), Giardina et al. (2015), Franza et al. (2017). The methods used to estimate the stiffness of the building vary. Lambe (1973) algebraically added the individual flexural rigidity of all floor slabs, $(EI)_{sl}$, to calculate the whole building stiffness: $(EI)_{bldg} = \sum (EI)_{sl}$, where E is the material modulus of elasticity and I is the cross sectional moment of inertia; subscripts *bldg* and *sl* denote building and slab, respectively. Potts and Addenbrooke (1997) proposed Eq. (1) to estimate the bending stiffness of a building relative to the soil.

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Nomenclature

α_{Kus}	a coefficient to account for the effect of the ratio of building length in the x-direction to one storey height
ρ^*	relative bending stiffness
ρ^*_{mod}	modified relative bending stiffness
A_{sl}	cross sectional area of a slab
B_{bldg}	width of a building parallel to tunnel axis
b_{fb}	cross sectional width of the floor beam
b_{sb}	cross sectional width of the supporting beam
B_{sl}	clear width of a slab
C_{bc}	a coefficient to estimate the degree of end fixity of the loaded floor
C_{bf}	a coefficient to convert the analytical floor bending stiffness to the numerical floor bending stiffness
C_{cf}	column-floor stiffening effect coefficient
C_{col}	column stiffening factor (Goh and Mair, 2014)
$C_{K,reduct}$	a reduction factor of the calculated bending stiffness
$C_{Kus,i}$	the ratio of the increased bending stiffness due to storey i
E_b	beam or building elastic modulus
E_s	soil elastic modulus
$(EI)_{bldg}$	flexural rigidity of a building's cross section
EI_{frame}	flexural rigidity of a frame's cross section (Goh and Mair, 2014)
$(EI)_{sl}$	flexural rigidity of a slab cross section
F_K	a factor depending on beam boundary condition and the applied force
G_b	shear modulus of the beam material
h_{fb}	cross sectional height of the floor beam
h_{sb}	cross sectional height of the supporting beam
$h_{fl,i}$	total height between the i^{th} floor and the foundation
I_b	beam cross sectional moment of inertia
I_{bldg}	cross sectional moment of inertia of a building
I_{fl}	moment of inertia of the floor cross section
I_{sl}	cross sectional moment of inertia of slabs
J_{sb}	polar moment of inertia of supporting beam
$K_{b,b}$	beam bending stiffness
$K_{b,eq,bldg}$	final value of the building bending stiffness
$K_{b,fl,an,fix}$	analytically calculated floor bending stiffness
$K_{b,fl,eq,1s,1y}$	bending stiffness of the loaded floor in the first storey of a single y-bay building
$K_{b,fl,eq,fix}$	equivalent bending stiffness of the fixed support floor
$K_{b,fl,eq,ms,1y}$	bending stiffness of a multi-storey building with a single y-bay
$K_{b,fl,eq,ms,my}$	bending stiffness of a multi-storey building with multiple y-bays
$K_{b,multi\ load}$	approximate bending stiffness of a multi-loaded beam
$K_{b,fl,num,fix}$	numerically determined floor bending stiffness
$K_{c,col}$	column stiffness
$K_{c,LC}$	average stiffness of the lower column (Goh and Mair, 2014)
$K_{c,sb}$	torsional stiffness of the supporting beam
$K_{c,Lfl}$	the stiffness of the loaded floor for the calculation of coefficients
$K_{c,Sfl}$	the stiffness of the supporting floor for the calculation of coefficients
$K_{c,UC}$	average stiffness of the upper column (Goh and Mair, 2014)
L_b	beam length
L_{bay}	span length of each beam bay (Goh and Mair, 2014)
L_{bldg}	length of a building perpendicular to tunnel axis
L_{col}	column length
L_{ds}	half length of soil displaced zone (surface settlement trough)
L_{inf}	length of building located inside the soil affected zone
$L_{sag,hog}$	length of the beam line in sagging or hogging (Goh and Mair, 2014)
L_{sb}	the length of the supporting beam
L_{sl}	clear length of a slab
L_{TB}	horizontal offset of the building edge to tunnel centreline
L_{xbay}	length of one bay in the x-direction
m	total number of building storeys
n_y	the number of building y-bays
t_{sl}	slab thickness
y_b	beam deflection
$\overline{y}_{sl}$	distance from the neutral axis of an individual slab to that of the building
z_t	tunnel depth

$$\rho^* = \frac{(EI)_{bldg}}{E_s\left(\frac{L_{bldg}}{2}\right)^4} \tag{1}$$

where ρ^* is the relative bending stiffness, E_s is the soil elastic modulus, and L_{bldg} is the building length in the direction perpendicular to the tunnel axis. The building was represented by an equivalent beam in their analysis. The expression $(EI)_{bldg}/(L_{bldg}/2)^4$ of Eq. (1) represents the bending stiffness of the building. The parallel axis theorem was used to evaluate the building moment of inertia, I_{bldg}, for a building of m storeys with $m+1$ slabs: $I_{bldg} = \sum_{i=1}^{m+1}(I_{sl,i} + A_{sl,i}\cdot\overline{y}_{sl,i}^2)$, where A_{sl} is the cross sectional area of a slab and $\overline{y}_{sl,i}$ is the distance from the neutral axis of the i^{th} slab to the neutral axis of the building. Potts and Addenbrooke (1997) also proposed the popular modification factor approach in which parameters used to evaluate building damage are compared based on displacements when soil-structure interaction is either considered or ignored (the greenfield condition).

Franzius et al. (2006) extended the work of Potts and Addenbrooke (1997) by considering the building width and the tunnel depth, as shown in Eq. (2).

$$\rho^*_{mod} = \frac{(EI)_{bldg}}{E_s z_t B_{bldg} L_{bldg}^2} \tag{2}$$

where ρ^*_{mod} is the modified relative bending stiffness, B_{bldg} is the building width parallel to the tunnel axis, and z_t is the tunnel depth. The expression $(EI)_{bldg}/(B_{bldg}L_{bldg}^2)$ represents the bending stiffness of the building in this case.

Goh and Mair (2014) used the column stiffening factor (C_{col}) proposed by Meyerhof (1953) to increase the flexural rigidity of an entire beam line in a rigidly connected frame:

$$C_{col} = 1 + \frac{L_{sag,hog}^2}{L_{bay}^2}\left(\frac{K_{c,LC} + K_{c,UC}}{K_{c,LC} + K_{c,UC} + K_{c,b}}\right) \tag{3}$$

where $L_{sag,hog}$ is the length of the beam line in sagging or hogging, L_{bay} is the span length of each beam bay, $K_{c,LC}$ and $K_{c,UC}$ are the average stiffness ($=(EI)_{col}/L_{col}$) of the lower (LC) and upper (UC) columns, respectively, L_{col} is the column height, and $K_{c,b} = (EI)_b/L_{bay}$ is the average stiffness of the beam line. The bending stiffness of the frame is then estimated by $EI_{frame} = \sum((EI)_b * C_{col})_{i^{th}\ floor}$

The accurate evaluation of building bending stiffness in tunnel-building interaction analyses is clearly important. However, the real behaviour of three-dimensional (3D) buildings in response to applied displacements from the ground is disregarded to a great extent. Results from the literature relating to numerical analyses of 3D buildings provide a good general appreciation of tunnelling effects on buildings, but