

# Numerical Modelling of Building Response to Tunnelling

John Anthony Pickhaver



A Thesis submitted for the degree of Doctor of Philosophy  
at the University of Oxford

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## Abstract

The construction of underground tunnels in soft ground in urban areas involves the potential for ground movements caused by the tunnelling to affect existing surface structures. Masonry structures are at particular risk of crack damage. Conventional empirical building assessments do not fully capture all aspects of this soil-structure interaction situation. Numerical methods are increasingly used for such problems. It is common practice in empirical and numerical methods to model a building as an elastic beam in 2D. The objective of this thesis is the development of a new approach to the numerical modelling of masonry buildings using surface beams in 3D.

In phase one of this project, finite element analyses of elastic and masonry facades are undertaken and the traditional beam method of modelling them is assessed. New equivalent elastic surface beams are developed, the properties of which account for the dimensions and openings in facades which were found to influence the response to settlements. Equivalent masonry beams are also developed which have a constitutive model that accounts for the different response of masonry buildings in hogging and sagging. Timoshenko beams are chosen to model the facades and these beams were implemented into the OXFEM finite element program with full 3D capability along with the new constitutive beam models.

Example masonry structures were modelled in 3D using the new surface beams in phase two. Tunnel construction was simulated under the buildings and the response of the beams compared to a full masonry building model. Example analyses included buildings both symmetric and oblique to the tunnel. Results showed that the equivalent elastic beams accurately simulate full masonry building response in sagging regions. Parametric studies confirmed the choice of equivalent beam parameters and the impact of different relative stiffnesses. The equivalent masonry beams displayed the same good agreement in sagging but were less accurate in hogging.

In phase three, finite element models are used to compare ground movements and structural response of buildings using the 3D equivalent masonry beam method and observed data from the construction of the London Underground Jubilee Line Extension. The surface beams showed good agreement with the observed building responses in both sagging, where the building response was essentially rigid and in hogging where a more flexible response was observed.

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# List of Notations

$A$	cross sectional area
$A^*$	effective cross sectional area
$a$ (1)	tunnel inner radius
$a$ (2)	a constant
$B$	building width
$\mathbf{B}$	strain-displacement matrix
$b$ (1)	distance to neutral axis
$b$ (2)	a constant
$C_1$	a constant
$C_2$	a constant
$c$ (1)	residual tensile strength
$c$ (2)	a constant
$c'_\alpha$	shear strength parameter
$c_i$	triaxial yield strength for yield surface $i$
$D$	tunnel diameter
$\mathbf{D}$ (1)	tangent stiffness matrix
$\mathbf{D}$ (2)	material property matrix
$DR$	deflection ratio
$\mathbf{d}$	array of nodal degrees of freedom
$E$	Young's modulus in compression
$E_r$	residual modulus
$E_s$	representative soil stiffness

$EEB$	equivalent elastic beam
$EMB$	equivalent masonry beam
$e$	eccentricity of building with respect to tunnel centreline
$F$	transverse applied force
$f$	residual stiffness factor
$\mathbf{f}$	nodal load vector
$f_b$	residual bending stiffness factor
$G$	shear modulus
$G_i$	tangential shear stiffness after yield surface $i$
$g'_\alpha$	shear stiffness parameter
$H$	building height
$H_{lim}$	limiting height
$H_{ji}^r$	Hermitian polynomial of level $r$ and order $j$ at node $i$
$h'$	effective height
$I$	second moment of area
$I^*$	effective second moment of area
$i$	distance to point of inflexion for a surface settlement trough
$i_z$	distance to point of inflexion for a subsurface settlement trough
$J$	polar moment of inertia
$K (1)$	trough width parameter
$K (2)$	stiffness
$\mathbf{K}$	stiffness matrix
$K_b$	beam stiffness
$K_{equiv}$	equivalent elastic beam stiffness
$K_{fe}$	facade stiffness
$K_o$	coefficient of earth pressure at rest
$k$	shear coefficient
$L$	building length
$L_i$	Lagrange polynomial at node $i$

$L/H$	length to height ratio
$L/H_{crit}$	critical length to height ratio
$M$	bending moment
$M_{sag}^{DR}$	deflection ratio modification factor in sagging
$M_{hog}^{DR}$	deflection ratio modification factor in hogging
$M_{sag}^e$	strain modification factor in sagging
$M_{hog}^e$	strain modification factor in hogging
$m$	soil constant
$N^*$	stability ratio
$N_i$	shape function for node $i$
$NSR$	normalised stiffness ratio
$n$	proportion of overburden stress on tunnel lining
$\mathbf{n}$	vector perpendicular to tunnel axis
$P$	point load
$Q$	shear force
$q$	load distribution
$R$	radius of curvature
$RS$	relative stiffness
$r$	tunnel outer radius
$S$	shear force
$S_h$	horizontal displacement
$S_{max}$	maximum vertical settlement
$S_v$	vertical settlement
$s_u$	undrained shear strength
$\mathbf{T}$	condensation matrix
$t(1)$	wall thickness
$t(2)$	distance between neutral axis and a beam edge
$V_L$	volume loss
$V_s(1)$	vertical displacement due to shear

$V_s$ (2)	settlement trough volume
$V_o$	volume required to construct a tunnel
$w_i$	lateral displacement of node $i$
$w_o$	parabolic load parameter
$\bar{x}$	non-dimensional beam position
$y$ (1)	transverse distance from tunnel centre line (2D analyses)
$y$ (2)	longitudinal distance from start of tunnel (3D analyses)
$z$	depth below ground surface
$z_1$	depth depth to the interface between two soil layers
$z_2$	distance of tunnel centre line below soil change interface
$z_o$	depth to tunnel axis
$\alpha$	angular strain
$\alpha^*$	relative axial stiffness
$\beta$	angular distortion
$\Delta$	relative deflection
$\Delta/L$	deflection ratio
$\delta$	differential settlement
$\delta_r$	radial displacement of tunnel lining
$\epsilon$	tunnel ground loss ratio
$\epsilon_o^{cr}$	stiffness reduction ratio
$\epsilon^{cr}$	cracking strain
$\epsilon_v$	vertical strain
$\epsilon_h$	horizontal strain
$\epsilon_{crit}$	critical tensile strain
$\epsilon_{lim}$	limiting tensile strain
$\epsilon_{bmax}$	maximum bending strain
$\epsilon_{dmax}$	maximum diagonal strain
$\epsilon_{br}$	limiting bending strain
$\epsilon_{dr}$	limiting diagonal strain

$\gamma$ (1)	self weight
$\gamma$ (2)	shear strain
$\gamma_0$	constant shear strain
$\kappa$	bending strain
$\kappa_{crit}$	critical curvature
$\mu$	increase in undrained shear strength with depth
$\mu_i$	rotation of beam neutral axis at node $i$
$\nu$	Poisson's ratio
$\theta$	rotation or slope
$\theta_i$	rotation of beam cross section at node $i$
$\rho^*$	relative bending stiffness
$\sigma_o$	initial total stress
$\sigma_1, \sigma_2$	principal stresses
$\sigma_x, \sigma_y$	stresses on an element
$\tau$	shear stress
$\omega$ (1)	increase in shear modulus with depth
$\omega$ (2)	building tilt