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An analytical study of tunnel–pile interaction

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ABSTRACT

Tunnelling under the foundations of structures is becoming more common because of the lack of available space for infrastructure, both above and below ground. The interaction between newly constructed tunnels and existing piled foundations is an important issue. This paper presents results obtained using a computationally efficient analytical approach which aims to estimate the effect that constructing a new tunnel will have on an existing pile. The method uses a spherical cavity expansion analysis to evaluate the end-bearing capacity of the pile, and cylindrical cavity contraction to estimate the decrease in the confining pressure and resulting reduction in pile capacity caused by tunnel volume loss. The paper extends previously published work using this method by considering the effect of tunnel location on the tunnel–pile interactions, examining different possible assumptions of soil stiffness used in the analysis, and by considering the effect that tunnel cavity contraction has on the friction along the pile shaft.

1. Introduction

The need for effective Civil infrastructure in cities is paramount. As populations grow and the demand on infrastructure systems increases, the need to further develop already congested underground space in many urban areas will become unavoidable. This will result in new underground construction activities taking place ever closer to existing structures and buried infrastructure. The resulting interaction between construction activities and the affected Civil assets must be considered in the design process.

Tunnels are arguably the most popular medium to large-scale underground structures in crowded urban areas. They are used to minimise the volume of traffic on the surface and can also have environmental benefits (e.g. traffic noise reduction). Tunnelling inevitably causes some ground movements which can have detrimental effects on buried and above-ground infrastructure and buildings. There has been considerable research conducted on the subject of evaluating the shape of tunnelling induced ground movements (Peck, 1969; O'Reilly and New, 1982; Mair et al., 1993; Marshall et al., 2012) and in determining the effects these movements have on man-made assets (Attewell et al., 1986; Klar et al., 2005; Vorster et al., 2005; Klar et al., 2008; Marshall et al., 2010; Zhang et al., 2012). In general, the potential for harmful interaction between tunnel construction and Civil assets is greatest for shallow tunnels, which suggests that a deeper tunnel is preferable. The cost of tunnelling varies considerably depending on local site conditions, however in general it increases with depth due to the additional cost of construction of associated excavations (e.g. shafts for tunnel boring machine launch, ventilation, and escalators/lifts). A careful decision must therefore be made at the design stage with respect to the optimum depth for new tunnel construction.

Piled foundations are particularly sensitive to the effects of tunnelling. Piles risk a reduction of their end-bearing capacity and shaft friction resistance due to the displacements and ground stress redistributions that occur as a result of tunnelling. A variety of research has been conducted on the subject, ranging from field studies (Kaalberg et al., 2005; Pang et al., 2006; Selemetas et al., 2006), experimental work (Bezuijen and Van der Schrier, 1994; Loganathan et al., 2000; Jacobsz et al., 2004; Marshall and Mair, 2011), and numerical or analytical modelling (Chen et al., 1999; Kitiyodom et al., 2005; Lee and Ng, 2005; Cheng et al., 2007). Analytical methods provide an efficient way for studying soil–structure interaction problems such as the effect of tunnelling on piles.

This paper studies the effect of a newly constructed tunnel on an existing pile using the analytical approach introduced by Marshall (2012, 2013). Some critical points from the original method are examined and some new ideas are presented which are intended to achieve a more sensible and thorough analysis approach. The paper includes data obtained using the original method of Marshall (2012) to elucidate the important effect that depth and the relative horizontal and vertical distance between the pile and tunnel have on results. Next, the selection and influence of soil stiffness used in the tunnel–pile interaction analysis are illustrated, and a new method for accounting for the effect of

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Nomenclature

a	current radius of a cavity
a_0	original cavity radius
C	cohesion
c	current radius of the plastic zone around a pile or a tunnel
c_0	original distance from pile tip to elastic–plastic interface
c_1	parameter used to calculate G_0
D_p	pile diameter
d_{tp}	distance from tunnel axis to pile tip
d_{lp}	distance from tunnel lining to pile tip
E	Young's modulus
G	soil shear modulus
G_0	small strain shear stiffness
$G_{0,mod}$	modified shear stiffness due to the effect of pile installation
$G_{0,tun}$	shear stiffness calculated at tunnel depth
I_d	relative density
I_R	relative dilatancy index
K_0	the coefficient of at-rest lateral earth pressure
k	cavity expansion parameter: spherical $k = 2$; cylindrical $k = 1$
L	embedded pile length
n	parameter used to calculate G_0
N_q	bearing capacity factor
p'	mean effective stress or confining pressure
p'_0	initial isotropic stress at tunnel or pile tip
$p'_{0,mod}$	modified pressure
$p'_{0,pile}$	confining pressure at pile tip
$p'_{0,tun}$	confining pressure at tunnel depth
p'_{mid}	confining pressure half-way between pile tip and tunnel lining
p'_{V_l}	confining pressure after tunnel volume loss
p_a	atmospheric pressure (100 kPa)
p'_{lim}	limiting stress for spherical cavity expansion
P	cavity pressure
P_a	current cavity pressure when cavity radius $= a$
q_b	end-bearing capacity of pile
$q_{b,0}$	end-bearing capacity of pile before tunnel volume loss
q_{b,V_l}	reduced end-bearing capacity of pile after tunnel volume loss
Q	total load capacity of the pile
Q_0	total load capacity of pile before tunnel volume loss
Q_{V_l}	total load capacity of pile after tunnel volume loss
r_p	pile radius
r_t	tunnel radius
R_{q_b}	pile end-bearing capacity reduction factor
R_Q	pile capacity reduction factor
$R_{Q,S}$	pile capacity reduction factor including effect on pile shaft
S	parameter used to calculate G_0
S_t	ratio of radial effective stress near pile tip at failure to q_b
V_l	volume loss due to tunnelling, in %
z	depth to any point below the ground surface
z_p	depth to pile tip
z_t	depth of tunnel axis
α_c	parameter used in calculation of q_b
β_s	ratio of shaft shear stress to vertical effective stress of soil
β_{min}, β_{max}	minimum and maximum values of β_s
δ_s	soil-shaft friction angle
θ	parameter used in calculation of α_c
ϕ	soil friction angle
ϕ'_{cv}	critical state friction angle
γ	soil unit weight
μ_s	a parameter to calculate β_s
v	Poisson's ratio
σ'	normal effective stress
σ'_r	radial stress
σ'^e_r	radial stress in elastic zone
σ'^p_r	radial stress in plastic zone
σ'_v	vertical stress
σ'_θ	circumferential stress
σ'^e_θ	circumferential stress in elastic zone
σ'^p_θ	circumferential stress in plastic zone
τ_s	shaft shear stress
$\overline{\tau_s}$	average shear stress on pile shaft
$\overline{\tau_{s,0}}$	average shear stress on pile shaft before tunnel volume loss
$\overline{\tau_{s,V_l}}$	average shear stress on pile shaft after tunnel volume loss
ψ	soil dilation angle

pile installation on soil stiffness is presented that gives a more sensible approach than the original method from Marshall (2012). A method for estimating the effect of tunnel cavity contraction on pile shaft friction is also proposed. Finally, data obtained using the original analysis method are compared against new results, and a recommendation is provided, based on analysis of available geotechnical centrifuge experiment data, on how to obtain a conservative evaluation of tunnel–pile separation or safe tunnel volume loss in order to avoid large pile displacements.

2. Cavity expansion methods

Fig. 1 shows the problem that is considered in this paper and the main geometric parameters considered. A tunnel of radius r_t is constructed beneath the tip of an existing pile with radius r_p. Distance d is measured along the path connecting the pile tip to the tunnel axis. The shortest distance from the centreline of the pile to the axis of the tunnel is given by d_{tp}; the distance from pile to the tunnel lining is given by d_{lp}. The paper focuses on driven or jacked piles which cause a significant impact on ground stresses around the pile tip. The analysis could, however, be applied to

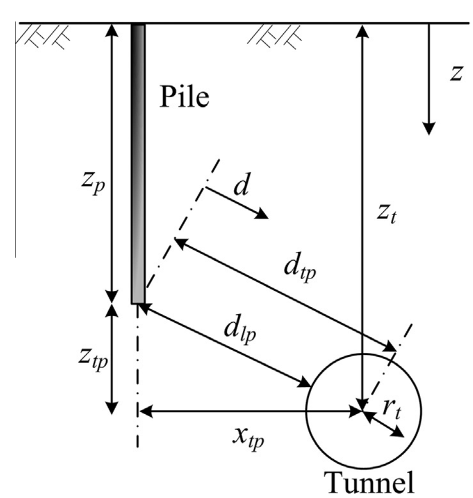

Fig. 1. View of the analysis problem.