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Semi-analytical model for umbrella arch systems employed in squeezing ground conditions

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A B S T R A C T

Methods of approximation that predict the mechanical responses of the tunnel support systems in conjunction with ground behaviour are invaluable to the tunnel design engineer. Analytical models are often used in order to predict and/or validate ground-support behaviour. Conventionally, these analytical models do not account for the complex loading and reacting conditions of umbrella arch support systems throughout the tunnel excavation and support sequence. As such, a semi-analytical model is proposed within this paper for umbrella-arch systems that employ an umbrella ache with forepoles, in squeezing-ground conditions. The semi-analytical model is based on an assortment of applicable methods and theories depending on the relevant loading. Beam theory, elastic foundation theory, and the Convergence-Confinement Method (CCM) are all incorporated within the proposed analytical method. After a review of the literature it became apparent that a limited amount of models existed for squeezing-ground conditions. Previous models were based on gravity-driven (Silo Theory) loading conditions rather than the more applicable stress-driven (squeezing) loading conditions. The results of the semi-analytical approach included herein were able to reasonably capture the displacement profiles associated with captured field data. This semi-analytical approach can be considered for use by tunnel design engineers in order to aid them with tunnel support design.

1. Introduction

There are many design challenges in relation to the determination of suitable tunnel support associated with anticipated squeezing ground conditions. The concepts introduced within this paper focus on the requirement for an improved analytical solution in order to aid in tunnel support selection and design. An Umbrella Arch (UA) is defined as a pre-support method that is installed during the first pass of an excavation from within the tunnel (i.e. above and around the crown of the tunnel face) which provides support and/or reinforcement due to the interaction between the support and the rock mass. Specifically, this paper focusses on determining the design and implementation of an UA system that is composed of forepole support elements as part of the temporary tunnel support system. Within literature, there is a consensus that there is no set standard with respect to the design of UAs (Carrieri et al., 1991; Hoek, 1999; Volkmann, 2003; Kim et al., 2005; Volkmann et al., 2006; Volkmann and Schubert, 2006, 2007; FHA, 2009; Volkmann and Schubert, 2010; Hun, 2011; Peila, 2013). As such, the semi-analytical model presented herein can be incorporated into the tunnel support design process as an approach for UAs. This approach is predicated upon the concepts introduced in Oke et al. (2014a) in terms of using the UA Selection Chart (UASC) in order to determine the type of UA to employ. The model that has been developed utilizes the Convergence-Confinement Method (CCM) (AFTES, 1983) approach in terms of expected tunnel behaviour due to excavation while also incorporating the loading condition (s) on the UA support elements (i.e. forepoles) using the principles associated with beam theory and elastic foundation (Winkler, 1867). The semi-analytical model created by the authors is able to capture the response of longitudinal support near the tunnel face and can be used to predict changing ground conditions ahead of the face. The model was validated using results from the Birgl Tunnel (Volkmann, 2003; Volkmann et al., 2006; Czopak, 2004; TU Graz, 2007). The results of numerical analyses using the semi-analytical approach were able to reasonably capture the displacement profiles associated with the behaviour of the forepole elements at the Bigl Tunnel.

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Nomenclature

S_{cfp}	centre to centre spacing of the forepole elements
c	cohesion
CCM	Convergence-Confinement Method
f	correction factor for shape
α_{fpa}	coverage angle of the forepole elements
A_L	curve fit variable: LDP, A_L
A_{La}	curve fit variable: LDP, A_{La}
A_{Lb}	curve fit variable: LDP, A_{Lb}
B_L	curve fit variable: LDP, B_L
B_{La}	curve fit variable: LDP, B_{La}
A_{o2}	curve fit variable: overloading, A_{o2}
B_{o2}	curve fit variable: overloading, B_{o2}
D_{o2}	curve fit variable: overloading, D_{o2}
A_{f2}	curve fit variable: tunnel face convergence, A_{f2}
B_{f2}	curve fit variable: tunnel face convergence, B_{f2}
E_{grou}	deformation modulus of the ground ahead of the face
c_s	distance between the springs
D	disturbed value
b	equivalent width of beam (loading)
b^*	equivalent width of beam (spring)
L_e	excavation step length
FEM	finite element method
FpCUA	forepole confined umbrella arch
FpGcUA	forepole grouted continuous umbrella arch
FpGUA	forepole grouted umbrella arch
FpGoUA	forepole open grouted umbrella arch
φ	friction angle
GSI	geological strength index
I_o	ground compressibility index
GRC	Ground Reaction Curve
λ	horizontal pressure coefficient
P_o	in-situ stress condition
α_{fp}	installation angle of the forepole element
E_i	intact deformation modulus
P_i	internal pressure
M_c	LDP curvature modifier variable, M_c
L_{fo}	length of forepole overlap
l_g	length of the depth of the influence in the ground
LDP	Longitudinal Displacement Profile
σ_L	longitudinal stress
R_m	mean radius of the silo
X^*	normalized distance from the face = X/R_t
$u_o{}^*$	normalized face convergence = u_o/u_{max}
$u_{fo}{}^*$	normalized final face convergence = u_o/u_{osup}
$u_f{}^*$	normalized final tunnel convergence ratio = u_{max}/u_{maxsup}
$\sigma_{cm}{}^*$	normalized rock mass strength ratio = P_o/σ_{cm}
P'	normalized stress overload
k'	normalized support stiffness ratio = k/E_{rm}
u^*_{sup}	normalized supported tunnel convergence = u/u_{maxsup}
u^*	normalized tunnel convergence = u/u_{max}
ϕ_{fp}	outside diameter of the forepole element
H	overburden
d_{pp}	Peila and Pelizza length d
g_{pp}	Peila and Pelizza length g
s_{pp}	Peila and Pelizza length s
σ_r	radial stress
R_f	reduction factor
E_{rm}	rock mass deformation modulus
G	shear modulus
γ	specific weight of ground
SpCUA	spile confined umbrella arch
SpGUA	spile grouted umbrella arch
B	steel set foundation size
q_s	stress on ground surface
Ps	support pressure
SRC	Support Reaction Curve
k	support stiffness
σ_t	tangential stress
TST	Terzaghi Silo Theory
t_{fp}	thickness of the forepole element
3D	three-dimensions
TBC	tunnel behaviour chart
u	tunnel convergence
u_{osup}	tunnel convergence at the face cross section, supported
u_o	tunnel convergence at the face cross section, unsupported
D_t	tunnel diameter
u_{maxsup}	tunnel max convergence, supported
u_{max}	tunnel max convergence, unsupported
R_t	tunnel radius
2D	two-dimensions
UASC	umbrella arch selection chart
L_u	unsupported span length
UA	Umbrella Arch

2. Background

2.1. General

An Umbrella Arch (UA) is defined as a pre-support method that is installed during the first pass of an excavation from within the tunnel (i.e. above and around the crown of the tunnel face) which provides support and/or reinforcement due to the interaction between the support and the rock mass. An illustration of relevant temporary support elements that include an UA (and associated parameters and arrangements) in tunnelling is illustrated in Fig. 1. The figure includes an assortment of tunnel support elements and their arrangements while focussing on the forepole element, specifically. Also included in Fig. 1 are the key spacing and length parameters associated with design.

It is important to note that as per the UASC, two different subcategories of UA systems with forepole elements are employed when considering squeezing-ground conditions: (a) Forepole Grouted UA (FpGUA) or (b) Forepole Confined UA (FpCUA) as defined by Oke et al. (2014a), and illustrated in Fig. 2. Therefore, the analyses conducted within this paper have utilized the properties associated with these types of UA systems.

The Birgl Tunnel located in Austria is the deepest comprehensive case study that focusses on capturing the behaviour of forepole elements within an UA arrangement. Instrumentation was installed longitudinally and directly above an UA consisting of forepole elements. The instrumentation consisted of a 10 link, 20 m long chain inclinometer (Volkmann, 2003). This allowed for an accurate representation of the displacement profiles at 2 m intervals of the forepole elements. These documented results were used in order to validate the semi-analytical method that was developed in MATLAB (Mathworks, 2012). A numerical model was also created to further validate the documented material properties. More details on these items are provided within the following sections of this paper.

2.2. Ground conditions and support

Prior to attempting to create an analytical model for an UA consisting of forepole elements, an understanding of how the system