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Numerical analyses in the design of umbrella arch systems

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ABSTRACT

Due to advances in numerical modelling, it is possible to capture complex support-ground interaction in two dimensions and three dimensions for mechanical analysis of complex tunnel support systems, although such analysis may still be too complex for routine design calculations. One such system is the forepole element, installed within the umbrella arch temporary support system for tunnels, which warrants such support measures. A review of engineering literature illustrates that a lack of design standards exists regarding the use of forepole elements. Therefore, when designing such support, designers must employ complex numerical models combined with engineering judgement. With reference to past developments by others and new investigations conducted by the authors on the Driskos tunnel in Greece and the Istanbul metro, this paper illustrates how advanced numerical modelling tools can facilitate understanding of the influences of design parameters associated with the use of forepole elements. In addition, this paper highlights the complexity of the ground-support interaction when simulated with two-dimensional (2D) finite element software using a homogenous reinforced region, and three-dimensional (3D) finite difference software using structural elements. This paper further illustrates sequential optimisation of two design parameters (spacing and overlap) using numerical modelling. With regard to capturing system behaviour in the region between forepoles for the purpose of dimensioning spacing, this paper employs three distinctive advanced numerical models: particle codes, continuous finite element models with joint set and Voronoi blocks. Finally, to capture the behaviour/failure ahead of the tunnel face (overlap parameter), 2D axisymmetric models are employed. Finally, conclusions of 2D and 3D numerical assessment on the Driskos tunnel are drawn. The data enriched case study is examined to determine an optimum design, based on the proposed optimisation of design parameters, of forepole elements related to the site-specific considerations.

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1. Introduction

As a design of underground excavations becomes larger and more complex, numerical analysis is required to combat increasingly difficult ground conditions, under which reinforcement may be required prior to excavation (pre-support). Due to its time and cost effectiveness in comparison with other pre-support methods (ground freezing, jet grouted columns, or pipe jacking), the umbrella arch method is increasing in popularity (Volkmann and Schubert, 2007). A corresponding increase in understanding of the interactions between the support system and the surrounding ground is required (Volkmann, 2003). Since 1991, literature has agreed that currently limited level of understanding is due to the lack of objective design criterion for the umbrella arch (Carrieri et al., 1991; Hoek, 1999; Volkmann, 2003; Kim et al., 2005; Volkmann et al., 2006; Volkmann and Schubert, 2006a, b, 2007, 2010; FHA, 2009; Hun, 2011; Peila, 2013). To aid design, Oke et al. (2014a) arranged the umbrella arch methods into thirteen sub-categories and associated them to applicable, specific failure mechanisms within the umbrella arch selection chart (UASC). This paper focuses on two of the sub-categories which employ the forepole element (confined and grouted in place) of the umbrella arch. It also illustrates the use of numerical modelling with regard to the overall response of the umbrella arch with forepole elements and the optimisation of selected design parameters for a squeezing failure mechanism, as illustrated in Fig. 1. Explicit numerical modelling for the optimisation of forepole element employed in other failure mechanisms, such as anisotropic conditions, is outside the scope of this paper. Investigation in the overall response of the forepole element was conducted using calibrated numerical models of two different tunnelling projects with in-situ data: the Driskos tunnel project (Vlachopoulos, 2009), and the Istanbul metro (Yasitli, 2013). Optimisation of selected design parameters was carried out for the severe squeezing ground at the Driskos tunnel at section 8 + 746 (Vlachopoulos and Diederichs, 2014).

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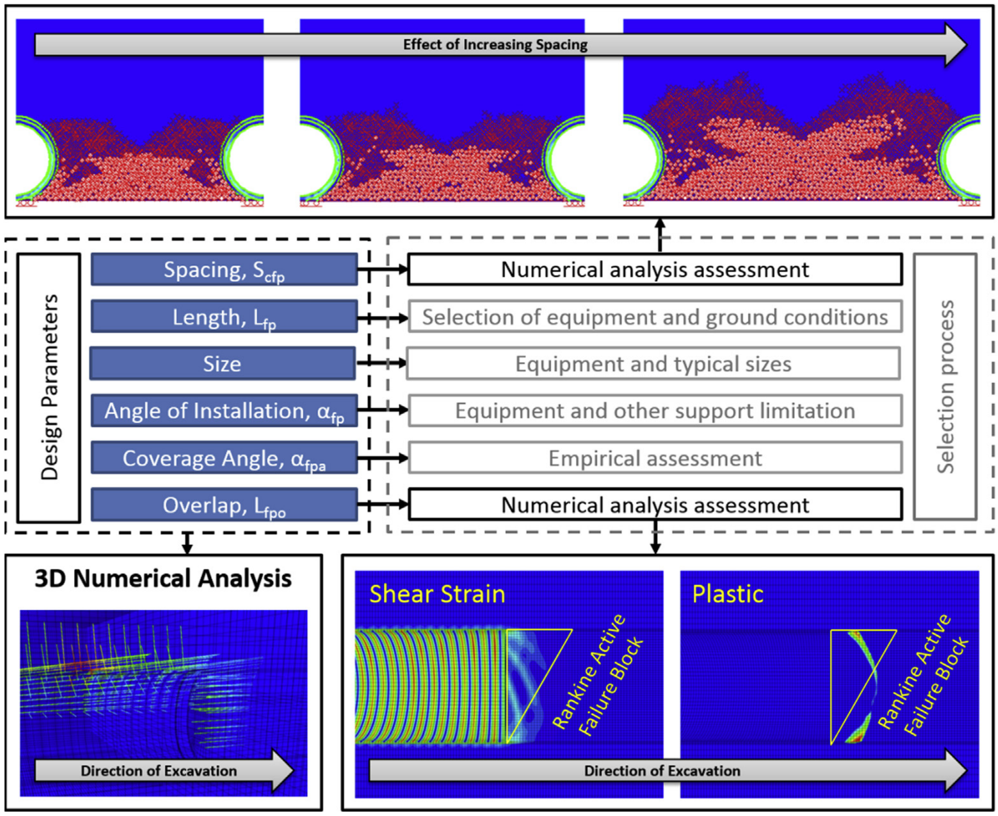

Fig. 1. Applications of numerical analysis for design parameters illustrated in Fig. 2, and overall response of forepole umbrella arch methods.

2. Background

Oke et al. (2014a) defined the umbrella arch as a pre-support installed within the tunnel, prior to the first pass of excavation, above and around the crown of the tunnel face which can be made up of spiles (length smaller than the height of excavation), forepoles (length greater than the height of excavation), or grout elements. This paper focuses specifically on the forepole elements, which are part of the temporary support system (e.g. shotcrete, steel sets, rockbolts, as shown in Fig. 2). However, prior to illustrating the extensive three-dimensional (3D) numerical analysis of forepole design, further details are necessary for the design parameters associated with the forepole umbrella arch, relevant investigations of cited literature that highlights important design considerations, the use of two-dimensional (2D) numerical investigation, and their disadvantages.

3. Design parameters

The design parameters for the forepole umbrella arch are shown in red in Fig. 2. Fig. 2a displays the length of forepole element (L_{fp}), and the length of forepole (or umbrella arch) overlap (L_{fpo}). The parameter L_{fp} cannot be optimised through numerical analysis as too many non-geomechanical factors governing the design exist. The L_{fp} depends on economic considerations, accuracy of drilling, accessibility of equipment and drillability with respect to ground conditions. The L_{fpo} can be optimised by using relevant numerical modelling. This overlap is required to ensure stability of the system and ground response, as illustrated in Fig. 1. In order to be effective in the longitudinal direction, the embedding of the forepole element requires sufficient distance (length) from the disturbed ground region. This embedment ensures that there will be sufficient longitudinal arching, which is the transfer of stresses at the tunnel face to the support system (in front of the face) and to the stable ground (ahead of the face), as illustrated in Fig. 3b. These parameters will be explained further in subsequent sections.

Fig. 2b illustrates the centre to centre spacing of the forepole elements (S_{cfp}), thickness of the forepole element (t_{fp}), and the outside diameter of the forepole element (ϕ_{fp}). The maximum S_{cfp} is defined by the requirement of developing a local arching effect, as shown in Fig. 3a (Volkmann and Schubert, 2007). This local arching can be analysed and captured with numerical models, as illustrated in the top portion of Fig. 1. It is important to note that the FHA (2009) has commented on the occurrence of a common misjudgement of the longitudinal (overestimation) and radial effects (underestimation) of the forepole design. Thus, there is a requirement for analyses on both a local (arching between forepole elements) and a global (complete system response) scale. The size of the forepole element is defined by two parameters: t_{fp} and ϕ_{fp}. Ultimately, these parameters will define the stiffness of the forepole as well as the loading area. This paper will illustrate that numerical modelling can be effective in determining an optimum size of the forepole elements within an umbrella arch arrangement. This optimum size, however, is further influenced by the installation equipment and the commercially standardised elements (pipes) available.

Fig. 2c displays the installation angle (α_{fp}) of the forepole element and the length of the unsupported span (L_{us}). The α_{fp} for spile element within umbrella arch methods can range from 5° to 40° as it is designed to lock in structural components or to ensure a certain thickness of grout barrier around the excavation. For forepole elements, however, the α_{fp} is defined by other temporary support elements (thicknesses of shotcrete and steel sets) as well as equipment clearances, to allow for the minimum possible angle.

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