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Design Consideration for Shallow Urban Tunnels in Weak / Soft Ground Conditions

Considération de la conception pour les tunnels urbains peu profonds en conditions de terrain faible ou doux

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ABSTRACT: When constructing tunnels in shallow ground environment it is important to keep ground movement (subsidence) to a minimum to prevent damage to adjacent infrastructure. One type of support that is used to mitigate the disturbance of ground during excavation is the umbrella arch system. An umbrella arch is defined as a pre-support method that is installed during the first pass of the tunnel from within the excavation, above and around the crown of the excavation face, which reinforces through the interaction of support and the rock mass. The support elements of an umbrella arch redistribute the stresses from the face onto other support elements (i.e. additional loading on steel sets) resulting in less subsidence if designed correctly. This paper discusses: the current limitation of subsidence reduction in empirical design guidelines for these support elements; how analytically solutions require special consideration, and how sensitivity analysis and engineering judgement are required for the multiple input parameters used for numerical analysis in order to create a realistic response. This paper also illustrates how a well instrumented umbrella arch, installed in-situ, can provide cost saving opportunities for the current operation and optimize future design.

1 INTRODUCTION

When constructing tunnels in a shallow ground environment it is important to keep ground movement (subsidence) to a minimum to prevent damage to adjacent infrastructure. Umbrella arch systems are often employed to mitigate the disturbance of ground and subsequently subsidence. An umbrella arch is defined as a pre-support method that is installed during the first pass of the tunnel from within the excavation, above and around the crown of the excavation face, which reinforces through the interaction of the support and the rock mass (Oke et al. 2014a).

An accepted design methodology for umbrella arch systems still does not exist (Oke et al. 2016), however there are some design considerations that can be made for umbrella arch systems employed in shallow ground. These include: empirical design charts, analytical solutions, and numerical analysis. Each of these design approaches and their limitations are discussed within the paper. Instrumentation of umbrella arch systems are seldom employed although it is the only way to capture the true mechanical response of the system. A discussion on how this type of monitoring solution can be used in design is also included within the paper.

2 UMBRELLA ARCH SUPPORT SYSTEMS

Oke et al. (2014a) found that many different authors use different terminology/nomenclature for similar support systems, or the same terminology for different support systems. Based on this finding, Oke et al. (2014a) proposed a nomenclature, to prevent any further confusion. Additionally, an Umbrella Arch Selection Chart (UASC) was produced, to aid designers in selecting the most applicable umbrella arch system based on the rationale for why the support is being used in the first place. When designing for urban tunnels in weak / soft ground, based on the UASC, umbrella arch systems are employed to either improve the ground around the excavation and/or reduce surface settlement. The focus of this paper is the latter.

2.1 Numerical Analysis

The most reliable method of analysis in terms of understanding the behaviour of umbrella arch systems is three-dimensional numerical analysis. Three-dimensional analysis is required due to the three-dimensional mechanistic response of the umbrella arch system. Due to limitation of computational time, it is

currently unrealistic to simulate the umbrella arch elements discretely. These elements need to be simplified to structural elements which are embedded into the numerical mesh. However, this approach has the current limitation of many input parameters that require a parametric analysis and review to ensure that the structural support behaves correctly. Details of this process are explained in Oke et al. (2014b), although this process can still be too time consuming for practical applications.

Two-dimensional numerical analysis, possibly the most common practice for designers, should not incorporate the umbrella arch structural elements into the design. For example, the simplified improved homogenous region as proposed by Hoek (2001) will provide displacement behaviour at the excavation boundary or surface which appear to be correct. However, if a homogenous region is used within these numerical analyses, the stress redistribution to the other support elements, such as steel sets will not be correct.

The only applicable time when two-dimensional analysis may be used for analysis is when grout in the umbrella arch is continuous around the periphery of the excavation face. The author proposes that, based on the current understanding of the mechanics, if two-dimensional design is used, the umbrella arch system should be ignored, and the improvements to the ground response can be estimated based on empirical data which will need to be later verified. This approach requires an observational type of design method and is not applicable for all type of contracts tendered.

2.2 Subsidence reduction empirical design

Oke et al. (2014a) collected case studies and published numerical analysis to produce an empirical design guideline for subsidence, as shown in Figure 1. Figure 1, related the different umbrella arch sub-categories to a possible reduction in subsidence. This type of design chart can be used in conjunction with two-dimensional analysis to predict improvements of surface settlement if umbrella arch systems are installed. Additionally, Figure 1 can be used to gain confidence in three-dimensional numerical analysis by comparing analysis with and without the support system is installed.

Figure 1 has been updated to include 2 additional data points from Choi and Shin (2004), and Yang et al. (2008) as well as the trend lines for Spile Grouted Umbrella Arches based on Krenn et al (2008). It is important to note that the Yang et al (2008) data point falls below the originally proposed trend line for Forepole

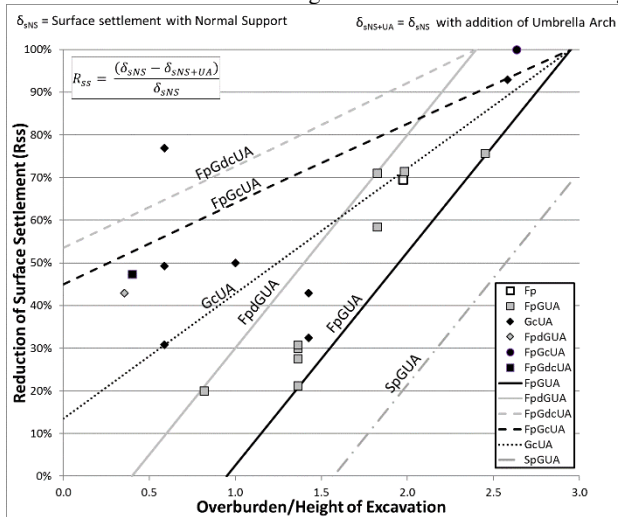


Figure 1: Literature review data of tunnelling projects that have had analysis conducted or observed the reduction of the surface settlement based on the usage of an umbrella arch. Trend lines indicate the potential reduction of surface settlement due to the employment of an umbrella arch system (above the associated line). FpGUA Forepole Grouted Umbrella Arch, FpdGUA Double Forepole Grouted Umbrella Arch, FpGcUA Forepole Continuous Grouted Umbrella Arch, FpGdUA Forepole Double Continuous Grouted Umbrella Arch, GcUA Continuous Grouted Umbrella Arch, SpGUA Spile Grouted Umbrella Arch. Modified after Oke et al. (2014a)

Grouted double continuous Umbrella Arch, which suggest that the trend line, based on limited data, needs to be updated. Due to the limited amount of available data, the trend lines should be used only as an estimation, and not be used to calibrate a numerical model.

2.3 Analytical Solutions

There are two different analytical solutions that can be used for umbrella arch systems when forepoles or spiles are employed, as explained in Oke et al. (2016). The first is a simple beam analysis that can estimate the expected moment of the support system, but not the deflection. The second is a complicated elastic beam foundation that can re-create the deflection profile of the umbrella arch system. The benefit of the former is that it can provide a quick estimation with limited required input. The benefit of the latter is that it can be used in conjunction with instrumentation to predict and quantify changing geological conditions. Both solutions simplify the loading condition to silo theory, with an imposed stress to simulate additional loading, such as buildings and other infrastructure.

3 INSTRUMENTING UMBRELLA ARCH SYSTEMS

Previous instrumentation of umbrella arch systems consisted of discrete measurement points along an individual support element, such as the work conducted by Volkmann (2003). It has been found through numerical analysis that the spatial resolution of measurements captured along these structural elements with current discrete technologies (e.g. electrical-resistance-strain-gauges) is not fine enough to capture the true deflection profile of the umbrella arch elements (Oke et al. 2016). However, advancement in sensing technology in the form of distributed optical strain sensing currently has capability to capture strain at a spatial resolution of 0.65mm along optical instrumented support elements. Furthermore, this increased resolution is also capable of complex loading combinations and can separate it into axial and 3D lateral components without prior knowledge of significant loading location or orientation (Forbes et al. 2016). This type of instrumentation when installed on spiles or forepole elements will finally give a true deflection profile. The author is

currently in the process of supervising an instrumentation program with these new sensors. Results from this instrumentation program will be used to calibrate a three-dimensional numerical model. The calibrated numerical model will allow the designers to further optimize the spiling design being employed for the current excavation as well as within an adjacent excavation.

4 CONCLUSIONS

The current state of design of umbrella arch systems for urban tunnels in weak / soft ground is very poor. Empirically there is limited data in the literature to provide any real confidence in trend lines which predict surface settlement reduction. Analytically the solutions are either too crude or complex to provide any quantifiable results. Numerically there is limited understanding on the behaviour of the systems, and therefore, numerical analysis requires parametric analysis for three-dimensional analysis and crude approximations for two-dimensional analysis. The only way to improve the design methodology is through instrumenting these systems coupled with complex analytical solutions or three-dimensional numerical analysis.

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