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Investigation the design criteria of umbrella arc system based on the instrumentation data and numerical simulation

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Abstract

One of the main challenges of tunnel excavation in urban areas is subsidence control, which can affect surface and underground structures. Nowadays, the performance of the umbrella arch system is accepted as an effective solution for controlling subsidence and tunnel excavation in conditions where face of tunnel is unstable. In this research, using the Birgel tunnel instrumentation data and its construction method, the numerical model has been calibrated and the three scenarios of cantilever beam, critical strain and reinforced zone have been investigated applying numerical simulation. The first scenario showed that if the internal forces of the pile element are examined, the stability factor 1 should be used as the design criterion. In the second scenario, using the level three of Sakurai warning is proposed as a design criterion. In the third scenario, relationships are developed to calculate the geometry and geomechanical parameters of the reinforced zone considering the second scenario. Based on the analysis results, the internal friction angle in the reinforced zone could be kept unchanged and just the modulus of deformation and cohesion in the reinforced zone are raised up according to the proposed relationships.

Key words: *Forepoling, Ground Subsidence, Numerical Simulation, Birgel Tunnel*

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Extended Abstract:

1. Introduction

Due to population growth in urban areas, the continuous development of subway lines is inevitable. Because of existing surface structures in urban area, excavation of new underground projects faces limitations such as subsidence. Umbrella arch system (Forepoling) is accepted as an approach to control the subsidence (Tunçdemir et al., 2012; Li and Niu, 2012; Morovatdar et al., 2020). The researches in this subject could be categorized into three general groups. The first group of studies examines the amount of subsidence. (Peila, 1994; Muraki, 1997; Yoo and Shin, 2003; Lee et al., 2004; Volkmann, 2004; Volkmann and Schubert, 2007; Hisatake and Ohno, 2008; S.Ockac, 2008; Jong et al., 2008; Volkmann and Schubert, 2010). The amount of subsidence was determined using numerical simulations, laboratory tests and in situ measurements and in all studies, a significant reduction of subsidence has been mentioned if the umbrella arch system is used. The second category of studies focuses on the operational parameters of this system. The third category of studies examines the action mechanism of umbrella arch system. As a result of limited knowledge to design the Forepoling or umbrella arch system, the design and implementation of this system is based on empirical knowledge gained from similar projects and so far no comprehensive method to design this system has been developed. Most of the existing studies have focused only on subsidence in this method, and few studies have considered the design of umbrella arch system. Therefore, in this study, in order to analyze and design the umbrella arch system, first of all, using back analysis carried out based on monitoring data gained from the Birgel Tunnel's instrumentations which is located in Austria, the geomechanical parameters of the tunnel has been evaluated. Then, according to the tunnel instrumentation data, geometry and its excavation method, three scenarios for designing the umbrella arch system in the mentioned tunnel have been examined and verified using numerical simulation. In the first scenario, the umbrella arc system is considered as a cantilever beam and its performance is investigated according to the internal forces created in the element. The second scenario is based on the allowable deformation and critical strain around the excavation zone. The third scenario proposes the use of a strengthened zone around the tunnel as an alternative to the zone reinforced by forepoling, the geometric characteristics and the amount of strengthening of the geomechanical parameters of this zone.

2. Materials and methods

In this research, Birgel railway tunnel was considered due to the installation of monitoring tools and the existence of an umbrella arc system as a calibration reference for the numerical model. In order to cross the fault section with the least possible displacement, one-meter advancing cycle has been used. Numerical simulation of the tunnel was performed using finite difference method and FLAC3D software. Before excavating of the tunnel, pre-support operations have been carried out around the tunnel using the umbrella arch system.

The constitutive model used in the numerical simulation before tunnel excavation and creating in-situ stress is elastic and after tunnel excavation the Mohr-Columb constitutive model is considered. Because, there is not any information about the dilation angle, its value is assumed to be zero in the numerical simulation.

After the initial equilibrium and the formation of in situ stresses, all the displacements and velocities of the nodes are zeroed. According to the forepoling pattern in the Birgel tunnel and its excavation sequence, after the formation of in situ stresses, the pile elements of the umbrella arch system are installed and the tunnel is excavated. Then the lattice is installed.
Therefore, first a series of pile elements with a length of 15 meters with an angle of 5 degrees to the horizon in a 120 degree arc is installed in the crown of the tunnel. The overlap of the pile elements is three meters. Then the excavating is done in cycles with one meter. After each stage of excavating, lattice and shotcrete are installed according to the interaction with the ground and the umbrella arch system is also installed to the proposed pattern in the crown part of the tunnel.
Due to the uncertainty in the geomechanical parameters provided for the Birgel tunnel, the geomechanical parameters of the tunnel have been verified using back analysis and the displacements recorded by the Monitoring tools. In order to evaluate the geomechanical parameters of the tunnel, based on the back analysis, the range of cohesion changes of 15-60 KPa, the internal friction angle of 15 to 25 degree and the modulus of deformation of 45 to 100 MPa have been considered.

3. Results

According to the strengthed zone scenario, by placing the steel pipe around the tunnel, the amount of modulus of deformation of the surrounding environment increases based on Eqs. 1 and 2.

$$E_{equ} = \frac{(A_{rf} - A_{pile} \cdot N_{fp}) . E_{gr} + A_{pile} . E_{pile}}{A_{rf}} \quad (1)$$

$$A_{rf} = \iint_{r_{tu}}^{r_{tu}+l_{fp}.\sin\alpha_{fpa}} r\, dr\, d\theta \quad (2)$$

Where A_{rf} is the strengthed zone area, A_{pile} is the steel pipe area, N_{fp} is the number of piles element, E_{gr} is the ground modulus of defromation, E_{pile} is the pipe elastic modulus, l_{fp} is the pipe length and $\sin\alpha_{fpa}$ is the instalation arc angle at the tunnel crown.
The modulus of deformation equivalent to the reinforced area should be used to estimate the allowable strain. Based on the available displacements and the stability criteria based on the critical strain, all criteria, except Sakura's third warning level, predict the instability of this type of umbrella arc system arrangement. Taking into account the existing geomechanically conditions and the equivalent modulus of deformation, the cohesion of the alternative strengthed zone, has to be considered 500 times the initial one.

4. Conclusion

Due to the internal forces of pile element and the low level of axial forces, the behavior of this element is close to the behavior of beam instead of beam-column. So, safety factor one according to the geometric and mechanical properties of the installed pile element should be considered as a stability criteria. In the design of the forepoling system according to the allowable strain, first the modulus of deformation of the reinforced zone must be modified and replaced with the equivalent modulus. Due to the location of Birgel tunnel and most of the urban tunnels that need to be reinforcing with forepoling at a shallow depth and sensitivity analysis has been done, the effect of the internal friction angle on the tunnel displacement can be ignored and its value can be considered equal to the initial value in the numerical analysis of the altenative strengthed zone. Also, the amount of cohesion in this zone can be evaluated by inferring from the critical strain relationship, the Mohr-Columb consitutive criterion and the equivalent deformation modulus. The geometry of the alternative strengthed zone can also be calculated using the installed forpoling pattern. It is possible to use the reinforced zone scenario with the recommended geometry and geomechanical parameters to design the forepoling system.

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