Journal of Rock Mechanics and Geotechnical Engineering xxx (2018) 1–20

CSRME

Contents lists available at ScienceDirect

Journal of Rock Mechanics and Geotechnical Engineering

journal homepage: www.rockgeotech.org

Full Length Article

Numerical modeling of time-dependent deformation and induced stresses in concrete pipes constructed in Queenston shale using micro-tunneling technique

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A R T I C L E I N F O

Article history:
Received 19 July 2017
Received in revised form
26 September 2017
Accepted 5 November 2017
Available online xxx

Keywords:
Numerical model
Micro-tunneling
Queenston shale (QS)
Lubricant fluids (LFs)

A B S T R A C T

Effects of time-dependent deformation (TDD) on a tunnel constructed using the micro-tunneling technique in Queenston shale (QS) are investigated employing the finite element method. The TDD and strength parameters of the QS were measured from tests conducted on QS specimens soaked in water and lubricant fluids (LFs) used in micro-tunneling such as bentonite and polymer solutions. The numerical model was verified using the results of TDD tests performed on QS samples, field measurements of some documented projects, and the closed-form solutions to circular tunnels in swelling rock. The verified model was then employed to conduct a parametric study considering important micro-tunneling design parameters, such as depth and diameter of the tunnel, in situ stress ratio (K_0), and the time lapse prior to replacing LFs with permanent cement grout around the tunnel. It was revealed that the time lapse plays a vital role in controlling deformations and associated stresses developed in the tunnel lining. The critical case of a pipe or tunnel in which the maximum tensile stress develops at its springline occurs when it is constructed at shallow depths in the QS layer. The results of the parametric study were used to suggest recommendations for the construction of tunnels in QS employing micro-tunneling.

1. Introduction

The time-dependent deformation (TDD) behavior of shales in southern Ontario, Canada was extensively investigated during the past four decades (e.g. Lo et al., 1975, 1978; Yuen, 1979; Lo and Yuen, 1981; Lo and Lee, 1990; Lee and Lo, 1993; Hefny et al., 1996; Lo and Hefny, 1996; Hawlader et al., 2003). These studies provided good insights into the swelling phenomenon of these shales, and its measurements, causes and controlling mechanism. Lo and Yuen (1981) developed a closed-form visco-elastic solution to predict deformations and stresses in concrete lining of circular tunnels in swelling rocks. Hefny et al. (1996) extended this solution to account for long-term swelling and critical stress, defined as the minimum stress required to stop rock swelling. Both solutions were utilized to analyze many tunnels in southern Ontario, as indicated by Lo and Hefny (1996).

The strength of shales in southern Ontario was also investigated (Lo and Hori, 1979; Yuen, 1979; Lo and Yuen, 1981; Wai et al., 1981; Lo et al., 1987; Lee, 1988). The strength was found to be anisotropic with respect to the rock bedding. Investigations on similar rock types demonstrated that increasing their moisture content reduced their strength significantly (Colback and Wiid, 1965; Paterson, 1978; Baud et al., 2000; Claesson and Bohloli, 2002; Paterson and Wong, 2005; Gorski et al., 2007; Liang et al., 2012; Dan et al., 2013; Wasantha and Ranjith, 2014).

Al-Maamori (2016) investigated the impact of lubricant fluids (LFs) used in micro-tunneling applications on both of TDD and strength of the Queenston shale (QS). The TDD behavior of QS in LFs was found to be different from that in water, and its strength decreased with different percentages after being soaked in water and LFs. Given that the TDD behavior of QS and its strength degradation are different in LFs compared to those in water, it is necessary to investigate the effects of LFs used in micro-tunneling technique on the constructed pipe or tunneling.

Several numerical studies were conducted to investigate the TDD of swelling rock employing the finite element (FE) method. Hawlader et al. (2003) developed a plane-strain FE model to predict

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Peer review under responsibility of Institute of Rock and Soil Mechanics, Chinese Academy of Sciences.

https://doi.org/10.1016/j.jrmge.2017.11.006
1674-7755

Please cite this article in press as: Al-Maamori HMS, et al., Numerical modeling of time-dependent deformation and induced stresses in concrete pipes constructed in Queenston shale using micro-tunneling technique, Journal of Rock Mechanics and Geotechnical Engineering (2018), https://doi.org/10.1016/j.jrmge.2017.11.006

deformations and stresses induced in tunnel lining due to swelling rock. Kramer and Moore (2005) used the swelling model proposed by Lo and Hefny (1996) and developed a plane-strain FE model to calculate the TDD of the rock and stresses due to rock-tunnel lining interaction. Heidkamp and Katz (2002) proposed an implicit integration scheme using Grob (1972)'s swelling law to predict volume increase of gypsum and clay minerals and implemented it in a FE program. Wittke-Gattermann and Wittke (2004) developed a constitutive elasto-plastic law to describe swelling of non-leached gypsum, considering its anisotropic behavior, and implemented it in three-dimensional (3D) FE program. Schädlich et al. (2012) extended this model to a general rock swelling model using Grob's swelling law. Schädlich et al. (2013) implemented the rock swelling model in PLAXIS computer program to back-analyze the in situ measurements of the Pfäender railway tunnel in Austria.

All the previous studies investigated the TDD effects due to soaking of rocks in water. However, the TDD behavior of shale in the LFs was found to be significantly different. Compared to water, the polymer and bentonite solutions have caused different amounts of decrease in the TDD of the QS (Al-Maamori, 2016; Al-Maamori et al., 2016). When these effects are considered, they may lead to a safer design of pipes and tunnels constructed in shales using the micro-tunneling technique.

The main objective of this research is to investigate the TDD and stresses induced in pipes or tunnels constructed using the micro-tunneling technique in QS. This objective is achieved through numerical modeling employing the FE analysis program PLAXIS 2D (PLAXIS, 2016). The rock swelling model developed and implemented in PLAXIS 2D environment is based on Grob's swelling law, which is mathematically identical to the Lo and Hefny (1996)'s swelling model. The results are envisioned to aid designers and contractors to determine whether micro-tunneling technique is a feasible construction technique for pipelines and tunnels in the QS of southern Ontario, Canada.

2. Geological background

Fig. 1 shows the geological map of southern Ontario. As can be observed from Fig. 1, most of southern Ontario region is located in the Appalachian sedimentary basin, which is bounded by the Precambrian basement highs in the west, Taconic mountain range in the east and south, and the Frontenac arch in the north (Perras, 2009). The QS layer in this basin is an argillaceous sedimentary rock formed in the upper Ordovician age in south-west region of Ontario. It forms most of south and west shores of Lake Ontario and extends to the north towards the Georgian Bay. Together with other rocks in the Appalachian basin, the QS layer dips 6 m/km to the south (Yuen et al., 1992), and it becomes thinner and overlain by other rocks from the Silurian and Devonian ages, such as Grimsby and Eramosa shales, dolomite, and limestone of different formations. This layer forms the host ground for many important engineering projects in Ontario, such as the Niagara tunnel (Perras, 2009). More recently, several pipelines and tunnels are constructed in the QS layer using the micro-tunneling technique.

3. Locations of investigated Queenston shale

The QS samples investigated in this research were collected from two boreholes located in Milton and Niagara Falls regions, as shown in Fig. 1. The rock quality designation (RQD) of the QS layer from Milton increased with depth from 50% to 99.2%, indicating fair to excellent rock condition. The bedrock in this region starts at a depth of 15.5 m below ground level (BGL). Based on the RQD value and the occurrence of joints, the QS layer of Milton can be divided into three sublayers: (i) upper sublayer (from 15.5 m to 22.5 m BGL) with an average RQD value of 68.9%, and 2–5 mm compacted clay joints occurring at an average of 4 joints/m, which corresponds to geological strength index (GSI) value of 42 (Hoek et al., 1995); (ii) middle sublayer (from 22.5 m to 26.5 m BGL) with an average RQD value of 89.9%, and 2–5 mm compacted clay joints occurring at an average of 1 joint/m, which corresponds to GSI value of 54; and (iii) lower sublayer (from 26.5 m to 34.52 m BGL) with an average RQD value of 96.8%, and compacted clay joints that occur at 1 joint/(4 m), corresponding to GSI value of 59. The Niagara QS was collected from a borehole drilled from the invert of the Niagara tunnel at its lowest part at a depth of 125–137 m BGL. The recovered samples were approximately 12 m long. The suggested GSI value for this layer is 59. Based on the GSI value, the strength envelope of each layer was developed utilizing RocLab software (Rocscience, 2016). The modulus, cohesion and frictional angle of the rock mass of each layer were derived from the developed strength envelopes. The parameters were derived for intact rock (i.e. as collected from site) and after soaking the QS samples in water and LFs for 100 d to account for the strength degradation of the shale near the excavation. The strength envelopes were established based on the results of an experimental study that was conducted to evaluate the strength degradation of the QS after being exposed to water and LFs (Al-Maamori, 2016).

4. Finite element PLAXIS 2D rock swelling model

The computer program PLAXIS 2D has two-dimensional (2D) user-defined constitutive model that can simulate rock swelling behavior (PLAXIS, 2016). This constitutive model simulates the TDD behavior of rocks based on swelling clay minerals that exist in their micro-structure. The mathematical formulation of the TDD behavior of rocks in this constitutive model was developed essentially based on Grob (1972)'s swelling law, which is shown in Fig. 2a. In this model, the swelling mechanism of rocks is related to the osmotic swelling and the inner-crystalline swelling of clay minerals (Madsen and Müller-Vonmoss, 1989). The osmotic swelling is caused by the differences in cation concentration in the clay and in the free pore water, and it occurs after the completion of the inner-crystalline swelling. This swelling is caused by the increase in the repulsive forces between the negatively charged neighboring clay layers, which in turn increases the distance between these layers. The inner-crystalline swelling occurs first, and it can result in 100% of volume increase of clay particles in the case of montmorillonite. This swelling occurs due to the integration of water molecules into the clay mineral crystals when the existing cations hydrate in the presence of water. When the energy released in the process of cations hydration exceeds the anion–cation bond within the clay mineral, swelling occurs. The swelling pressure in this process depends on the nature of the existing cations, where Na^+ cations result in larger swelling pressure than Ca^{2+} cations (PLAXIS, 2014). The stress-dependency of the TDD of rock follows a semi-logarithmic relation, as indicated in Fig. 2a. The TDD decreases with increasing applied stress in a logarithmic scale. The mathematical expression of the developed rock swelling model in PLAXIS (2014) is given by

$$\varepsilon_i^{q(t\to+\infty)} = -k_{qi}\log_{10}\left(\frac{\sigma_i}{\sigma_{q0i}}\right) \tag{1}$$

where $\varepsilon_i^{q(t\to+\infty)}$ is the final swelling strain, k_{qi} is the axial swelling parameter (i.e. swelling potential in axial direction under the applied axial stress in the Lo and Hefny (1996)'s model), σ_i is the applied stress in that direction, and σ_{q0i} is the maximum axial

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