Tunnelling and Underground Space Technology 73 (2018) 252–260

Contents lists available at ScienceDirect

Tunnelling and Underground Space Technology

journal homepage: www.elsevier.com/locate/tust

Parametric study of the impacts of various geological and machine parameters on thrust force requirements for operating a single shield TBM in squeezing ground

Rohola Hasanpour[a,c,*], Jamal Rostami[b], Markus Thewes[a], Jürgen Schmitt[c]

[a] Institute for Tunneling and Construction Management, Ruhr-University Bochum, Germany
[b] Department of Mining Engineering, Colorado School of Mines, USA
[c] Department of Civil Engineering, Darmstadt University of Applied Science, Darmstadt, Germany

ARTICLE INFO

Keywords:
Single shield TBM
Required thrust force
Shield jamming
Numerical modeling
Regression analysis

ABSTRACT

Excavation of long tunnels by shielded TBMs is a safe, fast, and efficient method of tunneling that mitigates many risks related to ground conditions. However, TBM applications in difficult conditions such as squeezing ground, which often happens in a combination of weaker rock and/or high depth, may lead to problems such as shield jamming. Insufficient thrust force, which cannot overcome the shield skin friction between the machine and the ground, causes shield entrapment. For successful tunneling in such conditions, it is essential to study the pertinent ground and operational factors and their impact on ground behavior, to assess the possibility of shield entrapment and to develop possible safeguards to mitigate the related risks. In this study, the controlling parameters influencing the risks of tunneling by single shield TBMs in squeezing ground are examined. For this purpose, a parametric study was performed by using a full 3D numerical simulation to quantify the influence of various factors on machine entrapment. Sensitivity analysis of most important parameters and their impacts on entrapment risks has been conducted and the results are discussed in this paper. Furthermore, nonlinear regression analysis was performed to develop a relationship between ground and machine parameters, and the required thrust force needed to overcome contact/frictional forces for propelling machine forward. The result of the modeling was compiled in a database to observe the trends and develop relationship between different parameters and risk of machine entrapment. This allows for assessment of the applicability of shield TBM in weak formations along the tunnel. Furthermore, the results of the analysis can be used to evaluate the operational parameters such as the installation of a higher thrust force to overcome contact friction loads and to make a choice between increasing the overcut or using lubricants between shield and ground. The results of this study show the role of ground conditions and in-situ stresses, as well as machine operational parameters on convergence and shield pressures.

1. Introduction

Application of Tunnel Boring Machines (TBM) in excavating long and deep tunnels has become the preferred choice of tunneling methods in recent years, as TBMs have become more adaptable to various ground conditions. To cope with difficult geological situations, single and double types of shielded TBMs were introduced. Despite successful use of these type of shielded TBMs in various fast track projects, several cases of machine entrapment have been reported when tunneling in squeezing grounds. Some of the recent examples include Arrowhead Tunnels (USA, L = 9.3 km, D = 5.82 m), Pajares Tunnel, Section 4 (Spain, L = 10.3 km, D = 9.88 m), Uluabat Tunnel (Turkey, L = 11.8 km, D = 5.05 m), T26 Tunnel (Turkey, L = 6.1 km, D = 13.7 m), Pinglin Tunnel (Taiwan, L = 12.9 km, D = 6.10 m), Ghomrud Tunnel (Iran L = 21 km, D = 4.4), and Hida Tunnel (Japan, L = 10.7 km, D = 12.8 m). TBM jamming is generally due to the presence of weak grounds or high in situ stresses where high ground convergence occurs and imposes high ground loads on the shield.

Entrapment incidents of the shield, cutterhead jamming, and backup seizure are major problems, which can bring the operation to a halt and reduce the advance rate drastically. In many cases, resuming the operation requires manual excavation to release the shield that is confined by the excessive ground convergence. This is a time consuming, costly, unsafe, slow, risky, and labor-intensive work that

* Corresponding author at: Institute for Tunneling and Construction Management, Ruhr-University Bochum, Germany.
E-mail addresses: ra.hasanpour@gmail.com (R. Hasanpour), rostami@mines.edu (J. Rostami), markus.thewes@rub.de (M. Thewes), juergen.schmitt@h-da.de (J. Schmitt).

https://doi.org/10.1016/j.tust.2017.12.027
Received 11 March 2017; Received in revised form 14 November 2017; Accepted 28 December 2017
0886-7798/

should be avoided as much as possible (Farrokh and Rostami, 2009).

Shield jamming is becoming a common issue in many cases of TBM applications at higher depth. In such conditions, insufficient thrust force, which cannot overcome the shield skin friction, have often led to TBM jamming. Therefore, accurate prediction of the thrust force required to overcome the high skin friction forces between shield and ground due to high stresses is important. This is for efficient tunneling operation and preventing the extended delays in excavation process, and perhaps implementation of countermeasures beforehand.

Studies on this topic involve the empirical methods presented by Farrokh et al. (2006), Jafari et al. (2007), Farrokh and Rostami (2009). These papers discuss empirical methods based on the field observation in special tunneling projects. However, in order to assess shield jamming and entrapment risks in squeezing conditions, it is essential to conduct full 3D numerical simulations of the excavation process by considering the interaction mechanism between ground and machine components. The 3D model should also take both of ground and TBM components into accounts.

To examine stress-strain behavior of the ground, advanced 3D models have been developed in recent years by Mansour (1996), van Dijk and Kaalberg (1998), Komiya et al. (1999), Dias et al. (2000) and Melis et al. (2002). Kasper and Meschke (2004, 2006), who have studied the influence of TBM operation parameters and design parameters for a shallow tunnel in homogeneous, soft, cohesive soil below the ground water table by using a full 3D numerical simulation. Moreover, studies regarding the computational modeling of mechanized tunneling in long and deep tunnels through adverse ground conditions have been reported by various authors. Lombardi and Panciera (1997), Einstein and Bobet (1997), Graziani et al. (2007), Sterpi and Gioda (2007), Wittke et al. (2007), Ramoni and Anagnostou (2007), Amberg (2009) and Schmitt (2009) are among the studies where numerical investigations on TBM tunneling by applying different computational methods have been conducted. Furthermore, Ramoni and Anagnostou (2010) have developed the dimensionless design nomograms using the analysis of several thousand of 2D simulated models, which allow a rapid preliminary calculation of the thrust force, required to overcome shield frictional forces and avoid shield jamming. Recently, detailed 3D finite difference modeling of tunneling process by shielded TBMs have been studied by Zhao et al. (2012), Hasanpour (2014), Hasanpour et al. (2014–2016). These models consider the main components of machine, ground, performance and tunnel parameters that distinguish them from other 3D models that have been developed using numerical simulation of shielded TBMs in the past. The results of the modeling can be used for estimation of tunnel convergence during excavation, prediction of the contact loads on the shield in order to calculate the required thrust force, and computation of ground pressures on the segmental linings.

This paper focuses on realistic evaluation of the interaction between ground and a single shield TBM and the possibility of machine jamming in squeezing ground. For this purpose, 3D finite difference modeling of the tunnel being mined by a single shield TBM through squeezing ground was used to simulate the ground behavior and calculate the amount of the contact loads between shield and ground. Estimation of ground pressure on the shield makes it possible to predict the required thrust force needed to propel the machine forward in squeezing ground conditions. The most important factors in the numerical analysis of tunneling by shielded TBMs were described in the previous studies. The follow up studies have led to better understanding of the ground behavior as will be explained in this paper. Moreover, this paper offers some recommendations on the most efficient handling of the important TBM and tunnel parameters when evaluating machine entrapment risks. A parametric study has been conducted for various combinations of rock mass and TBM parameters for evaluation impact of different tunneling conditions on the required thrust force. Based on the results of 200 numerical simulations, a nonlinear regression analysis was performed to find a relationship between ground and machine parameters, and anticipated ground loads on the shield.

It should be noted that the impact of uncertainties regarding the geological conditions such as tectonic stresses, adverse ground conditions with low Q values and blocky ground on shield jamming may not be evaluated using the relationships developed in this research. This is due to the possibility of generating errors in calculations for out of bound values. The risk of jamming in such difficult situations should be investigated in detail using data and relevant reports from field by considering the real mechanism and sometimes by means of the advanced simulation methods. Typical example for TBM jamming in tectonic zones due to excessive ground stresses is Dogancay Tunnel in Turkey. Furthermore, Kargi Tunnel in Turkey can also be referred as another jamming event within tunneling through a blocky rock mass with low Q values. More discussion about these tunneling projects and jamming events through difficult grounds can be found in the studies by Barton and Bilgin (2016) and Bilgin et al. (2016). On the other hand, the exact values of in situ-stresses and rock mass properties should be used in the numerical analysis when assessing the potential of shield entrapment in each underground project to achieve to the reliable results. The limitation of the numerical simulation when modeling the ground behavior and the step-by-step nature of the solutions should be added to the list of uncertainties when using this approach for design purposes

The results of numerical simulations allow for evaluation of the effective design and operational parameters of the TBM such as the shield length and installation of a higher thrust force on the machine. Furthermore, the results of this study can be used for assessing the role of overcut and ground improvements methods (grouting of the ground or lubricating the shield-ground interfaces). The results allow for objective evaluation of entrapment risks of single shield TBMs in difficult grounds. The suggested relationships make it possible to perform a quick preliminary assessment of the thrust force required to overcome shield skin friction in various formations and sections of a long tunnel. It also allows for the assessment of effective design parameters and operational measures such as reduction in the shield length and installation of a higher thrust force for single shield machines. The impacts of changes in overcut and implementing ground improvements methods or lubricating the shield surface can also be assessed.

2. Numerical modeling

FLAC3D software, which is based on Finite Difference Method (FDM), was used for modeling of the stress-strain behavior of the rock mass in a tunnel construction by a single shield TBM. Critical input parameters for simulation of tunnel in squeezing conditions are uniaxial compressive strength of intact rock, *UCS*, Geological Strength Index, *GSI*, Hoek-Brown material constant, m_i, elastic modulus of intact rock, E_i, the initial stress, P_0, tunnel radius, R, overboring or overcut, DR, shield length, L, the skin friction coefficient between rock and shield, μ. Considering various combinations of these parameters, numerical analyses for calculation of required thrust force when shield is subjected to ground loading were conducted. Table 1 shows data sets for

Table 1
Range of geomechanical parameters and geometrical dimensions for SS-TBM components considered for numerical investigations.

Ground properties, tunnel parameters and SS-TBM components	Unit	Value	Intermediate steps
Geological Strength Index (GSI)	–	20–60	5
Hoek-Brown material constant (m_i)	–	4–20	4
Uniaxial compressive strength (UCS)	MPa	5–75	10
Elastic modulus of the intact rock (E_i)	GPa	5–40	5
In-situ stress (P_0)	MPa	2–20	2
Tunnel outer radius (R)	m	2–9	1
Overcut (DR)	mm	20–200	2
Shield length (L)	m	8–12	1