Tunnelling and Underground Space Technology 26 (2011) 692–717

Contents lists available at ScienceDirect

Tunnelling and Underground Space Technology

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

Squeezing loading of segmental linings and the effect of backfilling

M. Ramoni [a,*], N. Lavdas [b,1], G. Anagnostou [a]

[a] ETH Zurich, Switzerland
[b] Rothpletz, Lienhard + Cie AG, Olten, Switzerland

A R T I C L E I N F O

Article history:
Received 22 November 2010
Received in revised form 17 March 2011
Accepted 6 May 2011
Available online 14 June 2011

Keywords:
Tunnel boring machine
Squeezing ground
Segmental lining
Squeezing pressure
Overstressing
Backfilling
Nomograms
Numerical investigation

A B S T R A C T

Overstressing of the segmental lining is one of the major hazard scenarios related to shielded TBM tunnelling in squeezing ground. The present paper deals with this specific problem, addressing the key question of the ground pressure acting upon a segmental lining installed behind a single shielded TBM. Starting with a structured discussion of the influencing factors and their interactions, the paper investigates how the type, location and thickness of the backfilling play an important role with respect to the loading of a segmental lining. Secondly, it explains how to take due account of the actual thickness of the backfilling (which is not known a priori since it depends on the deformations of the bored profile) in a numerical simulation. Thirdly, the paper advances a number of theory-based decision aids which cover the relevant range of ground parameters, initial stress, segmental lining and backfilling characteristics, thus supporting rapid initial assessments of the ground pressure acting upon a segmental lining and making a valuable contribution to the decision-making process.

1. Introduction

The main hazard scenarios for shielded TBM tunnelling in squeezing ground are sticking of the cutter head, jamming of the shield or damage to the tunnel support. Furthermore, the occurrence of significant deformations (ovalization) or even horizontal or vertical shifting of the segmental lining may lead to jamming of the back-up equipment or to violation of the clearance profile.

In a series of recent publications, the authors discussed the specific problems of – and experience with – TBMs in squeezing ground, reviewed the available countermeasures, commented on possible technological improvements (including the development of deformable lining systems), analyzed the interaction between the shield, ground and tunnel support quantitatively and provided design charts concerning the thrust force needed in order to avoid shield jamming (Ramoni and Anagnostou, 2010a, 2010b, 2010c, 2010d). The present paper extends this research by addressing the potential hazard of lining overstressing.

A realistic estimation of the loading of a segmental lining is only possible if due account is taken of the backfilling features. Section 2 of the present paper shows – with a structured discussion of the influencing factors and their interactions – that the type, location and thickness of the backfilling play an important role with respect to the ground pressure acting upon a segmental lining. Section 3 explains how to take due account of these features in a numerical simulation and, more specifically, how to deal with the non-linearity of the problem. The problem is demanding because the actual thickness of the backfilling is not known a priori, as it depends on the ground deformations that occur between the tunnel face and the point at which the backfilling is completed. Section 4 presents, in the form of dimensionless design nomograms, the results of a comprehensive parametric study into the ground pressure acting upon a segmental lining which exploits the numerical efficiency and reliability of the computational model introduced in Section 3. The nomograms cover the relevant range of ground parameters and initial stress, as well as different characteristics of the TBM, the segmental lining and the backfilling (type and location), and allow a quick preliminary assessment to be made of the loading of a segmental lining. This is the first time that such a systematic and thorough investigation has been presented.

An extended literature review on computational methods for TBM tunnelling in squeezing ground can be found in Ramoni and Anagnostou (2010b). Recent publications closely related to the topic of the present paper include those of Simic (2005), Graziani et al. (2007) and Schmitt (2009). Simic (2005) carried out numerical investigations for the assessment of the loading of the segmental lining in the “La Umbria” Fault of the Guadarrama Tunnel

* Corresponding author. Tel.: +41 44 633 32 71; fax: +41 44 633 10 97.
E-mail address: marco.ramoni@igt.baug.ethz.ch (M. Ramoni).
URL: http://www.tunnel.ethz.ch

1 Formerly: ETH Zurich, Switzerland.

0886-7798/$ - see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.tust.2011.05.007

Nomenclature

D	boring diameter
d_b	thickness of the backfilling
d_l	thickness of the segmental lining
d_s	thickness of the shield
E	Young's modulus of the ground
E_b	Young's modulus of the backfilling
E_l	Young's modulus of the segmental lining
E_s	Young's modulus of the shield
f_c	uniaxial compressive strength of the ground
$f_{c,l}$	uniaxial compressive strength of the segmental lining
G	ground
H	depth of cover
K_b	stiffness of the backfilling
K_c	composite stiffness (segmental lining and backfilling)
K_l	stiffness of the segmental lining
K_s	stiffness of the shield
L	length of the shield
L_f	length of the front shield (double shielded TBM)
L_r	length of the rear shield (double shielded TBM)
N	number of entities of a N^2 chart
p	ground pressure
p^*	normalised ground pressure
p_{max}	bearing capacity of the segmental lining
R	tunnel radius
$R_{l,o}$	outer radius of the segmental lining
$R_{s,i}$	inner radius of the shield
$R_{s,o}$	outer radius of the shield
SF	safety factor
t	difference between radius of the shield intrados and radius of the segmental lining extrados
u	radial displacement of the ground at the tunnel boundary
u_b	radial displacement of the bored profile before completion of the backfilling
v_g	gross advance rate
x	radial co-ordinate (distance from the tunnel axis)
y	axial co-ordinate (distance behind the tunnel face)
ΔR	difference between boring radius and radius of the shield extrados
ΔR_l	difference between boring radius and radius of the segmental lining extrados
ΔR_r	difference between boring radius and radius of the rear shield extrados (double shielded TBM)
γ	unit weight of the ground
φ	angle of internal friction of the ground
λ	location (distance behind the shield), where backfilling is completed
λ^*	location (distance behind the shield), where the ground closes the gap around the segmental lining
ν	Poisson's ratio of the ground
σ	stress
σ_0	initial stress
ψ	dilatancy angle of the ground

(Spain, double shielded TBM, D = 9.51 m), taking into account the effect of creep. Graziani et al. (2007) investigated a double shielded TBM drive (D = 11.00 m) for the planned Brenner Base Tunnel (Austria/Italy) in the framework of the "TISROCK" research project, gaining a valuable insight into the effects of the length of a shear zone and of the stiffness of the backfilling on the sectional forces in the segmental lining. The work of Schmitt (2009) is of a more general nature and investigates the effects of non-uniform convergence and of non-hydrostatic shield and lining loading for single shielded TBMs. All of these investigations are based upon fully three-dimensional, step-by-step numerical simulations, assuming a priori the thickness of the backfilling and, consequently, the stiffness of the tunnel support. As will be shown later in the present paper, this simplification is unavoidable when using the commonly available computational codes. Furthermore, it leads to a major reduction in the computational effort (particularly when carrying out parametric studies).

2. Backfilling

2.1. Introduction

The factors influencing the ground pressure acting upon a segmental lining – particularly the properties of the backfilling – and their interactions can be mapped easily and efficiently using a so-called "N^2 chart" (Lano, 1990; NASA, 2007). Fig. 1 shows an N^2 chart drawn up for the topic of the present paper. This is an N-by-N square matrix containing N = 13 entities on the main diagonal and depicting their existing interactions in the non-blank off-diagonal cells. The interactions have to be read directionally between the elements, i.e., first horizontally in the row and then clockwise in the column. There are two further mapping rules concerning the shape and the colour of the off-diagonal cells. Concerning the shapes, rhombuses indicate that an interaction exists only under certain conditions, while circles denote unconditional interactions. As for the colours, green is used for interactions with a positive effect (an increase in the first involved factor leads to an increase in the second involved factor), red for a negative effect and black, where the effect may be either positive or negative. For a more detailed description of the applied diagramming technique the reader is referred to Ramoni and Anagnostou (2010d), where an N^2 chart was applied (using the same rules as in the present paper) for mapping the system behaviour of a gripper TBM drive through squeezing ground.

Section 2.2 discusses – by making reference to the N^2 chart of Fig. 1 – the usual case for rock TBM tunnelling, where backfilling of the segmental lining is carried out with pea gravel in the upper part and with mortar in the bottom third of the cross-section at a given distance behind the shield (Fig. 2a). Section 2.3 deals with the rather rare case of grouting immediately behind the shield via the shield tail (Fig. 2b). For the sake of economy, details concerning backfilling technology are not given here, but can be found, e.g., in Thewes and Budach (2009).

For the sake of simplicity, pairs of numbers within curly brackets will be used for making reference to Fig. 1 and denoting the interactions of the respective factors (e.g., {4-12} denotes the effect of the factor 4 on the factor 12), while a series of number in curly brackets will denote a sequence of interactions (e.g., {7-9-10} abbreviates {7-9} and {9-10}).

As the shield slides along the tunnel floor, the gap around the shield and the segmental lining is wider above the centre than in the lower portion of the tunnel cross-section (Fig. 2). However, for the sake of simplicity, Sections 2.2 and 2.3 consider the theoretical case of axial symmetry, as this simplification can be made without loss of generality in the conclusions drawn.