Tunnelling and Underground Space Technology 74 (2018) 131–144

Contents lists available at ScienceDirect

Tunnelling and Underground Space Technology

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

# Mechanical behaviour of segmental lining of a sub-rectangular shield tunnel under self-weight

Xin Huang[a,b], Yeting Zhu[a,b,c], Zixin Zhang[a,b,*], Yanfei Zhu[c], Shuaifeng Wang[a,b], Qianwei Zhuang[c]

[a] Department of Geotechnical Engineering, Tongji University, 1239 Siping Road, Shanghai 200092, China
[b] Key Laboratory of Geotechnical and Underground Engineering of the Ministry of Education, Tongji University, Shanghai 200092, China
[c] Shanghai Tunnel Engineering Co. Ltd., Shanghai 200082, China

ARTICLE INFO

*Keywords:*
Shield tunnel
Segmental lining
Deformation
Self-weight

ABSTRACT

In this paper, a novel loading setup was developed for performing full-scale loading tests on 'standing' segmental lining of a sub-rectangular shield tunnel, which for the first time allows the mechanical behaviour of segmental lining subject to self-weight to be assessed in a full-scale loading test. Granular rubber bearings with an equivalent coefficient of subgrade reaction close to hard plastic clay were used to simulate subgrade soils. The experimental results showed that the internal force distribution and deformation pattern of lining ring subject to self-weight loading differed significantly from that observed in a 'lying' loading test considering soil-and-water pressures due to the absence of lateral confinement and different boundary conditions. Specifically, maximum positive bending moments were observed at the crown and invert regions, and the largest negative bending moments occurred at the two waists. Stress concentration was not observed at the corners. The axial force was not universally compressive with tensile axial forces present at the crown region. Furthermore, the convergence deformation under self-weight loading was non-negligible. The overall lateral expansion deformation was close to the vertical convergence deformation, but the deformation was smaller at the invert than that at the crown. It is suggested that the influence of self-weight be considered in future full-scale loading tests, especially for shallowly-buried tunnels.

## 1. Introduction

Nowadays, as the tunnels go deeper and become multi-functional, the increasing dimension and variety of cross-section geometry of tunnels impose great challenges on the design of segmental lining. A common practice of evaluating the mechanical behaviour of shield tunnels is to perform either full-scale (Kashima et al., 1996; Schreyer and Winselmann, 2000; Blom, 2002; Nakamura et al., 2003; Molins and Arnau, 2011; Liu et al., 2016, 2017) or reduced-scale (Yu et al., 2017; Afshan et al., 2017) loading tests on segmental linings. These tests allow the assessment of the mechanical responses of lining structures either under designed loads or subjected to various adverse situations that may be encountered at construction and operation stages.

Most previous tests were based on a 'lying' testing setup, in which the effect of self-weight was ignored. The rationale behind 'lying' loading tests is that gravitational dead weight of lining structure is negligible in comparison with the external water-soil pressures as the tunnel burial depth is usually much larger than the thickness of lining segments. In contrast, Blom et al. (1999) showed that the fabrication process (effects of self-weight and assembling imperfection) could lead to a non-uniform 3D stress distribution in the segmental lining. Li et al. (2015) found in their 3D finite element simulations that the ovalisation deformation caused by self-weight could be significant and will affect the stress and deformation of lining structure after the soil-and-water pressures have been exerted. Both these studies indicate that the influence of self-weight on the mechanical behaviour of segmental ling cannot be ignored and may affect the stress and deformation of segmental lining in the subsequent loading scenarios. On the other hand, due to the absence of lateral confinement it can be deduced that the force transmission and deformation pattern of a segmental lining subject to self-weight should be different from those under soil-and-water pressures. Nevertheless, all these issues were barely investigated in previous structural loading tests of segmental lining. Furthermore, the mechanical behaviour of a rectangular segmental lining structure could be largely different from that of a circular one due to their differences in geometry and external loading distribution pattern. However, apart from Nakamura et al. (2003), very limited studies have dealt with rectangular tunnels.

In this paper, a 'standing' testing setup is developed to perform full-scale loading test on the segmental lining of a sub-rectangular shield

* Corresponding author at: Department of Geotechnical Engineering, Tongji University, 1239 Siping Road, Shanghai 200092, China.
*E-mail address:* zxzhang@tongji.edu.cn (Z. Zhang).

https://doi.org/10.1016/j.tust.2018.01.016
Received 24 October 2017; Received in revised form 9 December 2017; Accepted 12 January 2018
0886-7798/ 

**List of symbols**

| | |
|---|---|
| $k$ | coefficient of subgrade reaction |
| $K_s$ | the radial shear and axial shear stiffnesses of seams |
| $K_A$ | the axial tension and compression stiffnesses of seams |
| $K_\theta$ | the rotational stiffness of seams |

tunnel. For the first time, the behaviour of segmental tunnel lining with a large cross section under self-weight is explored experimentally through full-scale loading tests. The challenges of fabricating the testing setup and the segmental linings as well as their solutions are elucidated. The experimental data were compared with the numerical simulation results. The differences between mechanical responses of segmental lining under self-weight and that under soil-water pressures are discussed.

## 2. Standing full-scale loading test

### 2.1. Challenges

In order to consider the effect of self-weight, the loading setup and the testing segmental lining should be changed from a 'lying' state to a 'standing' state in a full-scale loading test. However, several challenging issues need to be solved before conducting the 'standing' loading tests.

(a) First of all, unlike in a real situation where the out-of-plane movement of the lining ring is confined by the existing lining rings and the thrust force imposed by the shield machine, in a 'standing' test, the segmental lining has no backup at both rear and front, and thus has a possibility of overturning.
(b) Secondly, due to the absence of automated lining erector, the procedure of lifting and fabrication of lining segments must be carefully designated, especially for the crown elements.
(c) Thirdly, it is crucial to find an equivalent subgrade that is neither too soft nor too stiff. Resting the testing segmental lining on a real soil stratum is risky, as it may result in significant subsidence during loading, which may cause dislocation of jack head from the testing segments. Moreover, large subsidence may bring about unfavorable bending moment and shear force in the hydraulic jacks in the lower half of the testing lining. The subgrade should also not be too stiff; otherwise the deformation of segmental lining in the subsidence area will be restricted, resulting in an internal force distribution pattern that is different from a real one.

All the aforementioned issues will be addressed in the following sections.

### 2.2. Testing specimens

The cross-sectional outline of a testing full lining ring is composed of eight arcs (see in Fig. 1): top (Arch-1) and bottom (Arch-5) arcs, left (Arch-3) and right (Arch-7) arcs and four angle arcs (Arch-2, Arch-4, Arch-6 and Arch-8). A full ring is fabricated from six element blocks: one seal roof block (F), two adjacent blocks (L1 and L2) and three standard blocks (B1, B2 and B3). The lining ring is cast by CF50 steel

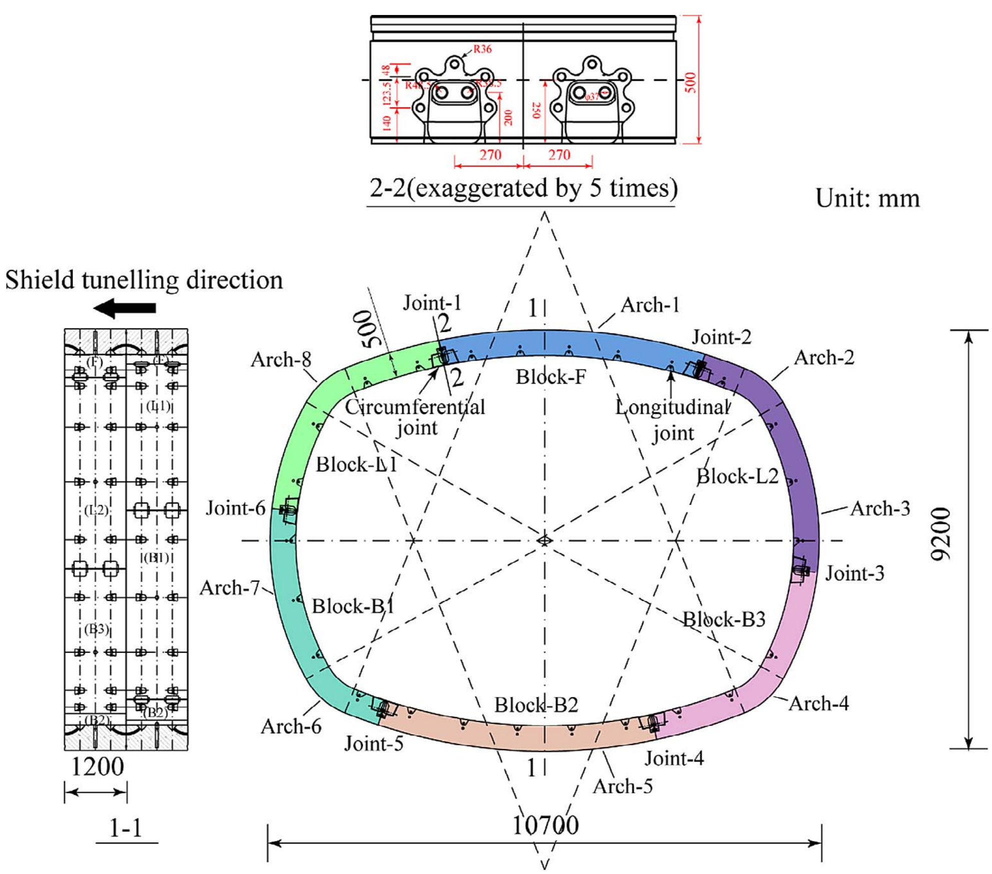


Fig. 1. Structure layout of the testing segmental lining.