Tunnelling and Underground Space Technology 83 (2019) 231–242

Contents lists available at ScienceDirect

Tunnelling and Underground Space Technology

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

Robust retrofitting design for rehabilitation of segmental tunnel linings: Using the example of steel plates

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ARTICLE INFO

Keywords:
Robust design
Segmental tunnel lining
Steel plates
Uncertainties
Decision making

ABSTRACT

This paper presents a general framework for the robust retrofitting design for rehabilitation of segmental tunnel linings installed using shield tunnelling, and specifically using steel plates bonded to the lining as a typical example of such a rehabilitation design. A two-dimensional finite element model is established as part of the robust design which can simulate the deformational response of the steel plates reinforced segmental tunnel lining. The surrounding soil, the tunnel lining, the steel plates and the interactions between each of these are all properly simulated in this model and verified by full-scale test results. The change in horizontal convergence (ΔD_{hs}) subjected to environmental impact, such as unexpected placement of ground surface surcharge is measured to reflect the performance of segmental tunnel linings reinforced by steel plates. The standard deviation of the reinforced tunnel performance due to uncertainties in the soil conditions and the ground surface surcharge is derived to measure the design robustness. A robust rehabilitation design is then accomplished by varying the steel plates sizes (i.e. width and thickness) to maximize the design robustness and minimize the cost using a multi-objective algorithm, also considering the safety requirement constraints. The optimal designs are determined as a set of design points, namely a Pareto Front, which presents a trade-off relationship between the design objectives and is demonstrated as being useful for decision making. Finally, the robust rehabilitation design method is applied to the retrofitting design of tunnel lining using steel plates in a real case study, and a comparison between the actual design and the design derived by the proposed method has been made to show its applicability and potentially significant advantages for designers, as the method allows consideration of both the highest robustness and the lowest cost simultaneously.

1. Introduction

The worldwide long-term development of urban metro system has driven the wide use of shield tunnelling in construction especially in soft ground. Hence, segmentally lined tunnels installed by shield tunnelling have been utilized for decades, for example London, Tokyo and Shanghai. However, as a typically prefabricated assembled concrete structure, a segmental tunnel lining is vulnerable to nearby disturbance especially in soft ground conditions such as those experienced in Shanghai. Large deformation in terms of transverse convergence and longitudinal settlement, and the associated severe structural defects such as leakage, concrete cracking and spalling have been detected in segmentally lined tunnels from on-site inspection and monitoring data (Shi and Li, 2015; Yuan et al., 2013). The structural health of segmental linings are likely to be adversely affected by nearby engineering activities and human-error related hazards. A typical example was reported by Huang et al. (2017) for a field case study involving an extreme surcharge being applied to a running metro tunnel in Shanghai. Therefore effective rehabilitation treatments for distressed concrete segmental linings are of great importance, especially at this time of rapid development of shield tunnel construction.

There are several methods suitable for repairing and strengthening segmental tunnel linings, for example bonding fiber reinforced polymer (FRP) or steel plates to the inner surface of segmental concrete linings (Liu and Zhang, 2014; Kiriyama et al., 2005), and grouting on either side of the tunnel at its spring line (Zhang et al., 2014). From these repair measures, bonding steel plates to an existing lining is often chosen as a permanent strengthening method. This rehabilitation approach using bonded steel plates can potentially enhance both the structural stiffness and the ultimate capacity (Kiriyama et al., 2005).

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https://doi.org/10.1016/j.tust.2018.09.016
Received 20 November 2017; Received in revised form 24 August 2018; Accepted 30 September 2018

Furthermore, the construction operations associated with bonding steel plates can rely on standard machinery resulting in a fast and effective repair procedure. Hence, bonding the steel plates has been successfully adopted as a permanent rehabilitation method in many projects involving damaged segmental tunnel linings worldwide (Chang et al., 2001; Huang and Zhang, 2016).

Kiriyama et al. (2005) presented an analytical analysis for the design of steel plate reinforcement for existing deformed tunnels utilizing a beam spring model. In the model, the steel plates are modelled as a circumferential beam, and a series of nonlinear springs with no tensile resistance are applied in the radial direction to simulate the interaction. Based on the practice of steel plate reinforcement frequently used in Shanghai, Zhao et al. (2015) conducted a full scale load test on a steel plate reinforced segmental lining ring. In their study, a simplified numerical model was established to further investigate the mechanical and deformational behaviour of reinforced tunnel linings. Apart from these researchers providing insight into the structural response of the lining, other research has focused on the bonding behaviour and failure mode of epoxy bonded steel plate reinforcing concrete structures (Ziraba et al., 1995; Adhikary et al., 2002). Previous literature on numerical simulations provide a basic understanding of the effectiveness of bonding steel plates on the disrupted tunnel structures. However, the model used previously simplified the behaviour of the surrounding soils by using soil springs based on Winkler's model (Do et al., 2015; Zhang et al., 2017). This simplification will further contribute to any discrepancy between the prediction and the field measurements, especially when the ground conditions are very uncertain in the context of soil properties. Furthermore, the design of steel plate rehabilitation mainly depends on the engineering experience. Hence, an appropriate design model for the rehabilitation of segmental tunnel linings that can be robust appropriate for the environmental uncertainty would be extremely welcome.

A robust design methodology was originally developed by Taguchi and Wu (1979) for improving the industrial product quality and manufacturability. Since then a great many studies have been conducted to understand this idea and make it applicable to other areas. The main idea behind a robust design is to make the system response insensitive to (robust against) hard-to-control disturbances (called noise factors) at a low cost (Tsui, 2007). Based on this concept, some researchers have put effort into robust designs of various kinds of structural systems under different uncertainties (Doltsinis and Zhan, 2004; Beer and Liebscher, 2008). In contrast to the design of structures, the geotechnical uncertainty may significantly influence the design associated with geotechnical problems (Phoon and Kulhawy, 1999). Recently, Juang and Wang (2013) proposed a robust geotechnical design (RGD) methodology and applied it to different forms of geotechnical problems such as spread foundations, drilled shafts (Juang et al., 2013) and braced excavations (Juang, et al., 2014). Gong et al. (2014) have applied the robustness design concept for the design of segmental tunnel linings, the idea of this robust design model is to reduce the variation of tunnel lining performance under normal conditions caused by the uncertainty of the input design parameters.

The aim of this paper is to present a general framework for the rehabilitation design for segmental linings from shield tunnelling under the conceptual umbrella of robustness. The goal of robust retrofitting design is to enhance the robustness of the reinforced segmental linings against the design uncertainties with consideration given to minimizing cost, which can be accomplished by varying the design parameters to minimize the variation of the reinforced segmental tunnel lining performance given some uncertainty level of the surrounding environments. The general framework for a robust design model is presented first. Secondly a two-dimensional finite element model is established to simulate the steel-plate-reinforced segmental tunnel lining for the design. The interactions between the steel plates and the lining and also between the lining and the surrounding ground are carefully modelled and verified by full-scale load test results. Finally, a detailed design example is carried out demonstrating the applicability of proposed robust design methodology for the rehabilitation of segmental tunnel linings using steel plates.

Fig. 1. Photograph of a steel plate reinforced segmental tunnel lining.

2. Framework of robust retrofitting design for segmental tunnel linings

2.1. Practical design method of steel plate strengthening

Fig. 1 presents a photograph showing segmental tunnel linings strengthened by steel plates in the Shanghai metro. The steel plates were installed separately and welded together to form an integral ring. Epoxy was injected into the gap and to provide a bond between the lining and the steel plates. Due to the complexity and potentially large differences between the damaged tunnel conditions from case to case, there isn't a common design method for the steel plate rehabilitation method. In fact, the steel plates are usually only applied to damaged tunnel linings with a horizontal convergence of over 10 cm. The size of the steel plates used is nearly the same in each case based on past engineering experience, having a width of 850 mm and a thickness of 20–30 mm. Although this may be convenient in practice, there is certainly room for improvement and optimization in the design of steel plate reinforcement for particular cases.

2.2. Robust retrofitting design methodology

In the robust rehabilitation design procedure, it is aimed to find an appropriate set of design parameters, which makes the performance of reinforced tunnel lining robust enough with the lowest possible total cost. The horizontal convergence is widely adopted as an indicator of tunnel lining performance both in the research field and in engineering practice (Huang and Zhang, 2016). In this study, the change in horizontal convergence (ΔD_{hs}) as a result of an environmental impact such as an unexpected ground surface surcharge, compared to the horizontal convergence ΔD_{h0} just after the steel plate installation has finished is measured to reflect the performance of segmental tunnel lining reinforced by steel plates. However, the change in the convergence ΔD_{hs} as a result of a changed environment will be dependent on multiple sources of uncertainties, for examples the ground properties and the surcharge levels, while the degree of variation in ΔD_{hs} can be quantified by its standard deviation to show how sensitive the reinforced segmental tunnel lining is to the noise factors (Juang et al., 2014).

Therefore, the goal of proposed robust retrofitting design is to enhance the robustness of the reinforced segmental tunnel lining against the design uncertainties at low cost, which can be accomplished by varying the design parameters to minimize the standard deviation of