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Experimental investigations of bolted segmental grey cast iron lining behaviour

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ABSTRACT

The need for the research reported in this paper was driven by the Crossrail project in London for which new tunnels were constructed close to numerous existing operational tunnels of the London Underground (LU) network.

This research is based on experimental work conducted on half-scale grey cast iron (GCI) tunnel lining segments with chemical composition similar to the Victorian age GCI segments in the LU network. This paper discusses the deformation behaviour of the bolted segmental lining under the influence of factors such as overburden pressure, bolt preload and presence of grommets at small distortions. The measured behaviour of the segmental lining is compared against the calculated response of a continuous lining based on the assumption of elasticity.

The industry practice for tunnel lining assessment is to calculate the induced bending moment in the tunnel lining using an elastic continuum model, while adopting a reduced lining stiffness to take into account the presence of the joints. Case studies have recorded that both loosening and tightening of lining bolts have been used as mitigation measures to reduce the impact of new tunnel excavations on existing GCI tunnels.

The experimental work on the half-scale GCI lining has shown that a bolted segmental lining behaves as a continuous ring under small distortions imposed when subjected to hoop forces relevant to the depth of burial of LU tunnels. In the presence of hoop force, joint opening was minimal and the magnitude of preload in the bolts had little impact on the behaviour of the lining. It is therefore concluded that disturbance of the bolts in existing tunnels is not recommended as a mitigation measure as in addition to being ineffective it is both time consuming and introduces the risk of damaging the tunnel lining flanges.

1. Introduction

A major research project investigating the effect of tunnelling close to existing tunnels has been completed at Imperial College London (Standing et al., 2015). The need for the research project was driven by the Crossrail project in London for which new tunnels were constructed close to over forty existing operational tunnels.

A common practice in industry with relation to the assessment of bending moment in tunnel linings is to use Morgan's equation (1961) to calculate the bending moment induced in the tunnel ring from a certain distortion.

Morgan (1961) set out the basis of the elastic continuum method for the analysis of a circular tunnel in elastic ground by assuming that the circular lining distorted into an ellipse and neglecting shear stresses between the tunnel extrados and the ground. The maximum bending moments occur at the tunnel axis level and at the crown and invert and are given by the following equation:

$$M = \frac{3\delta EI}{a^2} \tag{1}$$

where
M = maximum bending moment,
δ = maximum distortion,
a = tunnel radius,

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E = Young's modulus of the lining,
I = second moment of area of lining per unit width of the lining.

In industry, it is common to reduce the flexural rigidity of the bolted lining ring (EI) by adopting Muir Wood's (1975) reduction formula for the second moment of area of the ring to take into account the presence of the joints:

$$I_e = I_J + \left(\frac{4}{n}\right)^2 I \tag{2}$$

where

I_e = reduced (effective) second moment of area of lining per unit width of the lining,
I_J = second moment of area of the joint per unit width of the lining,
n = number of segments.

However, there is a lack of experimental data to substantiate the use of Muir Wood's (1975) reduction formula for the second moment of area for a bolted segmental tunnel lining ring to take into account the presence of the joints.

Furthermore, two case studies reported in the literature suggest that mitigating measures to reduce the impact of new tunnel excavations on existing GCI tunnels have included loosening bolts in one case (Moss and Bowers, 2006), and tightening bolts in another case (Kimmance et al., 1996). Therefore, the laboratory experiments performed as part of this study were also set up to investigate the effect of different bolt preloads on the behaviour of bolted segmental GCI rings.

This paper describes the design and set-up of the loading and monitoring components for the test ring so that the state of stress in the lining could be related to its deformed shape. The experimental lining was tested at low stress levels to minimise plastic straining of the GCI material. The results from the parametric studies investigating the influence of hoop force (representing overburden pressure), bolt preload and inclusion of grommets on the response of the bolted segmental ring are presented.

As part of the research project, an extensive literature review was undertaken, focussing on cast iron, its properties and use in tunnel construction as well as other experimental work on tunnel linings. Much of this source material, whilst not directly referenced in this paper, contributed to the overall project. Notably, Copperthwaite (1906) and Hewitt and Johannesson (1922) provided a wealth of knowledge on the properties of cast iron and their historic use in the tunnelling industry and Craig and Muir Wood (1978) a good summary of earlier tunnel lining practice in the United Kingdom. Field measurements of stress and strain in cast iron and later concrete lined tunnels were reported by Rapp and Baker (1936), Skempton (1943), Cooling and Ward (1953), Sutherland (1955), Tattersall et al. (1955), Ward and Chaplin (1957), Ward and Thomas (1965), Smith Osborne (1970), Thomas (1976, 1983), Attewell and El-Naga (1977), Cooley (1982), Barratt et al. (1994), Davies and Bowers (1996), Nyren (1998), and Tube Lines (2006). Measurements of existing tunnelling distortion due to adjacent new tunnelling were reported by Kimmance et al. (1996), Cooper and Chapman (2000), Cooper (2001), Standing and Selman (2001), Cooper et al. (2002, 2003), Gue et al. (2014), Alhaddad et al. (2014) and Yu et al. (2014).

Prior to embarking on the detailed design of the experimental set-up described here, an extensive literature search identified a small number of studies involving large-scale tests where a similar methodology was used (i.e. without soil) although none-of them adopted the combined load-displacement control adopted in this study. Experimental work on cast iron tunnel segments was completed by Leung (1967) and Thomas (1977), with the latter still being the key source paper on this subject. Other studies involving large-scale experimental set-ups have been made for concrete segments, either singly or forming a full or part of a ring (Mashimo et al., 2001, 2002; Blom, 2003; Bilotta et al., 2006; Okano, 2007; Ahn, 2011; Blazejowski, 2012). A particular focus of these studies is often to assess new materials such as fibre reinforced concrete or the segment response during erection and grouting.

2. Experimental investigations

2.1. Overview

The details of the half-scale ring are given in Figs. 1–3. The adopted size was the smallest that could be manufactured with GCI while maintaining true proportionality of all dimensions, particularly the skin of the segment. The linings were manufactured to have a composition that matched that of existing linings.

The experimental investigations considered the influence of joint opening on the structural response of the ring. For a continuous ring of uniform stiffness made from linear elastic material, the first order bending moments related to an imposed change in radius are independent of the hoop force. The effect of having joints, as in the case of the bolted segmental ring, is to potentially reduce ring stiffness, the reduction in magnitude being dependent on the hoop force (from the radially applied load to simulate overburden pressure) and the change in radius. One of the objectives of the laboratory experiments was to examine this relationship and the validity of applying Muir Wood's reduction formula. The bending moments derived from strain measurements in the laboratory tests were compared with the analytically obtained bending moments of a continuous lining of uniform stiffness under the same deformation as the test lining. The tests were repeated for different initial bolt preloads.

Circularity surveys of 45 km of LU running tunnels conducted from 2004 to 2005 found that the tunnels had squatted – i.e. the horizontal diameter was greater than the vertical diameter (Tube Lines, 2007). London Underground (2014) suggested that for assessment purposes it was appropriate to assume, in the absence of in-situ data, ovalisation of 1% for all tunnel linings of less than 15 feet (4.57 m) internal diameter in cohesive ground.

In the 2D finite element (FE) analysis discussed in his PhD thesis, Avgerinos (2014) modelled the existing LU Central Line running tunnel at Lancaster Gate near Hyde Park. The maximum distortion of the existing tunnel was found to be 0.2% after 100 years of consolidation for the case with the lining modelled as fully permeable. When the tunnel lining was modelled as impermeable the distortion was significantly lower. This indicates that tunnel deformation as a result of ground loading alone could be significantly lower than the 1% ovalisation suggested by London Underground (2014). It is possible that for in-situ tunnels the ovalisation would have occurred during the construction of the tunnel rings, and under self-weight, prior to any ground loading being transferred to the lining.

Furthermore, Avgerinos' (2014) FE analyses showed that the action of shear stresses on the tunnel lining could control the deformed shape of the lining. However, in the laboratory set-up it was only possible to apply normal stresses to distort the ring. The effect of shear stresses was also neglected in Morgan's formulation (1961).

From a review of existing literature, it is noted that the previous maximum recorded distortion in bolted GCI tunnels due to new tunnel excavations is approximately 0.1% of diametral strain (Kimmance et al., 1996 and Cooper, 2001). Field monitoring