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Mechanism for buckling of shield tunnel linings under hydrostatic pressure

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ABSTRACT

In this paper, the effects of segmental joints, dimensions of segments, and ground conditions on buckling of the shield tunnel linings under hydrostatic pressure are studied by analytical and numerical analysis. The results show that radial joints have significant impacts on the buckling behavior: the shield tunnel linings with flexible joints buckles in a single wave mode in the vicinity of K joint, while those with rigid joints buckles in a multi-wave mode around the linings. Hydrostatic buckling strength is found to increase with the flexural rigidity of the radial joint and the thickness of segment increasing. This study shows that ground support increases the buckling strength dramatically, while earth pressure reduces the capacity to resist hydrostatic buckling. The tunnel linings during construction are found to be easier to buckle than that during operation. Meanwhile, the buckling of tunnel linings is studied by theoretical analysis of buried tube buckling.

1. Introduction

In recent decades, the use of deep underground beneath seas and rivers has rapidly increased in order to meet the civic requirements and improve the urban environment. Many new tunnel utilities, including undersea and riverbed tunnels, have been constructed at progressively greater depths by shield tunneling method, due to the congested uses of shallow ground and aboveground space in many large cities (Watanabe, 1990; JCRDB, 2006).

For such underwater tunnels, hydrostatic pressure should be considered as a principal design load, as it is almost equivalent to the acting load on the operating shield tunnel (Koyama, 2003; Mashino and Ishimura, 2003; Yahagi et al., 2005). Under high hydrostatic pressure, the tunnel linings are predominated by the compressive hoop force, which is required by the design of waterproof of joint. This eventually makes the flexible joint be utilized extensively and the circular shield tunnel can be designed more easily by the wide and thin segment (Kimura and Koizumi, 1999; Koizumi, 2000). Therefore, the structural stability of the tunnel linings should be checked to avoid the buckling of circular tube under hydrostatic pressure. However, the current design specifications of the shield tunnel (JSCE, 2007) only check the material safety by the allowable stress method and ultimate state method. Equivalently, the structural stability of the whole tunnel linings is ignored.

Tunneling accidents usually have complicated causes and eventually result in ground collapse, so that the structural problem of the tunnel linings is often underestimated and even ignored in design practice and relevant research, especially for reinforced concrete linings. Heathrow Express Tunnel (NATM) collapse in October 1994 (HSE, 2000), Gerrards Cross Tunnel (Tesco tunnel, three pin arch) collapse in June 2005 (Wikipedia, 2005), and Kurashiki Undersea Tunnel (shield tunnel) collapse in February 2012 (NBP, 2012) are some typical failure examples of the concrete linings in recent years. These accidents have motivated many researchers to investigate the buckling of tunnel linings (Croll, 2001; Tamura and Hayashi, 2005; Wang et al., 2014). Particularly, the recent shield tunnel collapse in Japan caused a loss of five lives, which is a very severe accident throughout the construction history of the modern shield tunnel. Structural failure of segmental linings has been analyzed to be the most likely cause of undersea tunnel collapses (NBP, 2012). However, the failure mechanism of the tunnel linings has not been clarified yet. Since the surrounding ground is dense and the external hydrostatic pressure is large, the buckling of segmental linings should be checked as the necessary influential factor in the collapse. Actually, the

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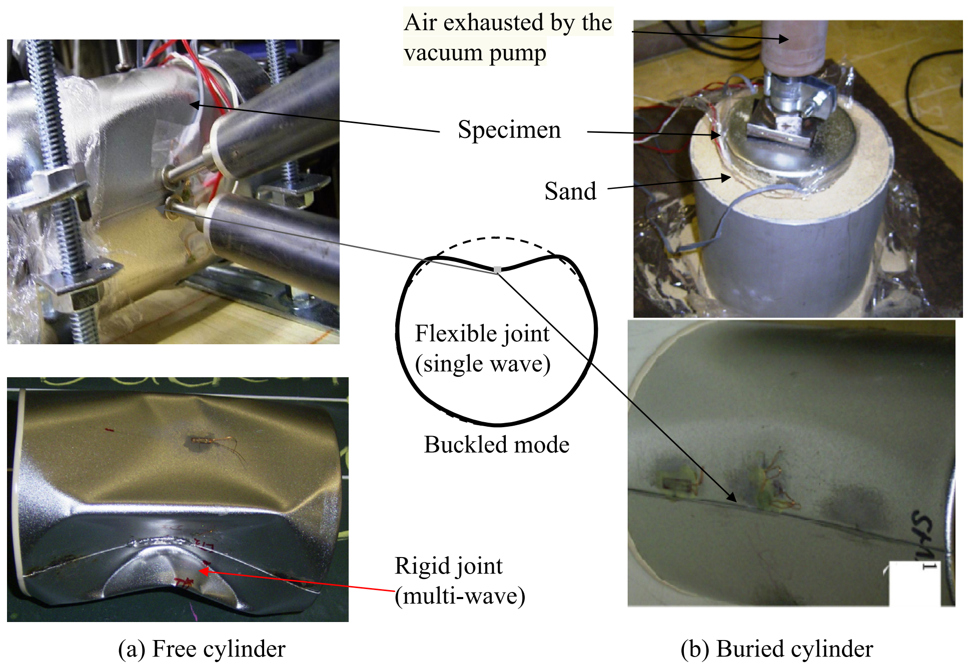

Fig. 1. Experimental profile and buckling of cylindrical shells with one flexible joint.

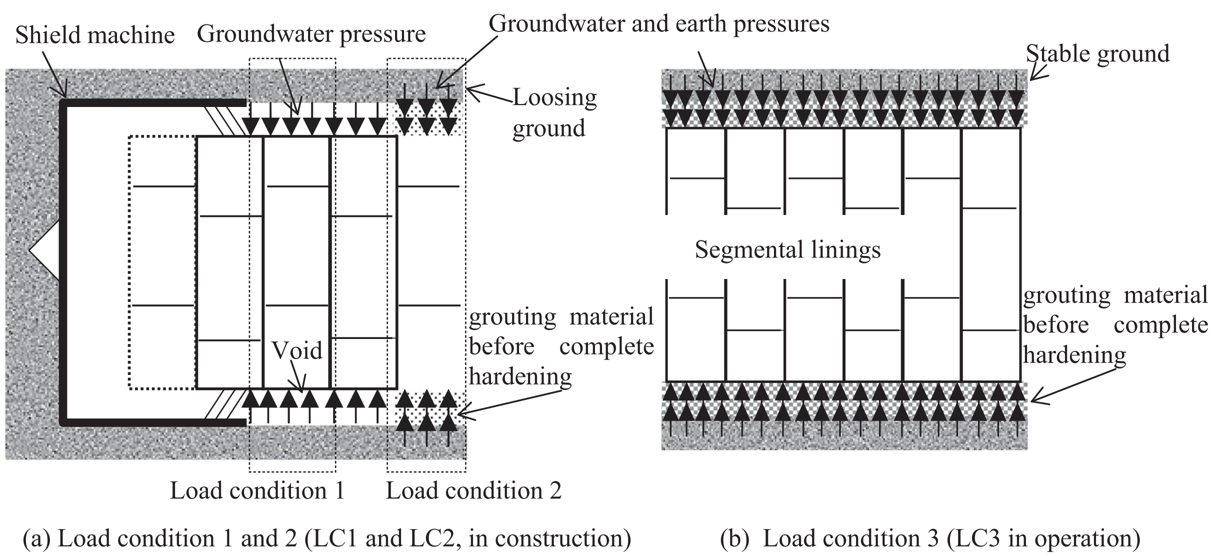

Fig. 2. Load conditions considered in buckling analysis during construction and operation.

experimental study using the tunnel models with radial joints has indicated that flexible segment joints reduces the buckling load of cylindrical shells significantly (Wang and Koizumi, 2010).

The aim of this paper is to study the stability of deep shield tunnel linings under hydrostatic pressure. The buckling of the segmental linings will be analytically and numerically investigated to clarify its structural failure mechanism. The following factors will be identified: (a) the rotational rigidity of radial joints; (b) the number and orientation of radial joints; (c) the thickness and width of segment; and (d) the overburden depth and ground support. In addition, the examination of stress will be performed to check the material safety by allowable stress method, and the buckling of tunnel linings will also be examined by the analytical solutions of Winkler model and the elastic continuum model.

2. Overview of cylinder buckling theories

2.1. Relevant buckling theories

Buckling of a free cylindrical shell under external pressure was studied by Levy (1884) and Timoshenko and Gere (1961). Buckling of a tube encased shell in rigid cavity was investigated by Cheney (1971), Amstutz (1970), Jacobsen (1974), Glock (1977), El-Sawy and Moore (1998), and El-Sawy (2001). The former was usually classified into the multi-wave buckling theory, while the latter into the single-wave buckling theory. The free buckling strength of a beam ring can be estimated by the following equation:

$$P_{cr}^{r} = \frac{3EI}{BR^3} \quad (1)$$