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Seismic mitigation for immersion joints: Design and validation

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ABSTRACT

Immersion joint, generally considered as the critical part for seismic design of immersed tunnels, could damage first under strong earthquakes due to its smaller stiffness compared to adjacent tunnel elements. Until now, however, solutions or measures for mitigating seismic damage to immersion joints are still missing in literature. In this paper, a seismic mitigation measure for enhancing the performance of immersion joints is proposed, i.e. the Buckling Restrained Brace (BRB). The optimized design of the device is obtained from a parametric analysis to ensure it works in coordination with the immersion joint in such a way that the maximum energy dissipation is reached. Validation tests of an immersion joint, i.e. with and without the optimized BRB device, are presented with a large geometric scale of 1/10. Test results indicate that the hysteretic performance of the immersion joint working with the optimized BRB device reaches a 69% increase, compared to that without such device.

1. Introduction

An immersed tunnel consists of prefabricated tunnel elements that are floated to the site, installed one by one, and connected to one another under water. The immersion joint, i.e. the connection of two adjacent elements, regarded as the most important part in water-proof safety, determines the behavior of the whole immersed tunnel significantly. According to the stiffness ratio of the joint to the tunnel element, immersion joints can be divided into three categories: rigid joints, flexible joints and partial-rigid (or partial-flexible) joints. Since the GINA-profile rubber seal was invented in 1960s, the flexible joints have become very popular and have been worldwide applied in a number of significant projects.

A typical cross-section of this type of joint can be seen in Fig. 1. The GINA rubber seal and Omega seal are regarded as the primary and secondary water proof of the joint respectively. The GINA rubber seal is placed along the cross-sectional contour of the immersion joint, as shown in Fig. 1. After installation of the joint, the GINA rubber seal is highly compressed and starts to provide capacity against leakage due to the initial hydrostatic pressure. If the GINA rubber seal fails, the Omega seal begins to work as the second barrier. It should be noted that the GINA rubber seal is the key component in the joint. When the immersed tunnel is submitted to an earthquake or differential settlement, large deformations and transversal forces may occur in the joint. To prevent it, the shear keys are applied horizontally and vertically to transfer these forces from one element to another. Normally the shear keys are made of reinforcement concrete or steel, providing high capacity in transversal direction. Between the shear keys, the rubber bearing is placed, allowing the occurrence of a small movement in the joint.

Generally, the stiffness of the immersion joint is far less than that of the tunnel element (Xiao et al., 2015). Due to its smaller stiffness, large deformations could occur in the joint when it is subjected to earthquake or differential settlement and the excessive deformations may induce leakage around the joint. The complicate configuration of the immersion joint also contributes to its uncertainty regarding its mechanical behavior. Hence, with regard to immersed tunnels in seismically active regions, the behavior and reliability of the immersion joint, especially under seismic loading, deserves more attention. Furthermore emphasis should be given to the consequences of longitudinal oscillations (Anastasopoulos et al., 2007), as shown in Fig. 2. This is the critical mode of earthquake-induced vibration, and one of the most severe loading situations for an immersed tunnel, since it may lead to decompression of the joint rubber seal, jeopardizing the water-tightness and, hence, the safety of the tunnel.

In fact, as one of the main deformable part in the immersed tunnel, the joint may have a relatively large deformation capacity subjected to seismic loadings, compared with that of the adjacent tunnel elements. Keeping this fact in mind, a seismic mitigation device installed on the immersion joint and working together with the joint could be an additional way to dissipate the energy caused by the earthquake.

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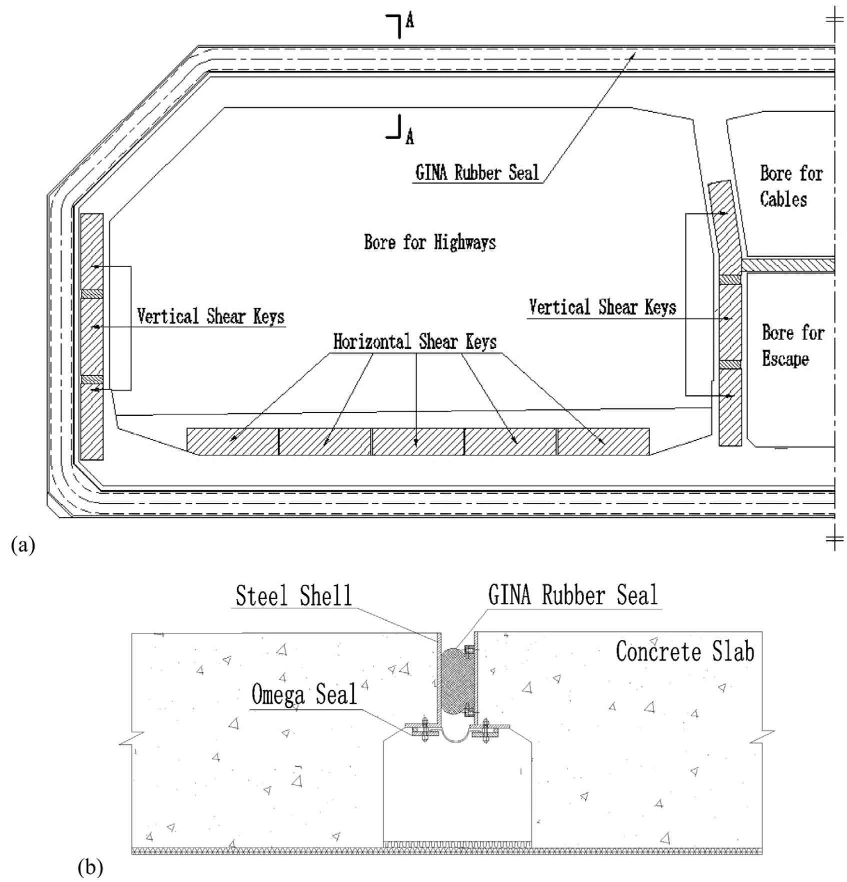

Fig. 1. Profile of a typical cross section of immersion joint: (a) cross section and (b) A-A profile.

In the present study, a seismic mitigation method for immersion joints is proposed by means of the Buckling Restrained Brace (BRB), which is widely used in seismic mitigation for buildings but not for underground structures. The design procedure of this method is described in detail and the optimized parameters for the BRB device are obtained to ensure the device works in coordination with the immersion joint in such a way that the maximum energy dissipation is reached. The validation test of an immersion joint is presented with a large geometric scale of 1/10. The validity of the proposed seismic mitigation method is verified by comparison tests of the joint with and without the optimized BRB device, in which the hysteretic performance of the joint is taken as an evaluation index of energy dissipation.

2. Motivation

The damage to subway tunnels caused by the 1995 Great Hanshin earthquake (Iida et al., 1996) has stimulated a sharp increase in research activities for possible measures to mitigate damage to underground structures. The seismic response of tunnels is affected considerably by the kinematic loading induced by the surrounding ground, while the inertial loads of the structure itself are of secondary importance (Wang, 1993; Hashash et al., 2001; Bobet, 2003; Huo et al., 2006; Yu et al., 2013a, 2013b; Pitilakis and Tsinidis, 2014; Yu et al., 2016). Therefore, large differences do exist between seismic mitigation design of underground structures and surface structures. Until now, however, current researches on seismic mitigation or isolation of underground structures are very rare in literature. One of the possible measures discussed so far was to cover a tunnel with a soft coating in order to minimize shear forces on tunnel-soil interface (Kim and Konagai, 2000). The seismic isolation effect of the soft coating material that spreads over tunnel linings was investigated by using simple solutions to idealized problems. Another possible measure was proposed for mountain tunnels, that is, a shock absorption layer (isolation layer) (Gao et al., 2005) or a grouting layer (Wang and Cui,

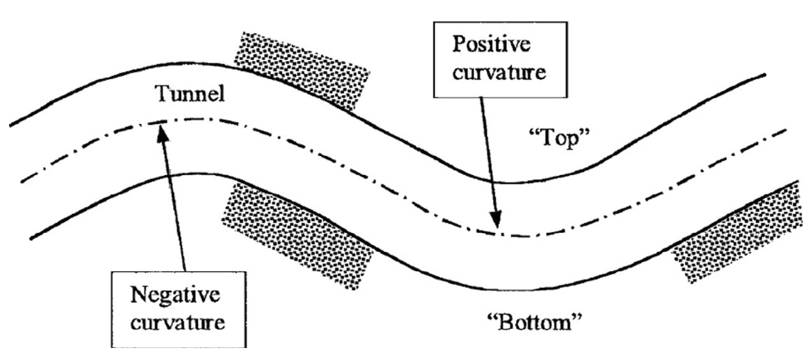

Fig. 2. Longitudinal bending along the tunnel (after Hashash et al., 2001).