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Seismic Response Analysis of Long Immersed Tunnel to Longitudinal Non-uniform Excitation

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Abstract

A simplified numerical model based on the equivalent mass-spring system is proposed to investigate the seismic response of a long immersed tunnel under longitudinal non-uniform earthquake excitation. The wave passage effects and local site conditions that cause the non-uniform excitation are taken into account. The results indicate that the seismic deformation of the immersion joints is significantly affected by the non-uniform excitation. Compared with the uniform excitation, the deformation range of immersion joints is larger in the non-uniform excitation cases. The results obtained from the numerical model are also influenced by the wave propagation directions. The non-uniform excitation should be considered in the seismic design of long immersed tunnel.

1. Introduction

The immersed tunnelling[1], a feasible alternative of tunnel construction, was widely applied in waterway crossings throughout the world. Especially for the projects across seas or harbours, the immersed tunnels are often of a length up to several kilometres. For example[2], the Oresund immersed tunnel connecting Denmark and Sweden is 4.0km long, and the Busan-Geoje immersed tunnel in South Korea is of a length of 3.4km. The object of this study, the under construction immersed tunnel of Hong Kong-Zhuhai-Macao link is even close to 6.0km which making it the world's longest immersed tunnel.

In general, tunnels have performed better during earthquakes than have surface structures. However, all immersed tunnels should be designed for seismic events appropriate to their location[3], particularly in soft alluvial soils and earthquake-prone areas. Recent observations have showed that the motions at different supports of a long tunnel can be quite different during an earthquake. The main reasons of such differences include the wave passage effect, the local site conditions and the incoherence effect[4]. Therefore, it is very important to consider the non-uniform earthquake excitation for seismic response analysis of long tunnels.

The main objective of this paper is to investigate the earthquake response of a long immersed tunnel subjected to the longitudinal non-uniform earthquake excitation. In view of the uncertainty and comlexity of the incoherence effect, the focus will be particularly on the non-uniform excitation caused by the wave passage effect and the local site conditions. Immersion joint is the crucial component for the seismic safety of the tunnel.. Hence, more attention will be paid to the deformation of immersion joint.

2. Seismic analysis method for immersed tunnel

For most of the underground structure, the inertia of surrounding soil is greater than that of the structure. Earthquake observations[5] show that the seismic response of a tunnel is not controlled by the inertia of itself, but rather the deformation of the ground. For tunnels in soft soil, the stiffness of structure is much larger than the stiffness of the surrounding soil. In such case, the soil-structure interaction is important[6]. Therefore, the seismic response of underground structure is essentially dependent on the free-field deformation of the ground and its interaction with the structure[7].

Based on these characteristics, an acceptable method for seismic response analysis of immersed tunnel is first to obtain the free-field motion and then to subject the obtained ground motion to the soil-structure system. Anastasopoulos et al.[8] utilized this method to investigate the nonlinear response of a deep immersed tunnel in Greece to strong seismic shaking. In his paper, the free-field motion is determined using a SHAKE analysis, and the tunnel structure is modelled as beam elements supported by interaction springs and dashpots, which is often known as the Winkler model. However, only the wave passage effect is taken into consideration of the non-uniform earthquake excitation due to the assumption of the uniform soil along the tunnel.

A more popular and convenient method is to established the dynamic mass-spring model[5,9] of immersed tunnel which was first proposed by Okamoto and Tamura through conducting model tests and earthquake observations for a submerged tunnel in Japan. In this model, the soil deposit is divided into a series of slices which are perpendicular to the tunnel axis. Each slice is represented by a mass, a spring and a dashpot connecting the mass to the base rock. The neighbouring masses are then connected to each other along the tunnel axis by springs and dashpots. Also the immersed tunnel is treated as a beam supported by springs and dashpots. This method, although which is not based on the wave propagation theory, seizes the essential fact that the ground displacement is dominated by the fundamental shearing vibration. In contrast to the Winkler model, the mass-spring model takes not only account of the soil-structure interaction but also of the interaction between the soil masses.

3. The immersed tunnel of Hong Kong-Zhuhai-Macao Link

The Hong Kong-Zhuhai-Macao Link, crossing the Pearl River Estuary and linking Hong Kong to the East, and Zhuhai and Macao to the West, is a combination of bridges, an immersed tunnel and artificial islands. The immersed tunnel is 5990 meters long. It has 33 concrete tunnel elements, which the length of a typical segmental tunnel element is 180m. The maximum water depth of tunnel element immersion is 44.5m. The cross section has two-bore and one middle gallery with the external width of 38m, the height of 11.4m and the outer wall thickness of 1.5m.

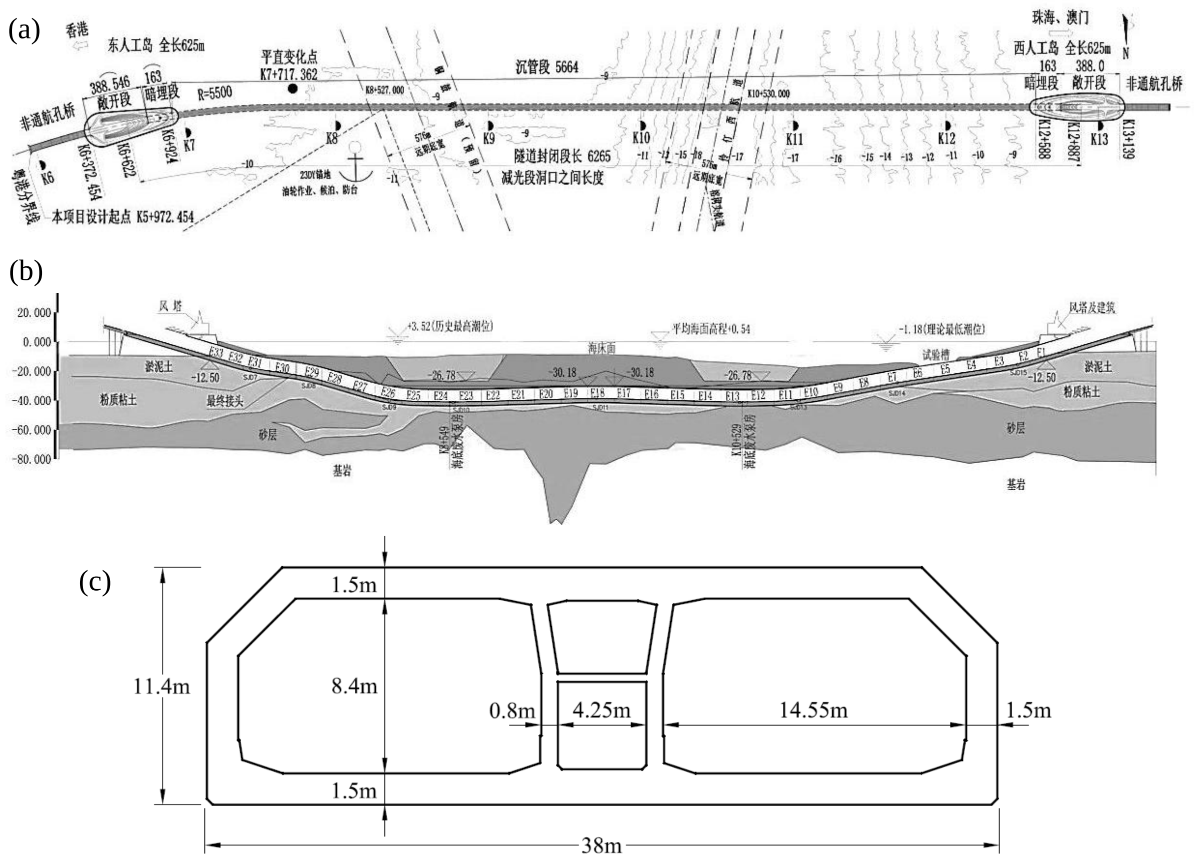
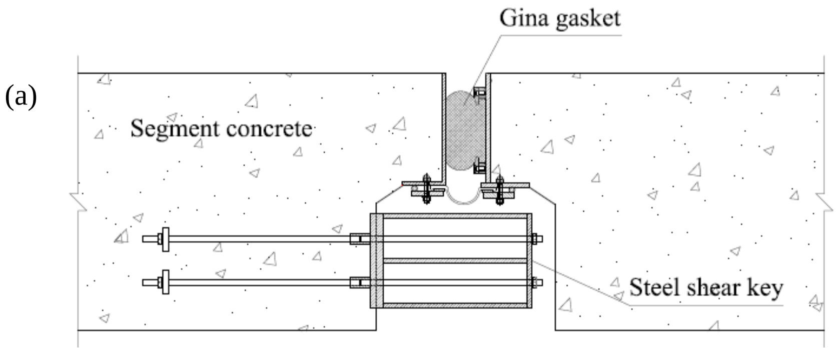


Fig.1 (a) Alignment layout of the immersed tunnel; (b) Longitudinal section of the immersed tunnel; (c) Immersed tunnel cross section

The immersion joint, which consists of a flexible Gina gasket and steel shear keys, is a key part between the adjacent tunnel elements to make up the tunnel. Four hardness of Gina gaskets are used to connect various tunnel elements in terms of the corresponding immersion depth. Fig.2 (b) represents the typical hyperelastic curve of Gina gasket. After the connection of two elements, the Gina gasket is compressed by the unbalanced hydrostatic force. The resulting compressive displacement makes the Gina gasket the initial stiffness to transfer the axial forces and bending moments and also to provide watertightness of the tunnel. Steel shear keys are installed in the immersion joints to deliver the transverse and vertical shear forces of tunnel. The typical mechanical curve of shear key is displayed in Fig.2 (c), where a lower stiffness allows certain differential movement between the tunnel elements.



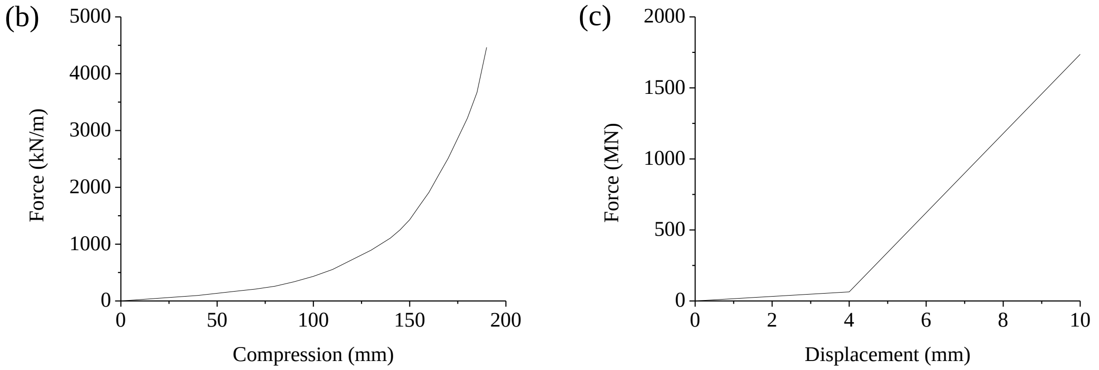


Fig.2 (a) Immersion joint profile; (b) Force-compression relationship of Gina gasket; (c) Force-displacement relationship of steel shear key

4. Seismic environment and wave selection

The immersed tunnel locates at the alluvial plain of the estuary delta, where the topography is simple and flat. In the vicinity of the tunnel area, the NE and NW trending faults are developed. However, all the faults are the non-Holocene active faults, and no destructive earthquake greater than Ms 4.7 was recorded in history. According to Chinese Code for seismic design of buildings[10], the seismic basic intensity of the study site is VII.

Geotechnical exploration data obtained in the tunnel area reveal that the alluvial deposit overlying the granite bedrock is of a depth of about 60m to 70m, locally greater than 80m. It consists of alternating layers of gravel sand, medium sand, fine sand, clay and muck. The shear wave velocity of each layer is also measured.

In terms of the seismic safety evaluation report of the tunnel area, an acceleration wave of 3% probability of exceedance in 120 years artificially generated from the bedrock is selected for this study. The corresponding PGA equals to 2.25 m/s^2.

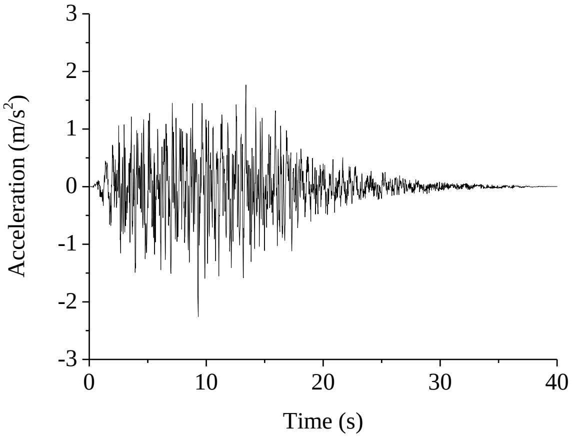


Fig.3 Artificial bedrock acceleration time history of 3% probability of exceedance

5. Modelling

A simplified numerical model based on the equivalent mass-spring system is proposed to analyse the seismic response of long immersed tunnel as demonstrated in Fig.4. This analysis model essentially consists of the soil mass-spring-dashpot system and the soil-structure interaction system.

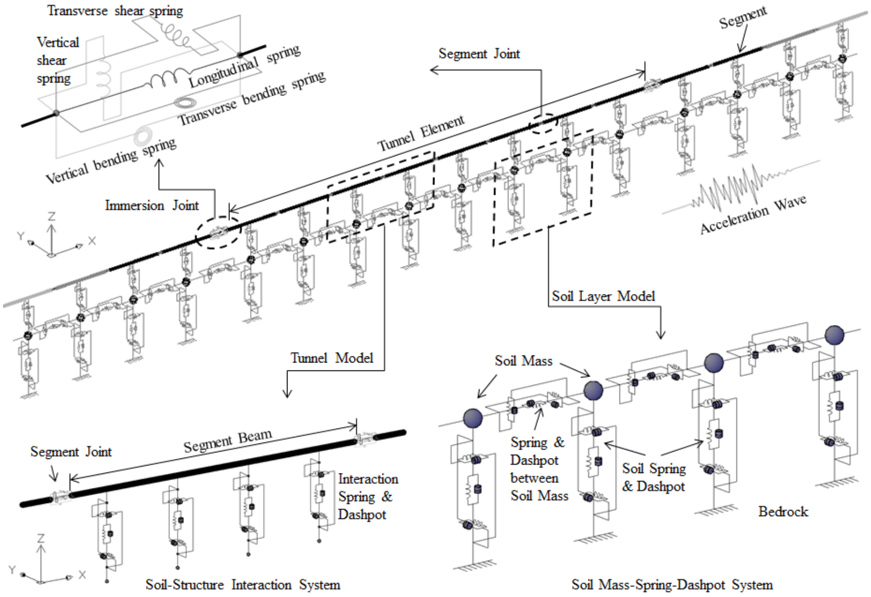


Fig.4 Simplified model for seismic response of immersed tunnels

The soil mass-spring-dashpot system is derived from the equivalent mass-spring model. In this system, the soil deposit is divided into a number of slices which are perpendicular to the tunnel axis. Each slice is represented by a mass, a spring and a dashpot connecting the mass to the bedrock. The parameters of the mass, spring and dashpot are determined by natural property of the fundamental mode of shear vibration of the slice, which can be given as

$$M_1 = \frac{\left(\sum_{i=1}^{n} m_i \varphi_{i1}\right)^2}{\sum_{i=1}^{n} m_i \varphi_{i1}^2} \tag{1}$$

$$K_1 = M_1 \omega_1^2 \tag{2}$$

$$C_1 = 2\xi \sqrt{M_1 K_1} \tag{3}$$

where, m_i, φ_{i1}, ω_1 and ξ are the mass of ith soil layer, the fundamental mode shape, the fundamental frequency and the damping ratio of each slice, respectively.

The neighbouring slices are connected through the masses by springs and dashpots. The springs between the soil masses can be determined by

$$K_{2x} = \frac{1}{\delta L_{ij}} \sum_{i=1}^{n} E_i A_i \delta_i \tag{4}$$

$$K_{2y} = \frac{1}{\delta L_{ij}} \sum_{i=1}^{n} G_i A_i \delta_i \tag{5}$$

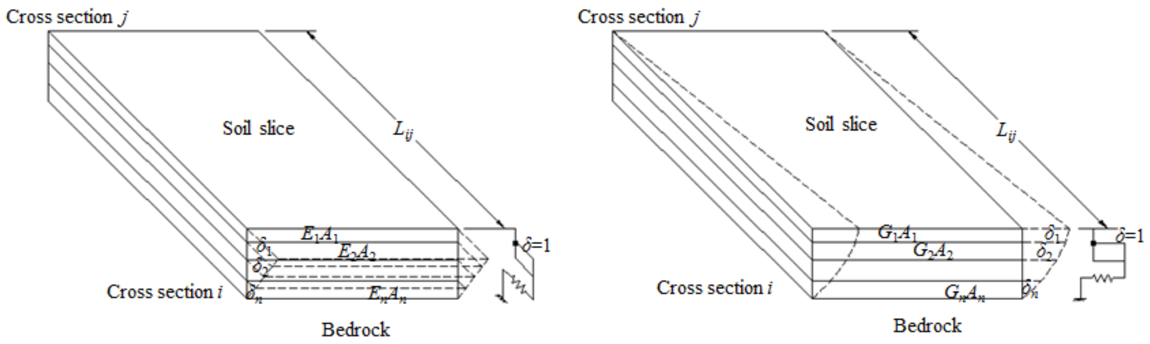


Fig.5 Calculation model for the springs between the adjacent soil masses

The soil-structure interaction system comprises of the tunnel structure and the interaction springs and dashpots connecting the tunnel to the soil masses. The tunnel is treated as an elastic beam supported on viscoelastic foundation. The immersed tunnel is a shallow embedded structure, so the determination of the interaction impedances can refer the works of Gazetas[11].

ABAQUS finite element procedure[12] is applied to establish the simplified model to carry out the dynamic analysis of the immersed tunnel. This model accurately simulates the tunnel, including the immersed section, the east and west cut-and-cover sections, and 34 immersion joints. The tunnel elements are discretized as a series of Timoshenko beam element.

As depicted in Fig.4, each immersion joint is modelled by a group of five nonlinear springs, i.e. longitudinal, transverse shear, vertical shear, transverse bending, and vertical bending components. The longitudinal, transverse and vertical bending components represent the function of Gina gasket, while the transverse and vertical shear components represent the function of steel shear keys.

Since the parameters of the mass-spring system express the properties of the soil slices along the tunnel, the local site conditions can be automatically taken into account. To consider the wave passage effect, the earthquake wave can be inputted with a time lag to the bottom ends of the soil slice springs. Field observations[9] in Japan have indicated that the apparent wave velocity may be in a range of 1000-2000m/s. For the sake of comprehensive study, three wave velocity of 1000 m/s, 2000m/s and 3000m/s, as well as the opposite propagation directions, are taken consideration in analysis of the non-uniform excitation.

In this way, once the input of uniform or non-uniform excitation act on the bedrock, the seismic response of the immersed tunnel can be calculated.

6. Results and discussion

Four characteristic sites, which respectively represent the vicinity of boundary, thinnest soil deposit, the thickest soil deposit, and the slope site, are selected to investigate the local site conditions as shown in Fig.6 (a). The longitudinal acceleration and displacement responses of the ground and tunnel at four sites are described in Fig.6 (2) and (3), respectively. It can be obtained that the earthquake wave is amplified through the soil deposit. Because of a thick soil deposit underlying, the effect of amplification at site C is larger than other sites. Also, the varying amplifications at different sites indicate the effect of local site conditions is significant. In addition, both the acceleration and the displacement of the tunnel are essentially consistent with those of the ground at four sites. It means that the tunnel basically follow the motion of ground.

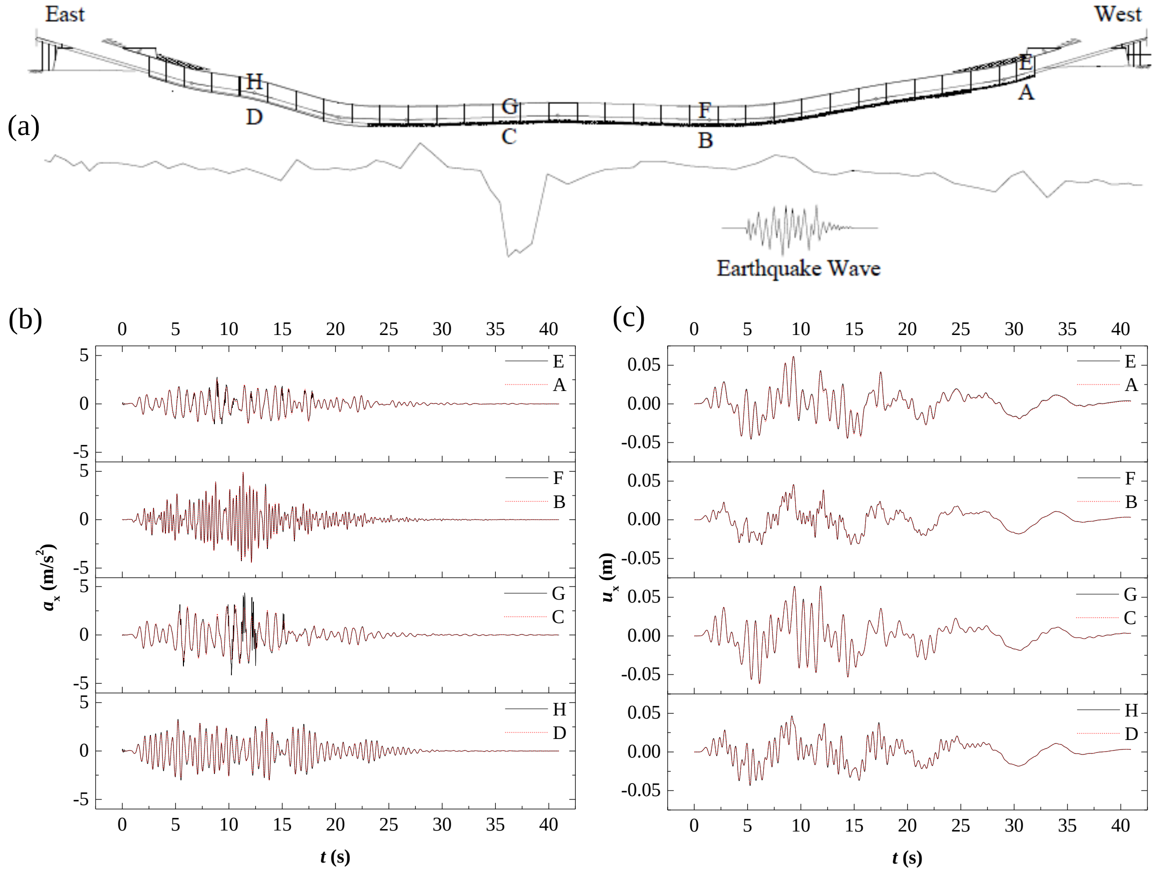


Fig.6 (a) Characteristic sites; (b) Longitudinal acceleration time histories; (c) Longitudinal displacement time histories

The longitudinal deformation of immersion joints is critical for the seismic safety of the tunnel. The range of extension and compression of the immersion joints in longitudinal direction under seismic excitation is illustrated in Fig.7. It can be known from the figure that the seismic deformation of the immersion joints is significantly affected by the non-uniform excitation. Compared with the uniform excitation, the deformation range of immersion joints is larger in non-uniform excitation cases. The low value of the wave velocity that leads to large time lags, consequently, results in more non-uniform excitation and large deformation of immersion joints. Furthermore, the results from the numerical analysis are also influenced by the wave propagation direction due to the varied site conditions along the tunnel. Therefore, the non-uniform excitation should be considered in the seismic design of long immersed tunnel.

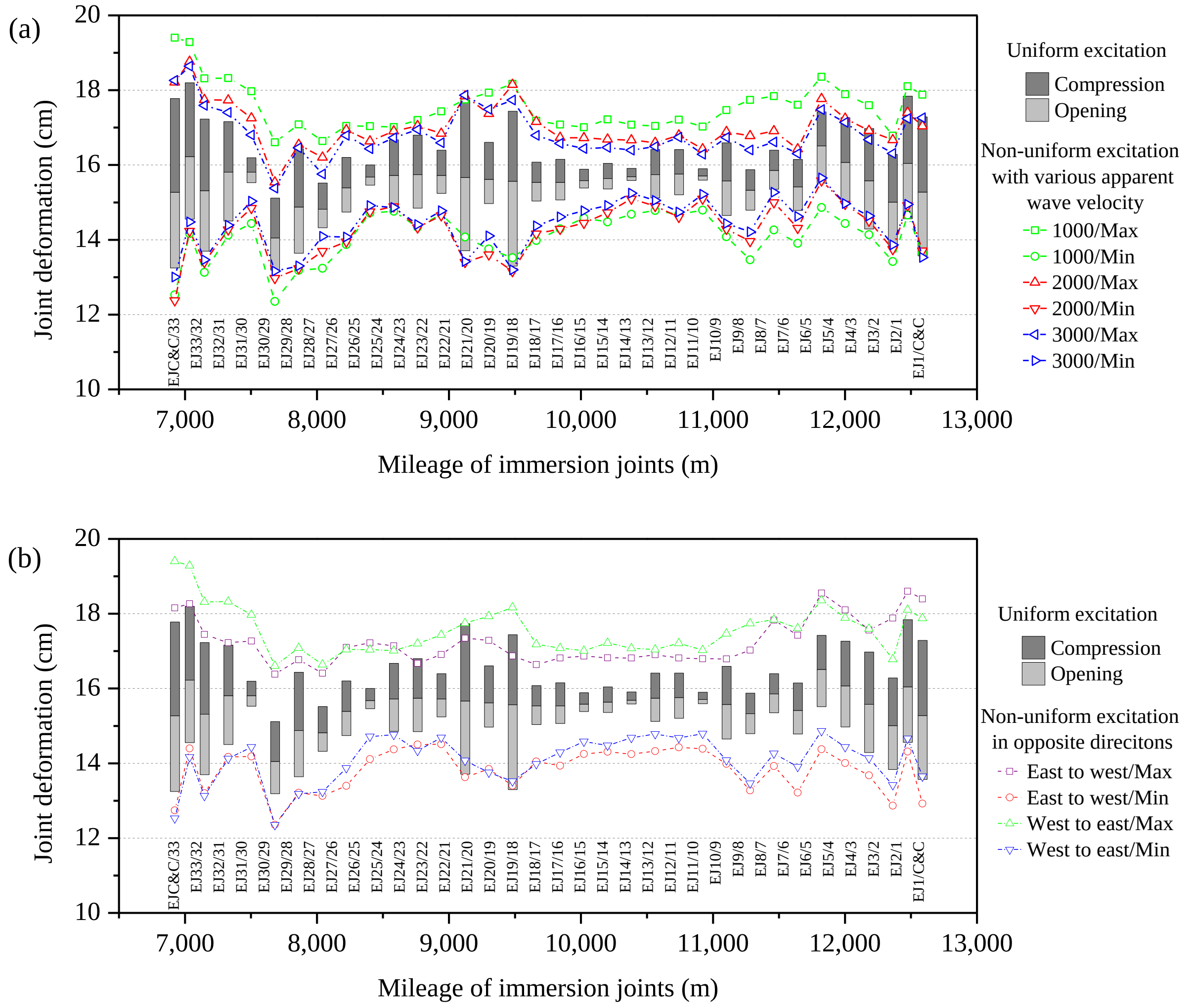


Fig.7 Longitudinal seismic deformation of the immersion joints (a) various apparent wave velocity; (b) opposite propagation directions

7. Conclusion

A simplified numerical model based on the equivalent mass-spring system is proposed to investigate the seismic response of a long immersed tunnel under longitudinal non-uniform earthquake excitation. The wave passage effects and local site conditions that cause the non-uniform excitation are taken into consideration. The numerical results demonstrate that the effect of local site conditions along the tunnel is significant. The results also show that the seismic deformation of the immersion joints is significantly affected by the wave passage effects. Compared with the uniform excitation, the deformation range of immersion joints is larger in non-uniform excitation cases. In additon, the results from the numerical analysis are also influenced by the wave propagation direction. In summary, the non-uniform excitation should be considered in the seismic design of long immersed tunnel.

Acknowledgements

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