Seismic and sealant behaviour of segmental joint gaskets in shallow immersed tunnel

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Abstract. Joint gaskets of the immersed tunnel are critical for the seismic safety of the immersed tunnel. In this study, a rigorous numerical model of rubber gaskets is conducted and validated against experimental results. Then, the model is used to estimate the mechanical and water tightness behaviour of three types of gaskets. Finally, a coupled nonlinear soil-structure interaction beam-mass-spring model is developed. The joints are simulated with the nonlinear hyperelastic elements following obtained load-deformation of three gaskets. The hydrostatic installation is modeled properly, then the seismic excitation is fired on bedrock. Finally, the results are discussed in the aspects of joint deformation and water tightness during the seismic loading.

1. Introduction
The immersed tunnel, as a unique underground structure, is different from other substructure both in the construction method and in form. Typically, the tunnel contains prefabricated floatable segments, which are usually concrete-lined steel or reinforced concrete only. The segments are constructed in a dry dock, with special bulkheads making sure the water tightness of segments. Afterward, they are floated over and sink into a dredged trench in the floor of the river or sea. The segments are connected through special rubber gaskets by water pressure. After completing water tightness, the bulkheads between the segments are removed, forming an integrity tubular tunnel in the bottom soil. Comparing to the shield tunnel, the immersed tunnel have certain advantages. The immersed tunnel can be located at a lower depth, minimizing both the total length of the tunnel and the water pressure. Meanwhile, fewer joints in the immersed tunnel help the control of joints leakage.

Thanks to these superiorities, more than 100 immersed tunnels have been constructed for road or railways in this century\textsuperscript{(1)}. Recently, construction of a 6 km immersed tunnel of the Hong Kong–Zhuhai–Macao Bridge (HZMB) started in 2011, while construction of another grand engineering – approximately 18 km long Fehmarn Belt immersed tunnel between Danmark and Germany planned to inaugural in 2022. Seismic resistance and waterproofing can be crucial challenges for a long deep immersed tunnel. When attacked by an earthquake loading, especially the longitudinal direction, high requirement of water tightness of deep tunnel joints can be challenged, since the oscillation may cause decompression of the joints gaskets. However, the seismic and water tightness of joints doesn’t only happen with long deep immersed tunnels. The rather shallow immersed tunnels, like immersed tunnels

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crossing city inner river, also have to face these problems but in another aspect. For a shallow immersed tunnel, the hydrostatic pre-stressing is lower to compact the gaskets, thus the initial compression is limited. Once a certain degree of seismic induced decompression of joints happens, though the requirement of water tightness is lower, the limited initial compression can lead to a threat to the water tightness (or safety) of tunnel. In any case, the behaviour of the gaskets can be crucial to the seismic resistance of the shallow immersed tunnel.

The immersed tunnels usually have a large cross-section, however, the tunnels are designed to be quite rigid compared to the surrounding soil. Thus, the analytical procedures based on the assumption of Winkler-foundation-beam can be fairly reliable, if only the behaviour of the joints and soil-structure interaction are carefully considered. In the late 1950s, engineers of the San Francisco Bay Area Rapid Transit (SFBART) proposed an analytical method to identify the effects of earthquakes on a submerged tunnel[2]. Then, Kuribayashi and fellow researches (1974) developed and modified the SFBART method, and soon became the basis of the seismic design approach of immersed tunnel of Japan Society of Civil Engineers (JSCE). Kawashima, (2000) applied the spring-mass model to compute the seismic response of a 1053 m immersed tunnel. Recently, several full three-dimension finite element analyses were utilized for calculating seismic response of immersed tunnel[4]. However, calculation efficiency is still quite a problem. Except for the computation methods, a number of experimental analysis of immersed tunnel were conducted both in centrifuge and large-scale (1-g) shaking tables[5,6]. Due to the limitation for the geometry scale, usually experimental method cannot reveal the seismic response for full range of the immersed tunnel.

The main intention of this paper, is to study the effects of gaskets mechanism, including compression and waterproofing behaviour, to the seismic behaviour of a shallow immersed tunnel crossing the Peral River in Guangzhou, China.

2. Modeling OF RUBBER GASKETS

The sealing components of the immersed joints are called Gina and Omega seal (Fig.3). The Gina is initially contacted with the adjacent element, using a low pulling force provided by hydraulic jacks. Then, with pulling out of the water between the bulkheads, the hydrostatic pressure compresses the Gina gasket and seals the joints. The secondary seal, Omega seal is then installed across the joint inside the tunnel. Compare to Omega, Gina is the main sealing and almost non-replaceable, meanwhile plays an important role in force transmission mechanism of joints. Thus, the following discussion of the gasket means the Gina seal, if it is not specified.

Figure 1 (a) Geometric scheme of existing and hypothetical Gina seal; (b) Compression of computed and experimental load-compression behaviour; (c) Computed load-compression relationship of Gina A, B, and C; (d) Analysed contact stress against compression on the tip of Gina A, B, and C.
The analysis is conducted in two steps. First, highly nonlinear analysis of the special rubber gaskets is carried out based on Finite Element Method (FEM). The model is validated against the compression tests of a certain existing GINA gasket. In the following step, two hypothetical gasket sections are designed and subsequently evaluated by the validated numerical model. The numerical predicted load-displacement behaviour is going to be considered in the following dynamic analysis. The water tightness capacity of the gaskets under different compression is evaluated grossly by contact stress between gaskets and segments.

The GINA gasket is to be manufactured from a blend of SBR (Styrene-butadiene Rubber) and NR (Natural Rubber). The rubber based material is considered to be typical hyperelastic with a Passion ratio as nearly 0.5. The Mooney-Rivlin model [7] utilizing a strain energy function $W$, is adopted to determine the stress components with respect to a certain strain component. The Mooney-Rivlin strain energy function is formed in:

$$W = \sum_{k=0}^{n} C_{km} (I_1 - 3)^k + (I_2 - 3) + \frac{1}{2} K (I_3 - 3)^2$$

where $W$ is the strain energy per unit volume; $I_1$, $I_2$, $I_3$ are the invariants; $K$ is the bulk modulus; $n$, $k$, and $m$ are hyperelastic material arguments without physical meanings, decide as 1, 1, and 0, respectively. $C_{km}$ (here, $C_{01}$ and $C_{10}$) are utilized to describe the mechanical behaviour of the hyperelastic rubber. The parameter $C_{km}$ can be obtained experimentally or empirically.

A plane-strain model is considered and implemented in a FEM code ABAQUS/Explicit. The segment is modeled as an idealized rigid body, while the rubber gasket is modeled by a 4-node continuum element following the constitutive relation of Mooney-Rivlin. The parameters $C_{km}$ are first estimated empirically and finally calibrated against the compression testing results. The compression between recorded compression testing results and predicted results of a certain type of GINA gasket noted as type A, are illustrated in Fig.1 (a). Though some discrepancy, the comparison is satisfied, especially with the fact that practical rubber products are not idealized incompressible. Then, to make a logical extrapolation, we anticipate two hypothetical types of joint gasket sections based on type A: a 1.5 times scaled sized gasket denoted as type B and a 1.5 times bigger sized gasket denoted as type C. Fig. 1 summarized the section geometries and load-deformation curves (either recorded or computed) of these three gaskets.

A simplified method to evaluate the potential of water-leakage of the rubber gaskets is to compare the contact stress to the water pressure outside. Further, Ding and fellow researchers [8] did a series of experimental and numerical studies of joint rubber gaskets on the aspects of the water-proofing capacity, sealant mechanism, and computation method of sealing failure progress. They found a positive correlation between contact stress and water pressure. Since evaluating accurately the waterproof capacity of the gaskets is not the main scope of this paper, we only apply the conclusion of previous publications, utilizing the contact pressure as an index to assess the joint water tightness capacity. Fig.1 (d) illustrates the computed contact stress on the tip of the gaskets with different compression.

3. Dynamic modelling of the immersed tunnel
The geotechnical exploration data and joint cross-section of the immersed tunnel is depicted in Fig.2 and Fig.3, respectively. The dynamic analysis methodology is schematically illustrated in Fig.4 and is going to be described subsequently in the following sections.

3.1. Modelling of the ground
With respect to modelling of the ground, two essential issues are: (1) the way of ground motion inputting to the structure and (2) the estimation of the interaction between soli and the tunnel. Anastasopoulos et al. (2007) proposed a decoupled two-step dynamic analysis methodology. First, the
nonlinear wave propagation of the ground soil is estimated using an equivalent linear approximation under a free-field condition. Then the estimated motion on the elevation of the bottom of tunnel is inputted to the tunnel through springs, dashpots, and slider. The work is comprehensive and convincing, however the proposed methodology is decoupled, thus, effects of tunnel to the soil are omitted. In presented model (Fig.4), soil above the uneven bedrock is sliced and lumped into masses of participating in vibrations respectively. The soil springs connecting the bedrock and mass points are determined by the various slices of soil layers in the longitude direction of the tunnel. The spring-mass system can reflect the natural period of each soil slice. In advance, the mass points are connected by springs and dashpots which representing the relative axial and shear stiffness (both in vertical and transversal) between the adjacent mass points. Finally, the tunnel is connecting to the soil-mass system by interaction springs and and dashpots. The ground motion input on the bottom of the model (bedrock). To sum up, the distribution of the layered soil, various amplification, and soil-structure interaction are considered in this integrated coupled ground model (Fig.4, d).

**Figure 2** Geotechnical exploration data along “central line” of the axis of the immersed tunnel: classification of soil layers

3.2. **Modelling of segments and joints**

The tunnel is modeled by the beam element. Each beam element is 5m length. The beam is assigned with the immersed and cut-and-cover cross-sections according to the design scheme, shown in Fig.4 (b). The longitudinal inclination of the tunnel is considered by defining the segmental beam elevation.

As schematically depicted in Fig.4 (a), each immersed joint is simulated with two multi-node frames of the joint cross-section. The number of nodes is decided by the length of the gasket, namely one node parameter. Considering the computational efficiency, the gaskets are modeled as a series of single degree-of-freedom (DOF) nonlinear spring connecting two frames. The nonlinear springs are based on the load-deformation results from the validated rigorous model (Fig.4). The frame is rigidly restrained, in all six degree-of-freedoms, to the end of the beam. The shear key is another important component in the joints. As shown in Fig.3 (a), the joints of immersed tunnel have six steel shear keys and six concrete keys on the sidewall and intermediary walls to constrain the differential vertical deformation between adjacent segments. Similarly, horizontal concrete shear keys located on the inverse slab of the joint restrain the horizontal relative deformation of the joint. The shear keys are modeled at the designed position in the plane of the joint frame, shown in Fig.4 (a). Fig.4 (c) illustrates schematically that the shear keys are modelled by nonlinear springs representing the stiffness. The load-deformation curves of both steel and concrete shear keys are calculated through elaborated numerical analyses.

3.3. **Modelling of the installation and seismic excitation**

The analysis contains two steps: (1) installation of the segments and (2) excitation of the seismic loading. First, the first segment on the left side of the model is activated and the hydrostatic pressure is loaded at the right end of the segment. Then, the second segment is activated and the new hydrostatic pressure is applied at the end of the second segment, while the “old” hydrostatic pressure on the first segment is removed. The procedure is repeated until all the six segments are installed. Therefore, the initial hydrostatic compression of joints is simulated. The initial compression of the joints with gaskets
is illustrated in Fig.3 (c). After the installation, synthetic earthquake is fired at the bottom of the model. The synthetic earthquake of the construction site is expected to predict bedrock movement under the specific geologic environment. The time history and frequency of the motion is shown in Fig.5.

Figure 3 Detailed cross-section of immersed joint: (a) distribution of shear keys, Gina and Omega sealing; (b) Gina before installation; (c) Gina after installation; (d) Horizontal shear keys

Figure 4 Schemed finite-element model: (a) detailed joint; (b) cross-section of immersed and cut-and-cover tunnel; (c) load-shear deformation of vertical shear key; (d) 3-D view of model.

Figure 5 Accelerograms of the target ground motions that were used to synthesize the artificial ground motions and their elastic spectral acceleration.
4. RESULTS AND DISCUSSION
The parametric study has revealed that the seismic response of the immersed joints is related to the mechanical characteristics of gaskets. Fig. 6 illustrates the initial hydrostatic compression of the joints (J1 - J7) in columns. With the same gasket, the initial compressions differ with the water-pressure of the joints. Fig. 6 also shows the correlation of gaskets mechanism on the dynamic maximum and minimum longitudinal deformation experienced by all the seven joints for the three types of Gina gasket (A, B, and C). From Fig. 6, it is found that with a smaller size of gasket (B), the minimum compress could be very low which can be a risk, while with a bigger one (C), it is safer. As we discussed previously, we can use the contact stress to evaluate the water tightness safety of the joints. Fig. 8 illustrates the contact stress in black lines (coordinates on the right side) when the minimum compression appears for three types of gasket. From the comparison of contact stress (positive correlation with water tightness), the big size gasket (C) is safer for immersed tunnel subjected to longitudinal seismic motion.

![Figure 6 Initial hydrostatic, maximum, and minimum joint compression and minimum gasket contact stress of joints J1 to J7 for three types of gaskets: (a) with type A; (b) with type B; (c) with type C;](image)

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