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Compression-shear behavior of a scaled immersion joint with steel shear keys

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ABSTRACT

The shear behavior of an immersion joint subjected to compressive-shear loads is investigated in this paper. To explore the performance of the immersion joint a scaled specimen, according to a specific protocol of a real project, is designed. A quasi-static shear force is applied horizontally while a constant compression force is maintained on the joint. A hysteresis effect is observed during the test and the area of the hysteretic loop increases with the shear force. An envelope curve of the shear force-displacement of the joint is obtained and divided into four stages based on the observed shear behavior of the joint. The shear stiffness of the immersion joint is calculated, showing a non-linear change with the shear displacement. The shear capacity of the model immersion joint and that of a single steel shear key are evaluated. It is found that the capacity of the joint is smaller than the sum of the capacities of all shear keys. This shows that the shear keys are not activated at the same time. The failure mode of the joint consists of a brittle shear failure in the single shear keys and a step-by-step failure way of the complete joint.

1. Introduction

An immersion joint is the connecting part between two adjacent elements of an immersed tunnel. Compared to the stiffness of the concrete elements, the stiffness of the immersion joint is relatively small. When it is subjected to shear actions, whether resulting from foundation settlement or horizontal earthquake movements, the shear resistance of the joint is one of the main concerns for a safe and reliable water-proof design, which is as important as the longitudinal response which has been analyzed by Xiao et al. (2015). As mentioned in available literature (Akimoto et al., 2002; Baber et al., 2011; Hung et al., 2009), the immersion joint is a vital part not only for the connection between elements but it is also critical for the water tightness.

A flexible immersion joint, which normally consists of a rubber seal and shear keys, is a common solution in practice. The way in which the shear keys and the rubber seal behave together in the joint is of vital importance to a thorough understanding of the shear behavior of the joint. However, very few experiments on the shear behavior of immersed joints are available in the literature although flexible joints have been used in practice for more than 50 years already.

Kiyomiya et al. (1992) carried out both a 3-dimensional experiment and a finite element analysis of a new type of a flexible joint referred to as the Crown Seal. The results indicated that this new type of joint can be used in practice due to the effective reduction of lateral deformation. However, the test only focused on the "rubber seal" and didn't take the shear keys into account. A simplified linear model was found in the numerical simulation analysis in the paper of Anastasopoulos et al. (2008) who describe the behavior of the shear keys, assuming that the stiffness of the shear keys tends to infinity. However, this model was not supported by subsequent literature and the effect of the rubber seal was ignored. As an improvement, a three-dimensional nonlinear stiffness mechanical model was developed by Ding and Liu (2014) to analyze the axial and shear structural performance of the immersion joint by considering different working modes of the joint. However, both the simplified and improved models of the joint behavior rely on the input parameters of the stiffness of the seal and the shear keys. This means that if different stiffnesses are selected, different results are obtained. Therefore, the selected parameters as well as the models themselves need numerical and experimental verification. The shear capacity of concrete shear keys in segmental joints was discussed by Van Oorsouw (2010) by considering the influence of both the reinforcement in the keys and the friction between the segments. Although some suggestions

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were given, the shear behavior of the concrete shear keys was not discussed in depth and the calculated shear capacity was not considered to be accurate as the model was not verified. To obtain a thorough understanding of the behavior of the joint, large-scale experiments were done by Kiyomiya et al. (1992) and Xiao et al. (2015) but only the axial and flexural behavior of the joint were considered but not the shear behavior.

Although the shear-keys play an important role in an immersion joint, no published reports on experiments concerning their mechanical behavior are found. In a numerical analysis of a joint under shear actions, the shear keys are always modelled as simplified linear or bilinear springs in the shear direction by lack of experimental data. Moreover, the shear capacity of the joint and how the rubber and the shear keys interact was never considered and neither was the shear failure mode of the shear keys or the joint. Hence, the shear behavior of the joint needs more attention in a comprehensive way, taking the shear stiffness, the shear capacity and the failure mode into account.

To clarify the mechanical behavior of an immersion joint under shear action, this paper presents the results of a large-scale experimental investigation. Compression-shear quasi-static loading was applied to a flexible immersion joint, with a geometric scale of 1/10 with respect to an actual design. The loading protocol in compression-shear was designed according to the axial water pressure, to which the joint would be subjected during its service life at typical buried depths, and to transverse shear movements due to seismic actions. The shear forces are applied reciprocally at increasing amplitude in the horizontal plane until the joint fails. Measuring devices were installed systematically to record the applied loads, the extension and closure of the joint. Through observed load-deformation curves, both the shear stiffness and the failure mode of the scaled joint are obtained and the results are discussed in detail.

2. Scaled model of immersion joint

2.1. Flexible joint

2.1.1. Prototype design

As the rubber seal becomes more common, flexible immersion joints have been widely used around the world. A typical cross-section of an immersion joint from an actual project, as well as its dimensions, are shown in Fig. 1(a). The cross-section is 37.95 m in width and 11.40 m in height with chamfered upper corners. There are two middle walls inside the tunnel, forming two traffic bores apart and one middle gallery.

The joint mainly involves a primary rubber seal, a secondary rubber seal and shear keys, as can be seen in Fig. 1(b).

The primary rubber seal is installed on the steel shell around the external perimeter of the joint, acting as the permanent water-tightness proof. When the immersed tunnel is being installed, the element is pulled towards the previously installed one. Then the primary rubber seal between the elements is pressed tightly and sealed completely due to hydrostatic pressure. After that, the secondary rubber seal is placed. If the primary rubber seal fails, the secondary rubber seal will be activated to work to avoid leakage.

Steel shear keys are box sections mounted on an embedded plate secured to the end of the concrete tunnel element by studs and steel bars as shown in Fig. 2. The steel box is a hollow box strengthened with stiffening ribs inside. The box-type steel shear keys are connected to the embedded plate by bolts going through the steel box. The dimensions of the steel box are 2400 mm × 760 mm × 550 mm. The diameter of the bolts ranges between 56 mm and 64 mm, depending on the position.

2.1.2. Compression-shear force in the joint

Due to the unique construction method of an immersed tunnel, an initial compression force caused by hydraulic static pressure always exists in the joint and consequently the joint is compressed and completely sealed. The hydraulic pressure depends on the water depth and as such, the initial compression force varies from the water depth where the joint is located. Hence, the compression force is constant for a specific joint and it is mainly transferred by the primary rubber seal.

Under seismic excitation, horizontal and vertical ground displacements caused by S-waves may occur, resulting in horizontal and vertical bending in the tunnel which is also referred as ‘snaking effect’. The resulting bending moments lead to a reciprocal shear effect arising in the joints. Also, differential settlements may occur between adjacent elements, resulting in vertical shear effects. All of these shear forces are transferred from element to element through the joint with the contribution of the shear keys. It should be note that the shear keys only resist shear force rather than compression force.

Based on that, both the compression and shear force need to be taken into account at the same time and the compression-shear behavior of the joint will be examined by means of the experiment.

2.2. Geometric scale

As shown in Fig. 1, the cross-sectional dimensions of the prototype tunnel are 37.95 m by 11.40 m, which is oversize and exceeds the loading capacity of the lab. Hence the dimensions of the model specimen need to be scaled down. In consideration of the available loading capacity, a geometric scale of 1/10 is selected.

As the same materials as the prototype are used, the same elastic modulus, the density and strain in the model are obtained. Based on the dimensional analysis, the scale of the stress, area and force can be obtained as follows:

$$C_\sigma = \frac{\sigma_m}{\sigma_p} = 1 \tag{1}$$

$$C_A = \frac{A_m}{A_p} = \left(\frac{l_m}{l_p}\right)^2 = 1/100 \tag{2}$$

$$C_F = \frac{F_m}{F_p} = \frac{A_m}{A_p} = 1/100 \tag{3}$$

where C_A,C_F,C_σ,A,F,σ and l represent the scale of the area, scale of the force, scale of the stress, the area, the force, the stress and the length respectively. The subscripts m and p represent model and prototype respectively.

Hence, the dimensions and the area of the scaled model are one tenth and one hundredth of the prototype respectively. In this case, the model has the same structural shape, structural form and reinforcement ratio as the prototype. The input loading and the capacity are scaled down as well, based on the obtained scale.

2.3. Scaled model

2.3.1. Model tunnel element

Shear deformations of an immersion joint can happen both in the vertical or horizontal direction. However, the horizontal and vertical shearing of the joint are basically the same from a mechanical point of view. The difference is the influence of the rubber due to its different lengths along the horizontal and vertical sides. Moreover, gravity needs to be considered for vertical loading, resulting in one more difficulty with the application of shear loading. Therefore, only a horizontal shear force will be considered as well as only the horizontal shear keys. Due to the negligible contribution to the horizontal shear behavior of the joint, the cross-sectional profile of the model element was simplified as a rectangle and the middle walls, which are present in the actual tunnel (see Fig. 1(a)), were not provided.

Fig. 3 also provides the dimensions of a single tunnel element with a width of 3800 mm, a height of 1150 mm, and a length of 1250 mm, as well as a 150 mm-thick concrete slab. Referring to the Chinese Code for concrete structure (GB50010-2010), the types of concrete and reinforcement are C50 and HRB335 respectively. The reinforcement ratio