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Numerical Analysis of Mechanical Behaviours of Immersion Joint

Wenhao XIAO[1*], Yong YUAN[2], Haitao YU[3], Lu JING[4], Yue CHEN[5]

[1] Department of Geotechnical Engineering, Tongji University, Shanghai, China, 200092, E-mail:1989siumanho@tongji.edu.cn, Presenter

[2] State Laboratory of Disaster Reduction of Civil Engineering, Tongji University, Shanghai, China, 200092, E-mail: yuany@tongji.edu.cn

[3] Key Laboratory of Geotechnical and Underground Engineering (Tongji Univeristy) of Ministry of Education, Tongji University, Shanghai, China, 200092, E-mail: yuhaitao@tongji.edu.cn

[4] Department of Geotechnical Engineering, Tongji University, Shanghai, China, 200092, E-mail: jinlu1989@126.com

[5] Hong Kong-Zhuhai-Macao Bridge Authority, Zhuhai, China, 519095, Email: cy@hzmb0.com

Abstract: The immersed tunnelling technique is commonly used for river or sea crossings worldwidely. Seismic safety criterions of immersed tunnels involve the shear stiffness, axial stiffness, flexural stiffness, and opening deformations of the immersion joints. Therefore, it is necessary to conduct mechanical analysis of joint between immersed tunnel elements. A pseudo-static numerical analysis of an immersion joint is presented in this paper, mainly involving the modelling method, loading mechanism and results. In this model, anchor bolts connecting shear keys and concrete segments are replaced by an assumed equivalent layer and the vibration isolation is simplified as tolerated value of contact. Additionally, the nonlinear feature of GINA gasket is also taken into consideration in this model. It can be concluded that the mechanical property of GINA gasket is significantly affected by both flexure and axial loadings. In contrast, the loading effects on the behaviours of shear keys can be neglected, which indicates hysteresis characters under cyclic loadings. The numerical results and conclusions are benefit to the further large-scale model tests of immersion joint in progress, and more related further publications are expected in future.

Key Words: *Numerical analysis, Immersion joint, Mechanical behaviours, Model test.*

1. Introduction

The immersed tunnelling technique [1] is commonly used for rivers or sea crossings worldwidely. The immersion joints are critical components between elements of an immersed tunnel. Generally, the stiffness of immersion joints is much smaller than that of tunnel elements. Therefore, deformation will be focused on immersion joints when immersed tunnels subject to earthquake or differential settlement, which result that immersion joints will be the key point with respect to load-carrying and deformation capacity of the whole tunnel. Undoubtably, the immersion joints are the weakest point of the whole tunnel as well as the critical components for seismic design of immersed tunnel. Consequently, more attention should be paid to mechanical analysis of joint between immersed tunnel elements.

Researches related to mechanical study of immersion joints mainly focus on [2] full-scale test, model test and numerical simulation. A full-scale test can reflect the real situation. However, it is still difficult to be carried out. Small scale model is reasonable to cope with this problem. Nevertheless, there still exists a great challenge to conduct various cases through model test. Inversely, numerical modelling for large-scale structures is an alternative way to diversify the geometric dimensions and loading mechanisms [3].

The mechanical properties of immersion joint can be reflected by its stiffness, involving shear stiffness, axial stiffness, flexural stiffness, and opening deformations. So far, researches about principles of stiffness are mainly based on numerical analysis: An longitudinal seismic analysis of Nanjing immersed tunnel using spring-mass model was done by YAN et al.(2004)[4], considering the influence of rigid, hinged and elastic joints respectively. DING et al.(2005, 2006)[5, 6] presented a 3D numerical simulation method for large-scale seismic response calculation based on the explicit FEM, considering surrounding soil, tunnel segments and the detailed flexible joints. Based on the reliability of numerical model, the comparison of solid element and shell element in modelling was analysed by PENG et al. (2007) [7]. The dynamic response of a deep immersed tunnel to the consecutive action of a major normal fault rupturing in an earthquake was investigated by Anastasopoulos et al. (2007) [8] through a 3D elaborate nonlinear model. Van Oosouw (2010) [9] investigated the behaviours of immersed tunnel under seismic loading with FEM, and calculated the stiffness of GINA gasket during different stages with couplers. All the aforementioned researches are limited to the dynamic response of tunnels instead of joints. Furthermore, the simulation of immersion joint was always simplified without consideration of its several components. Therefore, the mechanical properties of immersion joint need to be clarified and analysed elaborately.

A pseudo-static numerical analysis with respect to the mechanical properties of an immersion joint is presented in this paper. The simulation method is briefly introduced as well as material and component modelling. Both compression-bending and compression-shear cases are studied respectively using relevant loading mechanisms. Results and corresponding discussion of mechanical properties of immersion joints are also presented.

2. Methodology

2.1 Material model for GINA gasket

As the most important component of immersion joint, GINA gasket not only bears axial force but also ensures impermeability. GINA gasket shows nonlinear features in both geometric and material behaviour. Strain energy function is used by ABAQUS to express the hyper-elastic relationship of stress and strain instead of Yong’s modulus and Poisson’s ratio. As the most comment used strain energy function, the Mooney-Rivlin model [10] is widely applied to simulate incompressible rubber material, which is shown as follows:

$$U = C_{10}(\bar{I}_1 - 3) + C_{01}(\bar{I}_2 - 3) \tag{1}$$

where $\overline{I_1}$ and $\overline{I_2}$ are the first and the second invariant of the unimodular component of the left Cauchy–Green deformation tensor. C_{10} and C_{01} are empirically determined material constants which can be evaluated or obtained based on experiment. ZHENG et al. (2003)[11] pointed out the relationship between material constant and Young’s modulus (Poisson’s ratio is 0.5):

$$E_0 = 2(1+\mu)G_0 = 3G_0 = 3(C_{01} + C_{10}) \quad (2)$$

A series of studies were done by ZUO et al. (2008)[12] who found that the value of C_{01} / C_{10} is of nearly no sensitiveness to deformation properties of rubber and gave an evaluated value of 0.25. Based on ZHENG and ZUO, the material constant can be determined once E_0 is obtained.

2.2 Material model for steel shear keys

Steel shear keys presented in Fig. 1, are the most complicated components in immersion joint and consist of shear tenon, embedded part and anchor bolts. The model of shear keys is simplified and being described in next part. A double-linear elastic-plastic model is applied to simulate steel here. The plastic modulus is 5% of elastic one, which can be seen in Fig. 2.

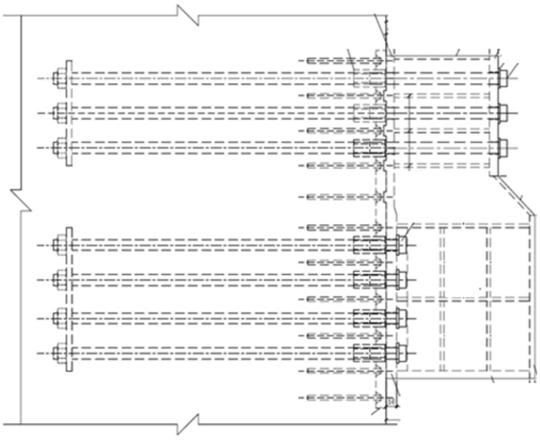

Figure 1 Profile of shear keys

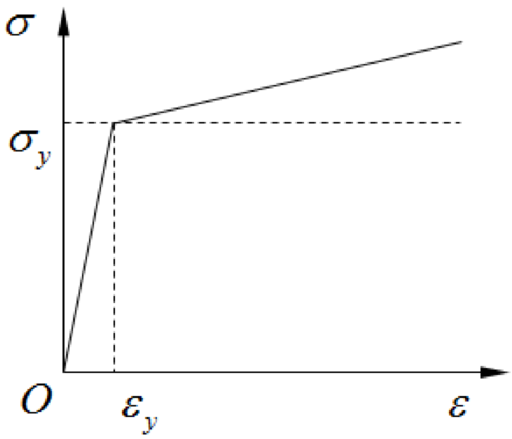

Figure 2 Applied constitutive model of steel

2.3 Algorithm for nonlinear contact of shear keys

Besides the GINA gasket, there is another rubber material "vibration isolation bearing" between the shear keys. Generally, this isolation bearing can be analysed using Mooney-Rivlin model as well. But under the circumstance that the material subjects to lateral load, volumetric locking will occur resulting in loss of calculating accuracy or misconvergence. To avoid this problem and reduce the amount of calculation, the concept of "adjustment factor" is proposed.

The applied adjustment factor method modifies the criterion of contact algorithm in order to avoid simulation of vibration isolation bearing. Generally contacts automatically detect master and slave roles for contact interactions. ABAQUS calculates an overclosure tolerance based on the size of the underlying element facets on a slave surface[13]. The logical variable k can be used to describe this calculation:

$$k = \begin{cases} 1, h \geq 0 \\ 0, h < 0 \end{cases} \quad (3)$$

where k is logical variable, k=0, surfaces closure; k=1, surfaces open. h is invasion distance.

In adjustment factor method shown in Fig. 3, an adjustment factor δ is used to describe the width of adjustment zone and Δ is used to describe the width of initial gap between surfaces. So the actual width of initial gap between surfaces is $\Delta' = \Delta - \delta$. The adjusted invasion distance is $h' = h + \delta$. Then the logical variable can be modified as follows:

$$k = \begin{cases} 1, h' \geq 0 \\ 0, h' < 0 \end{cases} \tag{4}$$

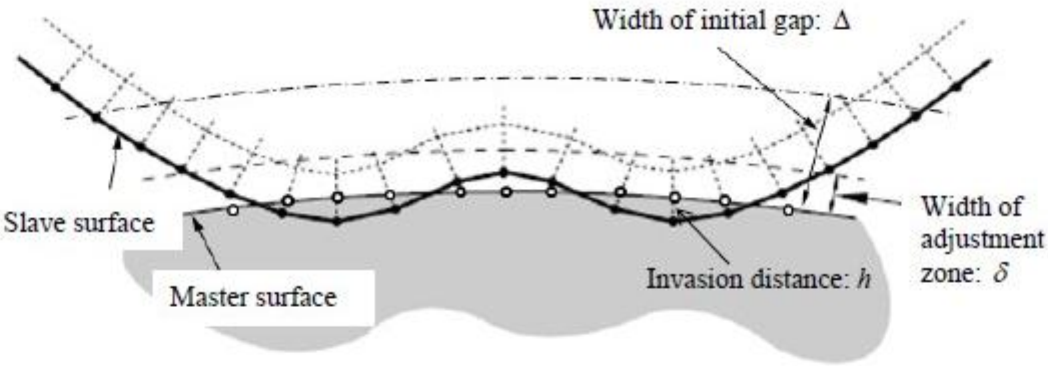

Figure 3 Adjustment zone in contact interaction

It can be seen that the value of δ depends on the amount of ultimate compression of vibration isolation bearing. To compare with the traditional method, this algorithm can avoid building contact between steel and rubber, resulting in reduction of the amount of calculation.

2.4 Equivalence method of shear keys

Shear keys are the main component to bear shear load and they are connected with segment through bolts, which is presented in Fig. 1. To avoid complicated modelling of shear keys, the bolts group can be equivalent to an elastic-plastic layer. The equivalent modulus can be defined as follows:

$$E_{eq} = (A_b l_{eq} / A_{eq} l_b) E_b \tag{5}$$

where E_{eq}、A_{eq}、l_{eq} are the Young's modulus, shearing area and shearing width of equivalent layer respectively, and E_b、A_b、l_b are the Young's modulus, shearing area and shearing width of bolts respectively.

3. Finite Element Model

The immersion joint analysed in this paper refers to flexible immersion joint which is gradually popularly used around the world. A flexible joint consists of GINA rubber gasket, shear keys and steel shells. The profile of applied immersion joint can be seen in Fig. 4.

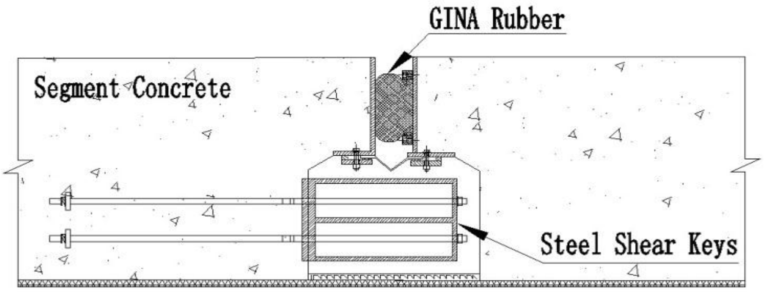

Figure 4 Profile of Applied Immersion Join

The joint model in this study includes two 38m x 11.5m x 22.5m segments with GINA gasket, horizontal and vertical shear keys between them.

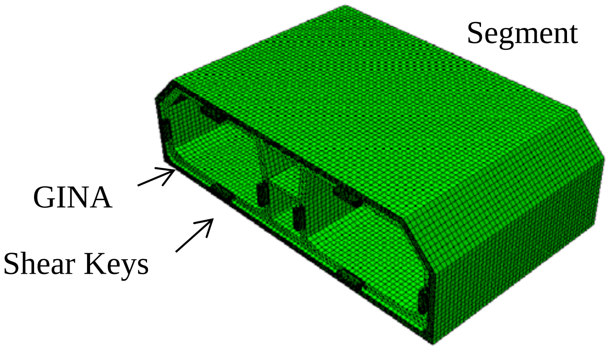

Figure 5 Numerical Model of immersion joint

Figure 5 shows the numerical model of an immersion joint. In the model, anchor bolts connecting shear keys and concrete segments are replaced by an assumed equivalent layer and the vibration isolation was simplified as tolerated value of contact. The finite element model of tunnel segment as well as shear keys and GINA has been built with solid element. Additionally, the nonlinear feature of GINA rubber[8] was also considered in this model. The numerical pseudo-loading mechanism of the test under horizontal seismic excitation is established according to a real project.

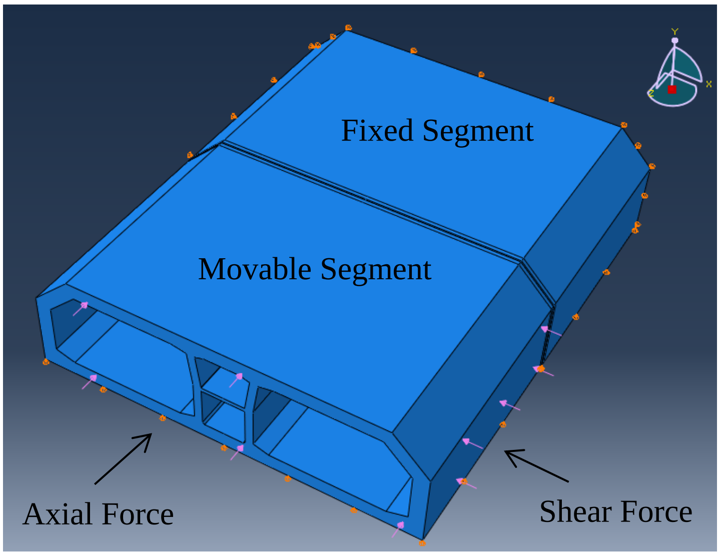

Figure 6 Assembling model of immersion joint

Fig. 6 shows the assembling model of immersion joint. In loading process, one segment is fixed and force is imposed in the other one which can be seen in Fig. 6. The axial force is applied in the end of the segment while the load applied on the side is shear force.

The value of input parameters is indicated in Table. 1.

Table 1 Values of parameters

Parameters	Value	Units
C_{10}	1.78x10^{5}	Pa
C_{01}	4.47x10^{4}	Pa
E_{eq}	3.4x10^{11}	Pa
δ	15	mm
Δ	20	mm

4. Results and discussion

Final calculations have produced plenty of data describing the mechanical properties of immersion joint, where the results can be proposed in two parts.

4.1 Results of compression-bending case

In this case only axial force has been applied. By controlling the loading mode of axial force, different levels of axial force and moment are imposed in immersion joints. The loading mechanism can be found in Table. 2.

Table 2 Loading mechanism of compression-bending cases

Case	Axial Force（MN）	Momernt（MN m）
1	50(20%)	160
2	100(40%)	160
3	150(60%)	160
4	200(80%)	160
5	250(100%)	160

As shown in Fig. 7, the maximum relative opening deformation of immersion joint subjected to horizontal moment decreases along with the axial force nonlinearly. The downward trend of this curve is stable in the first half part and the curve descends more slowly subsequently. Based on that, the flexural stiffness of immersion joint which increases along with the axial force nonlinearly is calculated and is presented in Fig. 8. Although the relative opening deformation changes significantly, the flexural stiffness of immersion joint is of the same magnitude. The maximum and minimum flexural stiffness are 7.61×10^5 MN/m and 1.89×10^5 MN/m respectively.

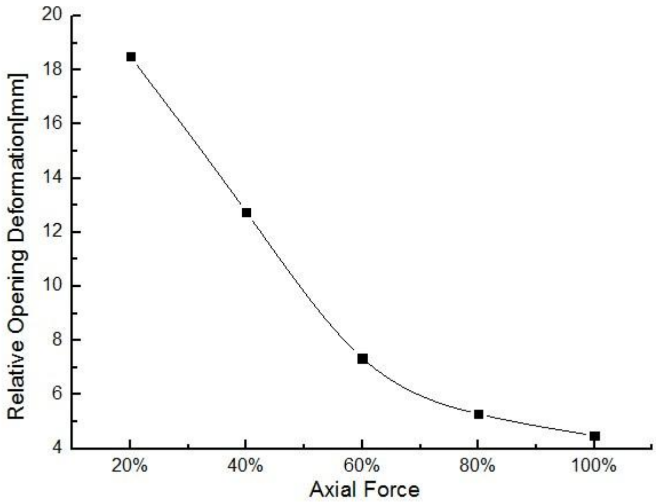

Figure 7 Relative opening deformation of immersion joint

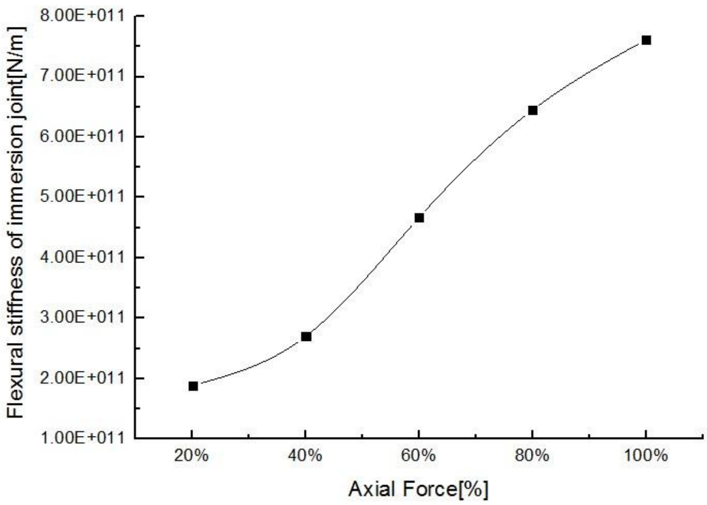

Figure 8 Flexural stiffness of immersion joint

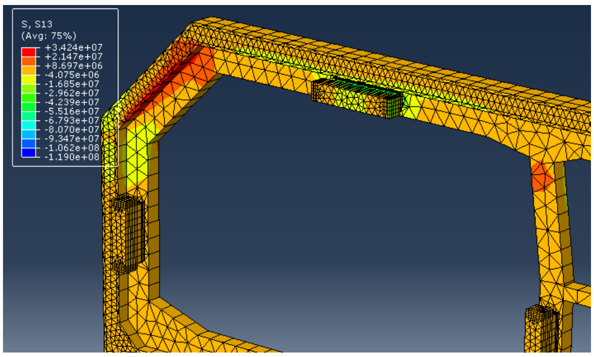

Figure 9 Shear stress cloud diagram of immersion joint

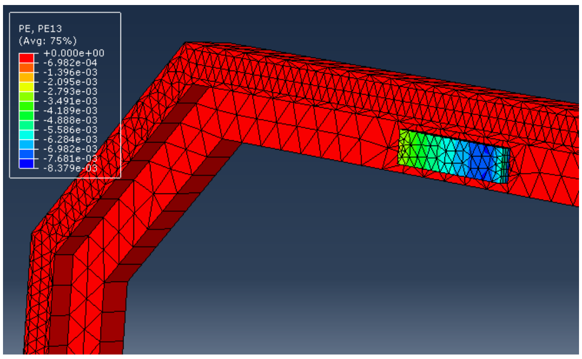

Figure 10 Shear plastic stress cloud diagram of equivalent layer

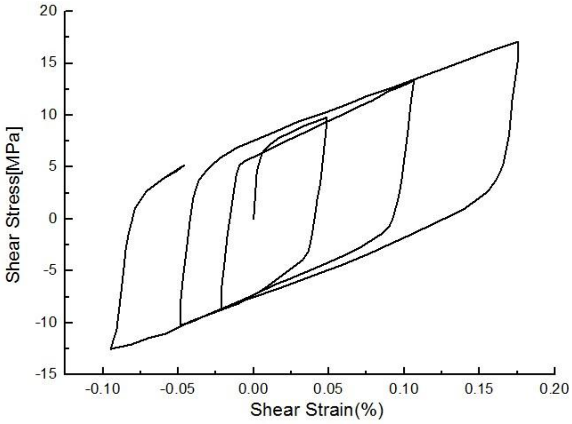

Figure 11 Stress-Strain curve of equivalent layer

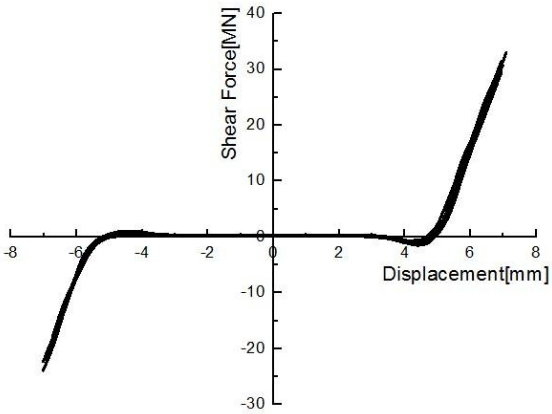

Figure 12 Load-displacement curves of shear keys

4.2 Results of compression-shear case

Fig.9 displays the shear stress cloud diagram of immersion joint. Under the cyclic load, the equivalent layer enters into the plastic state which is presented in Fig. 10 and its stress-strain curve and load-displacement curve are described in Fig. 11 and Fig. 12 respectively. It can be seen that yield point occurs when the shear stress τ of equivalent layer increases up to 5.2×10^{6} Pa and the hysteresis curve is symmetric with isotropic hardening effect. The shape of load-displacement curve of shear keys is close to the recommended curve in Anastasopoulos et al. (2007) [8], which means that the simplified method for contact and shear keys is feasible.

Due to the significant change of depth of immersed tunnel, different levels of applied axial force are also considered, which are listed in Table. 3, including the ones corresponding to the maximum and minimum water pressure of immersion joint.

Table 3 Loading mechanism of compression-shear cases

Case	Corresponding Joint	Axial Force（MN）	Initial Compression（m）	Types of GINA
SH-PULTRA	--	200	0.15	320-370-50
SH-PMAX	EJ12/11	163	0.15	320-370-50
SH-BZ	EJ30/29	85	0.15	320-370-50
SH-PMIN	EJC&C/33	43.6	0.15	320-370-50
SH-PINFRA	--	20	0.15	320-370-50

The load-displacement curve of shear keys and GINA gasket subjected to different levels of axial force are shown in Fig. 13 and Fig. 14 respectively. In Fig. 13, there are hardly differences on the shape of load-displacement curve between different levels of axial force. That is because the pressed area between shear keys changes slightly in different cases. On the contrary, GINA gasket performs variously from each case. In SH-PINFRA case, GINA gasket possesses repeatable hysteretic curves. As the axial force increases, the area of hysteretic curve decreases remarkably and GINA gasket behaves as elastic material when the applied axial force exceeds 122MN. The reason can be explained as follows: as the imposed axial force increases, the compressive stiffness of GINA gasket goes up rapidly, resulting in the occurrence of elastic-like behaviour.

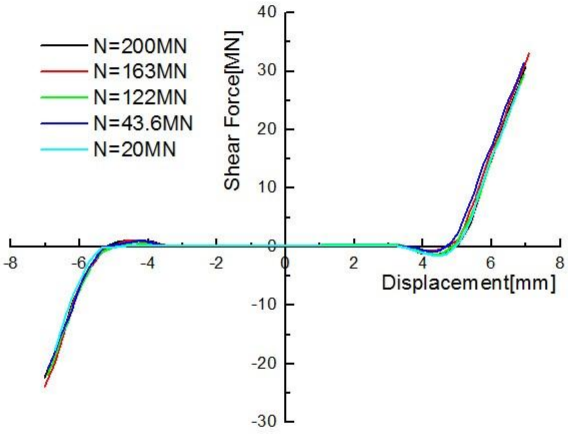

Figure 13 Load-displacement curve of shear keys subjected to different levels of axial force

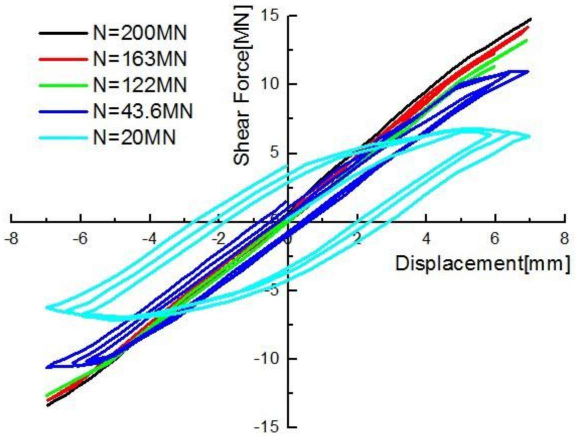

Figure 14 Load-displacement curve of GINA subjected to different levels of axial force

5 Conclusions

In this study, the numerical modelling and analysis were carried out to describe the mechanical behaviours of immersion joint subjected to pseudo-static load. The conclusions are summarised as follows:

1) The simplified method for the simulation model of immersion joint was put forward. The immersion joint model, consisting of simulation of GINA gasket and shear keys, adjustment zone method and equivalent layers, was built, which could provide a reference for further numerical analysis.

2) Different levels of axial force were considered to figure out the flexural behaviours of immersion joint. It can be concluded that the flexural stiffness of immersion joint increases nonlinearly along with the axial force.

3) Different levels of axial force were also considered in compression-shear case. There is little relationship between axial force and behaviours of shear keys while the changes of axial force greatly influence the behaviours of GINA gasket. When the axial force remains in the low level, hysteresis performance of GINA gasket occurs. As axial force increases, GINA gasket gradually turns to elastic-like material.

Acknowledgements

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REFERENCES

[1] I. Maekey, J. Baber, W. Janssen, et al.. ITA working group 11 for immersed and floating tunnels[R]. *ITA*., ITA report $N^0$007/OCT, 2011.

[2] O. Kiyomiya. Earthquake-resistant design features of immersed tunnels in Japan[J], *Tunnelling and Underground Space Technology*,1995, 10(4): 463-475.

[3] Y.N.A. Hashash, J.J. Hook, B. Schmidt, et al.. Seismic design and analysis of underground structures [J]. *Tunnelling and Underground Space Technology*, 2001, 16(2): 247-293.

[4] S.H. YAN, F. GAO, D.W. LI, et al. Study on some issues of seismic response analysis for submerged tunnel [J], *Chinese Journal of Rock Mechanics and Engineering*, 2004, 235): 846-850.

[5] J.H. DING, X.L JIN, Y.Z. GUO, et al. 3D numerical simulation method and its application in calculation of seismic response of immersed tunnel [J], *Journal of Vibration and Shock*, 2007, 24(5): 18-22.

[6] J.H. DING, X.L JIN, Y.Z. GUO, et al. Numerical simulation for large-scale seismic response analysis of immersed tunnel [J], *Engineering Structures*, 2006, 28: 1367-1377.

[7] H.K. PENG, G. MENG, H.G. LI. Modelling and model reliability analysis of immersed tube tunnel [J], *Noise and Vibration Control*, 2007, 27(6): 1-4.

[8] I. Anastasopoulos, N. Gerolymos, V. Drosos. Nonlinear response of deep immersed tunnel to strong seismic shaking [J], *Journal of Geotechnical and Geoenvironmental Engineering*, 2007, 133(9): 1067-1090.

[9] R.S. Van Oorsouw. Behaviour of segment joints in immersed tunnels under seismic loading [D], *Master Thesis*, Netherland: TU Delft, 2010.

[10] S. Hartmann. Numerical studies on the identification of the material parameters of Rivlin's hyperelasticity using tension-torsion tests [J], *ACTA Mechanic*, 2001, 148: 129-155.

[11] M.J. ZHANG, W.J. WANG, Z.N. CHEN, et al. Determination for mechanical constants of rubber Mooney-Rivlin model [J], *China Rubber Industry*, 2003, 50(8): 462-465.

[12] L. ZUO, F.X. XIAO. A method to determine material coefficient of rubber mooney-Rivlin model [J], *Machinery*, 2008, 46(527): 38-40.

[13] ABAQUS/CAE User's Manual.