Failure mechanism of the utility tunnel with flexible joints under reverse fault dislocation

Lianjin Tao
Key Laboratory of Urban Security and Disaster Engineering of Ministry of Education, Beijing University of Technology, Beijing, China

Zhigang Wang
Key Laboratory of Urban Security and Disaster Engineering of Ministry of Education, Beijing University of Technology, Beijing, China

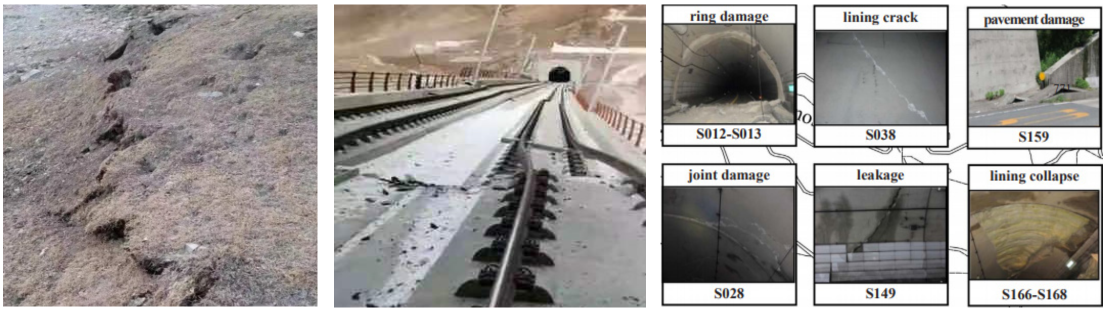
Zhibo Jia
Key Laboratory of Urban Security and Disaster Engineering of Ministry of Education, Beijing University of Technology, Beijing, China

ABSTRACT: The earthquake-damaged investigation found that tunnel structures crossed the active fault zone, and its affected area suffered the most severe damage. Through model tests and numerical simulations, the paper reveals the failure mechanism of the utility tunnel structure with flexible joints across the active fault zone. The results show that the damage range of the utility tunnel structure with flexible joints in the hanging wall is significantly larger than that of the footwall. The damage range is 2.5D and 1.25D, respectively. The utility tunnel structure is prone to stress concentration and damage in the corner area. The damage degree of the lining structure is classified according to the tensile damage factors, namely, no damage, slight damage, moderate damage, and severe damage. Combining the large deformation of flexible joints can effectively improve the design of tunnel structures across the fault zones and improve the seismic performance of tunnel structures.

Keywords: Reverse fault; Utility tunnel; Flexible joint; Model test; Numercial simulation; mechanical response.

1 INTRODUCTION

To meet the current social and economic needs, more and more underground pipeline projects (such as subway tunnels and utility tunnels) are emerging in high-intensity areas, and it is challenging to avoid projects that cross active fault zones (Tao et al. 2022). The active fault zone is a potential and high-incidence source of disasters, which breeds and induces major geological disasters' occurrence and chain evolution. Failure modes such as ground fissures and broken zones appear from the dislocation movement of the active fault zone to the surface (as shown in **Figure 1**). It brings significant challenges to the design and operation period of the underground pipeline structure crossing the active fault zone.



(a) Ground fissures (b) Bridge (Yang et al. 2022) (c) Tunnel (Zhang et al. 2018)

Figure 1. The damage caused by the dislocation of the active fault zone.

In recent years, utility tunnel projects have proliferated, and their significant advantage lies in the intensive laying of urban municipal pipelines. To better play the benefits and functions of the utility tunnel structures, it is necessary to conduct a risk assessment (Wu et al. 2021) and brittleness assessment (Ouyang et al. 2020) of the utility tunnel structure. Relevant scholars (Hu et al. 2019; Huang et al. 2022) have successfully carried out experimental research on the safety of the utility tunnel. Wang et al. (2023) proposed the mechanical response of the utility tunnel with flexible joints under thrust fault. Through the full-scale model static load test, Kuang et al. (2021) studied the mechanical properties of the joints of the new prefabricated double-cabin utility tunnel. However, considering the damage range of the utility tunnel with flexible joints, especially for crossing the active fault zone, the research on the progressive failure process and mechanical behavior have not yet been clearly revealed.

Therefore, the paper studies the failure mechanism of the utility tunnel with flexible joints across the active fault zone through model tests and numerical simulations. Then, the damage degree of the utility tunnel lining structure is classified by the tensile damage factor and the crack limit value, and then the damage range of the structure is determined. It is hoped that the research carried out in this paper can provide reference conclusions for the construction of similar underground pipelines crossing the active fault zone.

2 METHODOLOGY

2.1 Model test

The paper has designed a fault dislocation test device with a scaling ratio of 1:30, as shown in Figure 2. The device includes a model box, a loading device, and a data acquisition system. The dimensions of the model box are 2.2 m long, 1.2 m wide, and 1.0 m high. The loading system consists of four independent hydraulic jacks, placed in groups of two on the left and bottom, applying displacement loads to simulate reverse fault dislocation. The monitoring sections and measuring point layout are shown in Figure 3, and sections II-IV are selected as the main monitoring sections.

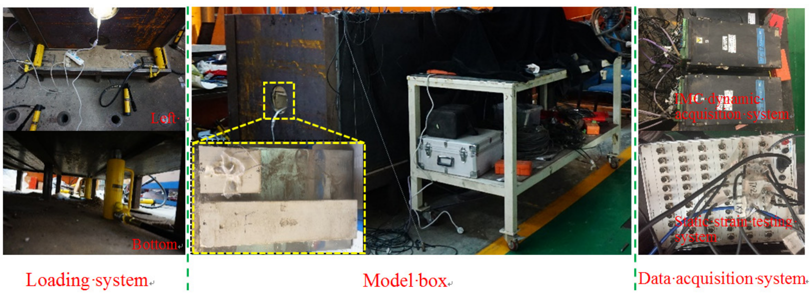


Figure 2. Photograph of the model test apparatus (original state).

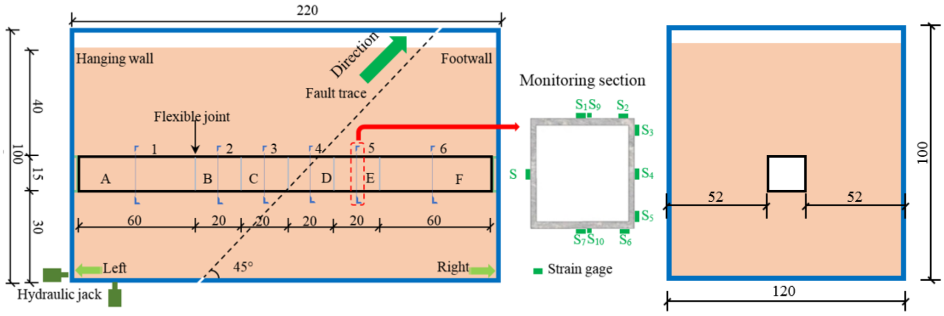


Figure 3. Distribution of monitoring section and sectional tunnel lining (Unit: cm).

2.2 Numerical simulation

The paper uses the finite element software ABAQUS to establish a three-dimensional nonlinear numerical model to verify the correctness of the model test results. The dimensions of the numerical models are 66 m long, 36 m wide, and 27 m high, as shown in Figure 4.

The surrounding rocks and lining structures used linear brick elements C3D8R to model. The contact surface between the surrounding rock and the tunnel is set as penalty friction, 0.4. The simulation process is divided into two stages: (1) Initial stress balance. (2) Fault dislocation. The parameters used in the simulation are summarized in Table 1.

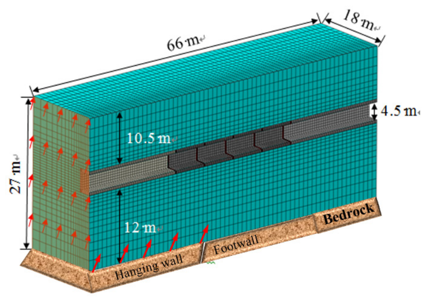


Figure 4. Three-dimensional nonlinear numerical model.

Table 1. Physical and mechanical parameters of the linings and soil adopt in numerical analyses.

Tunnel lining			Soil		Displacement	Dip angle
Young modulus [MPa]	Diameter [m]	Thickness [m]	Young modulus [MPa]	Poisson's ratio /	[m]	[°]
33500	4.8	0.6	18	0.4	0.8	45

The boundary of the numerical model is a normal constraint. This paper introduces the damage factor to reflect the damage mechanism behavior of the concrete under loading. In this paper, the CDP model in ABAQUS is utilized to simulate the mechanical response of the tunnel lining concrete.

3 DAMAGE ANALYSIS OF THE UTILITY TUNNEL LININGS

3.1 Failure process of the tunnel

Figure 5 shows that the fault dislocation is the progressive failure process of the pipe gallery structure. When the fault dislocation displacement reaches 0.3 m, the lining structure in the hanging wall area is significantly uplifted. When the dislocation displacement comes to 0.6 m, the flexible joint will be squeezed and deformed, the lifting displacement of block A will be significantly larger than that of block B, and the flexible joint can satisfy the small-scale deflection of the lining of block B through deformation.

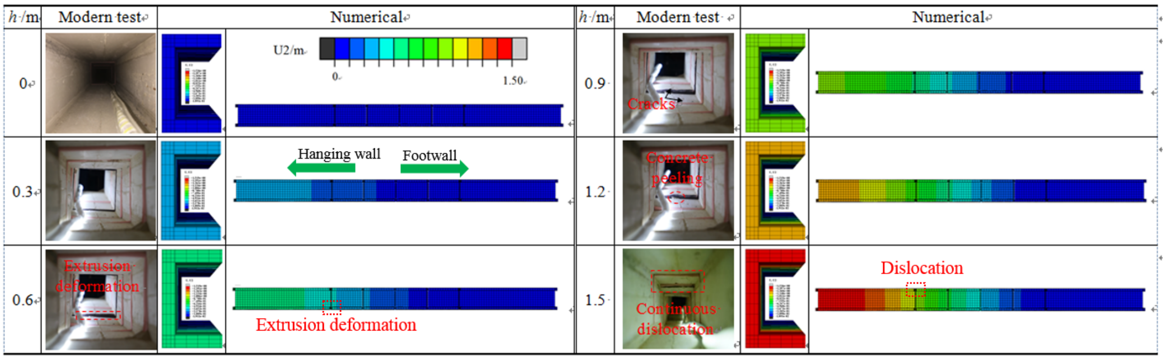


Figure 5. Failure process of the internal lining structure under fault dislocation.

When the dislocation displacement reaches 0.9 m, cracks appear in the joint area of the bottom plate. When the dislocation displacement continues to increase to 1.2 m, the damage degree of the lining at the joint of the bottom plate is intensified, manifested in the intensification of cracking and the concrete peeling off. When the fault dislocation displacement reaches 1.5 m, it is found that although the hanging wall of the utility tunnel structure is uplifted, the overall collapse has not yet occurred in a large area. The most significant displacement difference is mainly concentrated in the B and C linings, followed by the D lining. At the same time, the lining structure has an obvious continuous dislocation phenomenon at the joint of the top plate.

3.2 Analysis of tensile and compressive damage

We can be obtained that the tensile and compressive damage factors (GB 50010-2010) corresponding to the ultimate tensile strength (2.51 MPa) and compressive strength (29.6 MPa) of C45-grade concrete are 0.2374 and 0.2684, respectively. The tensile failure element is defined as the element with the tensile damage factor $d_t \geqslant 0.2374$, and the compression failure element is defined as the lining element with the compressive damage factor $d_c \geqslant 0.2684$. According to the tensile damage factor crack-opening displacement relationship (in Figure 6), combined with the standard of concrete crack width limit of 0.2 mm (Chen et al. 2011) and the corresponding damage factor of C45-grade concrete. So this paper divides the damage degree of the secondary lining into no damage, slight damage, moderate damage and serious damage, as shown in Figure 6.

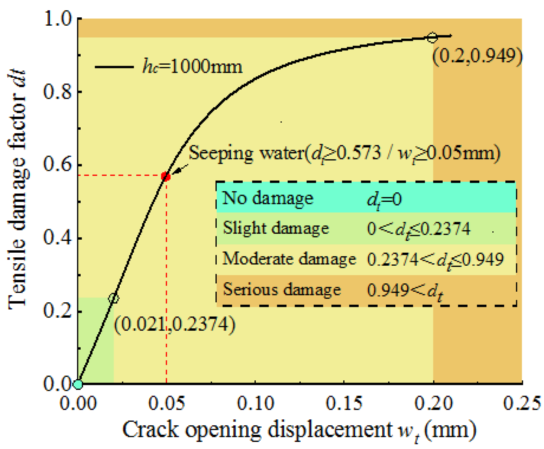


Figure 6. Tensile damage factor crack-opening displacement relationship.

It shows up clearly from Figure 7 (a) and (b) that the damage of the lining structure in the hanging wall area is more serious than that in the footwall, and the damage of the lining structure caused by the fault dislocation has obvious regional characteristics. The maximum value of the DAMAGET and DAMAGEC is 0.91 and 0.9421, respectively. The most seriously damaged areas are concentrated in the B and C blocks in the hanging wall, and the top plate, bottom plate and sidewall are all damaged. The second is that the lining of block C and block D in the footwall is damaged only in the joint area, which is consistent with the displacement distribution law of the lining. From the DAMAGTS and DAMAGES contours of secondary linings, it can also be found that the damage degree of the corners of the same sidewall is more obvious than that of the middle.

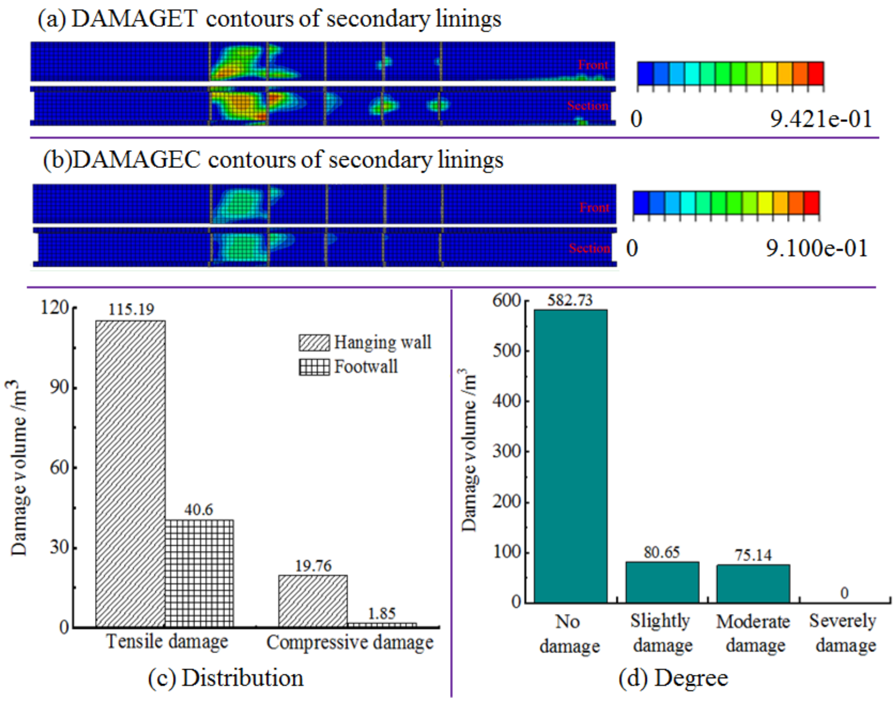


Figure 7. Tensile and compressive damage of tunnel lining under fault dislocation.

Figure 7 (c) shows the volume of the damaged lining structure. The volume of the lining with a tensile damage factor greater than 0.2374 is 155.79 m^3. The lining volume with a compressive damage factor greater than 0.2674 is 21.61 m^3. The damaged volume of the lining structure due to tension is several times that of the compressive damage, indicating that the tensile damage is the main cause of the reduction of the overall stability of the lining structure.

Figure 7 (d) presents the damage volumes corresponding to the damage degree. The volume of the lining structure with no damage and damage reaches 582.73 m^3 and 155.79 m^3, respectively. The lining structure without damage accounted for a large proportion. The proportion of lining structures damaged by fault dislocation accounts for 21.09%; only 10.17% of lining structures are moderately damaged. No serious damage to the lining structure is found. The above research shows that flexible joints can effectively improve the overall seismic performance of the utility tunnel structure through the local damage of the lining and the deformation of the flexible joint (Yan et al. 2020).

4 CONCLUSION

To reveal the failure mechanism of the utility tunnel structure with flexible joints across the reverse fault, this paper reveals the failure mechanism of the utility tunnel structure with flexible joints across the active fault zone. The following conclusions can be drawn:

(1) With the increase of the dislocation displacement, the response of the displacement of the utility tunnel structure in the hanging wall area is the strongest, and there is an apparent uplift phenomenon. Tensile and compressive damage analysis show that the utility tunnel lining structure's damage range and damage degree in the hanging wall are significantly more extensive than in the

footwall.

(2) According to the damage factor corresponding to the ultimate tensile strength of concrete and the damage factor corresponding to the crack width limit as the standard, the damage degree of the lining is divided into four types to evaluate the overall damage of the utility tunnel structure. Under reverse fault dislocation, the utility tunnel structure with flexible joints only has damage in local areas, mainly minor damage and moderate damage, and no serious damage unit appears.

(3) The flexible joint has good deformation performance at the expense of absorbing the dislocation and forced displacement caused by faulting, allowing slight deflection of the segmented lining structure, and cooperating with the local failure of the segmented lining structure. It can achieve the effect of improving the overall seismic performance of the underground tunnel structure.

ACKNOWLEDGEMENTS

The reviewer and executive editor are also thanked for their constructive comments which helped greatly improve the manuscript.

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