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Damage-Based Analysis for Optimizing the Arrangement of Articulated Anti-Fault Tunnel Structures

〇Guanxiong Zeng, Yasuo Sawamura, Kiyoshi Kishida

1. Introduction

In tunnel projects, crossing active faults is sometimes unavoidable. Numerous studies have documented significant damage to tunnels resulting from active fault dislocation during earthquakes. Articulated design is widely regarded as an effective method for mitigating damage to tunnels caused by active fault displacements. However, prior research has primarily focused on identifying suitable materials or structures for constructing articulated tunnels, with limited attention given to optimal arrangements for the articulated sections. By developing a plasto-elastic finite element (FE) model of a reverse active fault crossing tunnel structure, this study used a COMSOL-MATLAB coupling program to analyse the damaged length (L_{dmg}) of each case of 3,700 articulated arrangements. The articulated configuration with the lowest L_{dmg} was identified as the optimal arrangement.

2. Articulated design

"Articulated Design" is widely regarded as an effective anti-fault measurement, which enhances the allowable longitudinal deflection of the tunnel by introducing several articulated sections into the tunnel. These articulated sections are whether constructed with special materials[1] or structures[2][3], so as to concentrate the deformation and tunnel damage into these articulated sections (Fig.1).

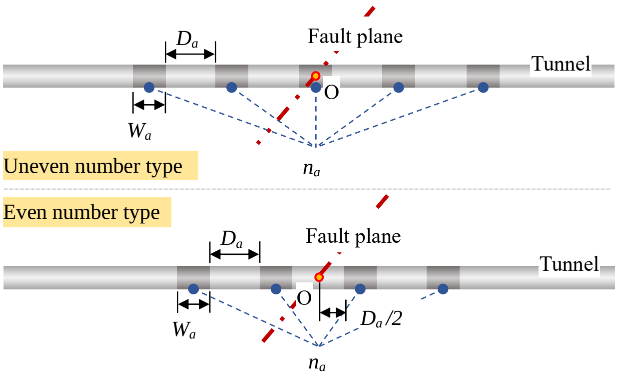

Fig.1 Two types of articulated arrangements

As shown in Fig.1, two types of arrangements are introduced in this study: the uneven-number and even-number types, precisely defined through three controlling parameters: the number of articulated sections ($\boldsymbol{n_a}$, m), the width of each section ($\boldsymbol{W_a}$, m), and the distance between sections ($\boldsymbol{D_a}$, m).

3. FE model and Calculation program

A 2D FE model was developed to respectively simulate tunnels crossing a reverse and a normal active fault, utilizing COMSOL software for analysis (Fig.2). The size of this model is 300m×100 m^2 and the fault dip angel is 60°. Positioned vertically at the center of the model, the tunnel has a height of 10 m. The elastic-perfectly plastic Mohr-Coulomb model and the Ottosen's 4-parameter criterion[4] are adopted to the constitutive models of the surrounding soil and the tunnel structure, respectively, in the FE model.

For simulating the reverse fault displacement during the earthquake, static displacements were assigned on the boundaries of the stratum. For simulating the interactions, both hard contact and friction contact[5] was applied on interface-pair (1): the interface between the tunnel and soil, and interface-pair (2): the fault plane between hanging wall and footwall. The classic Coulomb friction was applied to simulate the friction of the interface pairs, with the friction coefficient $\boldsymbol{\mu}$ was assumed as 0.4[5]for the interface-pair (1), and 0.08 [6] for the interface-pair (2).

Table 1 Material properties of the FE model[1][5]

Material	ρ /kg·m^{-3}	E /GPa	υ	σ_c /MPa	σ_t /MPa	C /MPa	φ /°
Tunnel	3016	54.3	0.22	45.8	2.55	-	-
PVA fiber concrete	2100	0.6	0.35	3.3	0.46	-	-
Soil	2000	0.65	0.35	-	-	1.1	32.4

P.S. $\boldsymbol{\rho}$ refers to the density; $\boldsymbol{E}$ refers to the elastic modulus; $\boldsymbol{\upsilon}$ refers to the Poisson's ratio; $\boldsymbol{\sigma_c}$ refers to the compressive strength of the concrete; $\boldsymbol{\sigma_t}$ refers to the tensile strength of the concrete; $\boldsymbol{C}$ refers to the cohesive of the soil; $\boldsymbol{\varphi}$ refers to the fiction angle.

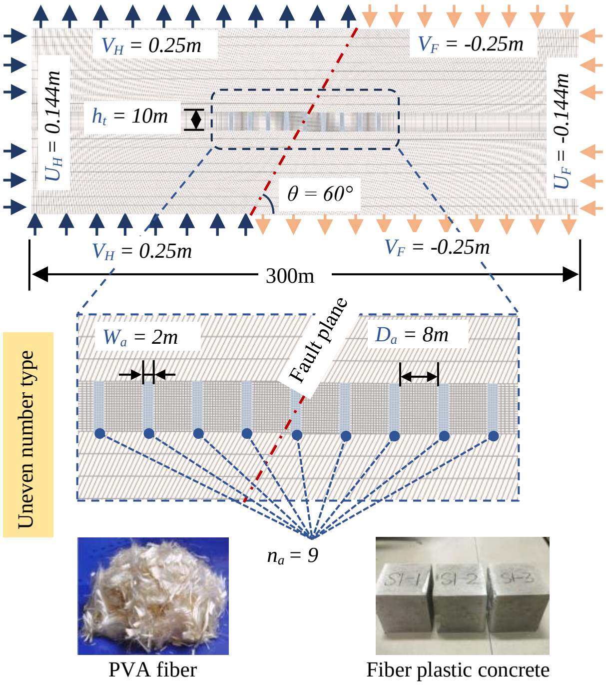

Fig. 2 FE model of the articulated tunnel structure

The articulated sections of the tunnel are modeled using the material properties of PVA fibre concrete as proposed in ref. [1], with the specific properties listed in Table 1. The articulated arrangements are quantitatively defined by parameters $\boldsymbol{n_a}$, $\boldsymbol{W_a}$, and $\boldsymbol{D_a}$, where $\boldsymbol{n_a}$ is set as 2:1:11, $\boldsymbol{W_a}$ as 0.5m:0.5m:5m, and $\boldsymbol{D_a}$ as 2m:0.5m:20m. A total of 3,700 articulated tunnel configurations are generated.

A COMSOL-MATLAB coupling program is employed to analyse all cases of the articulated arrangements. MATLAB is used to define the various articulated configurations ($\boldsymbol{n_a}$, $\boldsymbol{W_a}$, $\boldsymbol{D_a}$) and to record the $\boldsymbol{L_{dmg}}$ value for each case. COMSOL is utilized to establish the plasto-elastic finite element (FE) model based on the predefined articulated arrangements and to calculate the damage behaviour of the articulated tunnel under reverse faulting conditions.

4. Results

Fig.3 presents the distribution of the 370 $\boldsymbol{L_{dmg}}$ values when $\boldsymbol{n_a}$=3. As $\boldsymbol{D_a}$ increases from 2m to 20m, $\boldsymbol{L_{dmg}}$ exhibits fluctuations before transitioning into a stable zone. This behavior divides the $\boldsymbol{L_{dmg}}$ distribution into two distinct zones: the fluctuating zone and the stable zone. A comprehensive comparison of $\boldsymbol{L_{dmg}}$ across all 3,700 cases of articulated tunnel configurations identifies the optimal arrangement for the given geological conditions as follows: $\boldsymbol{n_a}$ =3, $\boldsymbol{W_a}$ =0.5m, and $\boldsymbol{D_a}$ =17.5m. This configuration results in the minimum $\boldsymbol{L_{dmg}}$ of 5.82m.

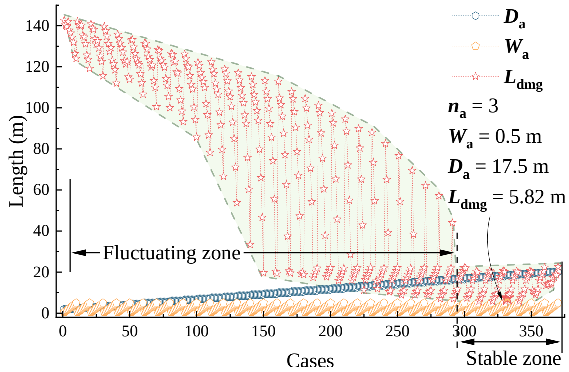

Fig.3 Values of $\boldsymbol{L_{dmg}}$ when $\boldsymbol{n_a}$ equals 3

Additionally, the results indicate that, regardless of $\boldsymbol{n_a}$ (ranging from 2 to 11), the lowest $\boldsymbol{L_{dmg}}$ consistently occurs when $\boldsymbol{W_a}$ =0.5m (Fig.4). This finding suggests that minimizing the width of the articulated zone is essential for mitigating tunnel damage through articulated design.

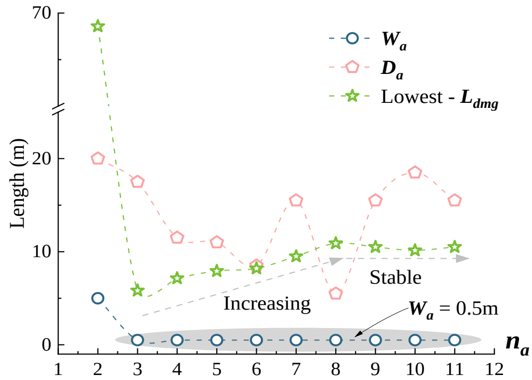

Fig.4 The lowest $\boldsymbol{L_{dmg}}$ of all cases

Reference

[1] Zhao, K., Chen, W., Yang, D., Zhao, W., Wang, S., & Song, W. 2019. Mechanical tests and engineering applicability of fibre plastic concrete used in tunnel design in active fault zones. Tunn. Undergr. Sp. Tech., 88, 200-208.

[2] Wang, T., Geng, P., Li, P., Wang, Q., & Wang, L. 2022. Deformation and failure of overburden soil subjected to normal fault dislocation and its impact on tunnel. Eng. Fail. Anal., 142, 106747.

[3] Wang, Q., Geng, P., Li, P., Wang, T., & Sun, W. 2023. Failure analysis and dislocation-resistant design parameters of mining tunnel under normal faulting. Eng. Fail. Anal., 143, 106902.

[4] Ottosen N., 1977. "A Failure Criterion for Concrete," J. Eng. Mech. Division, ASCE, Vol. 103, No. 4, pp. 527–535.

[5] Zeng, G., Sawamura, Y., Geng, P., & Kishida, K. 2024. Analytical approach for determining the response of a tunnel structure crossing a reverse active fault. Tunn. Undergr. Sp. Tech., 146, 105590.

[6] Fulton, P. M., Brodsky, E. E., et al., 2013. Low coseismic friction on the Tohoku-Oki fault determined from temperature measurements. Science, 342(6163), 1214-1217.