Research on the influence zone dividing of tunneling adjacent to existing tunnel based on ultimate strain criterion

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Abstract. This thesis estimates the effects of tunneling parallel to or crossing the existing tunnel. According to the ultimate strain criterion, this paper suggests effective method to simulate failure process of geological materials, which combines with strength reduction FEM. Through numerical simulation and criterion of the influence zone dividing, the regulation of the stability of an individual tunnel was proposed in this paper, moreover, dividing influence zones by using upper and lower limit if surrounding rock parameters, which was defined as the strong influence zone, the weak influence zone, and the non-influence zone. Furthermore, this thesis discusses the transverse and longitudinal effect of two orthogonal excavation. Conclusions that were drawn in this paper can be utilized in actual excavation.

1. Introduction
With the rapid development of transportation in China, the adjacent construction of underground structures is becoming more and more frequent, extremely for tunnelling adjacent to the existing tunnel. A great many researchers have studied mechanical behaviors and influence zones of adjacent excavation [1-8]. When the distance between two parallel tunnels less than 1-time newly-built tunnel diameter, the project should be carefully researched [5]. The degree of adjacent excavation could be divided into three zones: unconditional range, careful range and controlled range (need countermeasures) [6]. When two parallel tunnels in clay stratum, if H/R (H represents buried depth, and 2R represents tunnel diameter) greater than 3 and the center distance between two tunnels greater than 1.3 times tunnel diameter (2R), the plastic zone around two tunnels do not overlap [7]. Hoek and Brown [8] studied the stress distribution of interlaid rock with different distances in two parallel excavation, they concluded the stress of pillar increases and stress concentration coefficient decreases when their distance close. When the lateral pressure coefficient equal to 0.5, buried depth is 5 times tunnel diameter, there is no impact in parallel excavation if the distance between tunnels greater than 2 times tunnel diameter [9]. Team of Qiu W.G [10-12] systematic studied underground adjacent excavation, suggested the strong influence zone, the weak influence zone, and the non-influence zone as three zones of adjacent construction and proposed expression of influence zones.
Two adjacent excavation analysis method and criterion

2.1. Numerical simulation conditions and parameters

In view of the continuity of comparative analysis in two adjacent excavation, buried depth of existing tunnel are 13m, 30m, and 50m, respectively, diameter and height of existing tunnel are 17.11m, 11.64m, respectively. Regarding the upper and lower limit of surrounding rock grade\textsuperscript{[13]} as four distinct strata that could effectively cover geological conditions in actual construction, as shown in table 1.

| Surrounding rock grade | Density $\gamma$ (kN/m$^3$) | Deformation modulus E(GPa) | Poisson’s ratio $\nu$ | Internal friction angle $\Psi(\degree)$ | Cohesion $c$(MPa) |
|------------------------|-----------------------------|-----------------------------|----------------------|---------------------------------------|-----------------|
| III$_{up}$             | 25                          | 20                          | 0.25                 | 50                                    | 1.5             |
| IV$_{up}$              | 23                          | 6                           | 0.3                  | 39                                    | 0.7             |
| IV$_{low}$             | 20                          | 2                           | 0.35                 | 27                                    | 0.2             |
| V$_{low}$              | 17                          | 1                           | 0.45                 | 20                                    | 0.05            |

Parallel excavation and orthogonal excavation are two types of adjacent excavation in this paper. The main impact factors of adjacent excavation are the ratio of buried depth to existing tunnel diameter (H/D), relative positions (d, $\theta$). Setting different adjacent excavation conditions depend on two tunnels’ distance apart, as shown in table 2.

| Surrounding rock grade | Adjacent excavation types | H/D | d/m | $\theta(\degree)$ |
|------------------------|---------------------------|-----|-----|-------------------|
| V                      | Parallel excavation       | 0.75| 0.2D–5D | 0, 90, 135, 180  |
|                        |                           | 1.75| 0.2D–5D | 0, 45, 90, 135, 180 |
|                        |                           | 3   | 0.2D–5D | 0, 45, 90, 135, 180 |
|                        | orthogonal excavation     | 0.75| 0.2D–5D | 0, 180            |
|                        |                           | 1.75| 0.2D–5D | 0, 180            |
|                        |                           | 3   | 0.2D–5D | 0, 180            |

Numerical calculation obeys Mohr-Coulomb criterion, the stress field is considered as gravity stress field, taking 4 times tunnel diameter at both sides and bottom of the model boundary. Numerical models are shown in Figure 1.
2.2. SSR based on ultimate strain criterion

In adjacent excavation, geological materials are assumed losing bearing capacity when arriving ultimate strain, which might not happen displacement catastrophe or non-convergence of calculation. For utilizing the Mohr-Coulomb criterion, elements in the numerical simulation are still at the plastic-flow stage after yielding failure, which could not show failure elements.

According to conclusions of ABI \[^{[14]}\], when geological material under uniaxial pressure, the relationship that satisfies ultimate failure state between plastic-elastic total compression strain and total shear strain can calculate expression of ultimate shear strain as follow:

\[
\sqrt{J_{2f}'} = \frac{\varepsilon_1 - \varepsilon_2}{\sqrt{3}}
\]  

Where \( \varepsilon_1 \), \( \varepsilon_2 \) is axial strain and lateral strain, respectively; \( \sqrt{J_{2f}'} \) is ultimate shear strain.

Simulating uniaxial compression tests in FLAC\(^3D\), compressive strength and ultimate shear strain can be acquired through uniaxial compression tests, which are shown in Table 3.

| surrounding rock grade | Compressive strength \( \sigma / \text{MPa} \) | Ultimate shear strain \( \sqrt{J_{2f}'} / \% \) |
|------------------------|-------------------------------|-------------------|
| III\(_{up}\)            | 8.24                          | 0.95              |
| IV\(_{up}\)            | 2.93                          | 1.17              |
| IV\(_{low}\)           | 0.65                          | 0.75              |
| V\(_{low}\)            | 0.14                          | 0.52              |

When the distance of two tunnel equals a certain value, interlaid rocks could reach ultimate shear strain under distinct stress distribution, which would not happen displacement catastrophe or non-convergence in the calculation. With plastic zones expanding between tunnels, rock could occur shear instability. When the interlaid rock is penetrated by zones that already have reached ultimate shear strain, adjacent excavation would damage.

2.3. Criterion of influence zone dividing of adjacent excavation

In two adjacent excavation, when safety factor less than 1, the system could be regarded as instability, which means elements in interlaid rock have reached ultimate shear strain. Isoline of safety factor (equals to 1) is considered as influence zone dividing criterion in this paper, the strong influence zone, the weak influence zone, and the non-influence zone can be divided through obtaining safety factor field distribution. Detailed processes are as follows.

(1) In certain buried depth and surrounding rock grade, safety factor \( F_1 \) of the individual existing tunnel and safety factor \( F_2 \) of the newly-built tunnel could be acquired;

(2) In a certain existing tunnel buried depth and surrounding rock grade, a safety factor \( F_3 \) of two adjacent excavation could be acquired;

(3) If \( F_1 > 1, F_2 > 1, \) and \( F_3 < 1 \), an individual tunnel has certain self-stability and the system loses self-stability after adjacent excavation, this paper defines as influenced. If \( F_1 > 1, F_2 > 1, \) and \( F_3 > 1 \), the system has certain self-stability after adjacent excavation, this paper defines as non-influenced.

(4) If one of \( F_1 \) and \( F_2 \) less than 1 or \( F_1 \) and \( F_2 \) both less than 1, an individual tunnel lose self-stability. When \( F_3 < \min \{ F_1, F_2 \} \) in two adjacent excavations, this paper defines as influenced. When \( F_3 = \min \{ F_1, F_2 \} \), self-stability is not impacted by adjacent excavation, this paper defines as non-influenced.

(5) Safety factor field distribution could be obtained, influence zones could be divided by connecting points that safety factor equals to 1 or \( \min \{ F_1, F_2 \} \). The range of \( V_{up} \) and \( V_{low} \) includes all parameters in the grade-V surrounding rock, isolines of the safety factor in the same surrounding rock grade are superimposed to divide the strong influence zone, the weak influence zone, and the non-influence zone.
3. Results and Discussion

3.1. The stability of the individual tunnel
Carrying out the numerical calculation by SSR based on the ultimate strain criterion. Under four different surrounding rock grades when the buried depth of the individual tunnel rises from 1m to 100m, safety factors could be calculated. The safety factors of an individual tunnel can be acquired under different surrounding rock grades and buried depths.

![Figure 2. Safety factors of an individual tunnel in a growth range of buried depth](image)

As can be seen in figure 2: (1) In a certain surrounding rock grade, the distribution of safety factors of a tunnel shows a slight increase at a small scope and then a decreasing trend; (2) The higher the surrounding rock grade is, the worse the surrounding rock condition goes, the lower the self-stability of an individual when excavating. The tunnel cannot keep in self-stabilization in V low surrounding rock condition.

3.2. The influence zone dividing of tunneling adjacent to an existing tunnel based on isolines of the safety factor
Utilizing the upper and lower limit of surrounding rock parameters, the influence zone dividing of two parallel and orthogonal excavations based on isolines of safety factor is concluded as follows.

![Figure 3. The influence zone dividing of two parallel excavation in the grade-V surrounding rock](image)
Conclusions can be reached as: (1) The relative distance of 0° excavation is generally less than 180° excavation. (2) It is the most unfavorable position when two tunnels parallel excavating at 135° direction, at which the longest relative distance is required. Influenced by the self-stability of an individual tunnel, the relative distance of 45° excavation is generally less than 135° excavation.

3.3. Discussion
With respect to two orthogonal excavations, not only should research consider the transverse effect of the newly-built tunnel, but also should consider the longitudinal effect between the existing tunnel and the newly-built tunnel. The transverse and longitudinal effect of two orthogonal excavations can be calculated based on the influence zone dividing results, by utilizing the ultimate shear strain criterion. The transverse and longitudinal effect in grade-V surrounding rock can be obtained, as shown in Figure 5.

4. conclusion
The main conclusions are as follows:
(1) SSR that based on ultimate strain criterion could be utilized in numerical simulation, for this method could show the failure process of rock mass;
(2) A tunnel’s safety factor is considerably influenced by tunnel diameter D and tunnel height H; the ratio of buried depth to tunnel diameter H/D becomes the major influence factors with depth increasing;3
(3) The influence zone could be obtained through using the criterion of dividing. The most unfavorable position is two tunnels parallel excavating at 135° direction, at which the longest relative distance is required.

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