Strength Reduction Method Based Study on Tunnel Excavation Effect on Front Slope Stability

Wu Mengjun1,2,3*, Xi Yang1,4 Guo Hongyan1,2,3

1 China Merchants Chongqing Communication Research & Design Institute Co., Ltd., Chongqing 400067, China
2 National Engineering and Research Center for Mountainous Highways, Chongqing 400067, China
3 National Engineering Laboratory of Highway Tunnel Construction Technology, Chongqing 400067, China
4 Chongqing Jiaotong University, Chongqing 400067, China
* Corresponding author’s e-mail: 664618531@qq.com

Abstract. During tunnel excavation and support the stability of front slope is a prerequisite for safety tunnel construction. This paper covers strength reduction method based numerical simulation and observation of displacement and plastic zones in front slope soil using ANSYS finite element software to determine the sliding surface and failure mode of front slope soil. Analyses of calculation results show the effect of excavation on the sliding surface of front slope and the effect of support structure on plastic zone of front slope.

1. Introduction
Tunnel side and front slope stability is a prerequisite for safe construction. Li Chen studied the effects of excavation method and front slope ratio on the stability of front slope in transition section at tunnel portals [1]. In the context of Jialingjiang Bridge Tunnel Project in Chongqing City, Tang Yuan investigated the stability of side and front slopes at portals of urban shallow deviatoric pressure tunnel and the relationship between tunnel excavation method and side and front slope stability [2].

In 1975 British academic Zienkiewicz developed FE strength reduction method to obtain the shear surface and safety factor at the time of slope failure by incrementally reducing the shear strength indicators (cohesion C and tanφ) of slope soil. In the FE strength reduction method, slope soil reaches the ultimate equilibrium when soil shear strength indicator is reduced to k fold. k is considered the safety factor of the side slope. According to Yang Qingsong, the strength reduction method needs further study and discussion because simultaneous, even-fold reduction of shear strength cannot represent the true attenuation pattern of shear strength [3].

With the development of finite element (FE) software the strength reduction method has been widely used particularly in slope engineering. Han Lu, Zhang Yu et al. obtained sliding surface and safety factor in slope simulation for mine works using the strength reduction method and proposed suitable treatment measures [4-5]. Based on the strength reduction method, He Yang et al. established the slope reduction factor vs characteristic point displacement curve and developed a method to determine warning displacement and ultimate displacement for slope instability [6]. From comparison between monitoring results and simulation results from strength reduction method, Hong Wei found...
consistency between them and that the portion in the middle of slope where gradient is steeper is prone to instability and failure [7].

The FE strength reduction method has been widely used in calculating slope stability. It has also been widely accepted as a useful method for calculating the safety factor for tunnel side and front slopes. In 2008 Dong Yong described the mode of front slope failure (plane slide due to weak structural plane resulting from disturbance of soil mass during construction), analyzed the stability of side and front slopes in natural state under different geological conditions using the strength reduction method, identified the sliding surface in side and front slope and determined safety factor [8]. Zhang Youli et al. performed 3D analysis of the stability of high front slope at the portal of a highway tunnel using the strength reduction method, and calculated the effect of different slope ratios on front slope stability. In the context of actual project, Sun Baozhi et al. modeled the sliding surface and safety factor of front slope after tunnel completion using FE software and mild reduction method, and gave advice on reinforcement [9].

Based on FE strength reduction method, this paper investigates the mode of front slope failure at portals and safety factor at different excavation lengths during tunnel excavation.

2. Simulation and Calculation

2.1. Parameter selection
Select Class V surrounding rock, modulus of elasticity $E=2.5\text{GPa}$, cohesion $C=0.18\text{MPa}$, internal friction angle $\mu=25^\circ$, Poisson's ratio $\nu=0.4$, and specific weight $\gamma=22\text{kN/m}^3$. Nonlinearity of support structure is not considered; only elastic model is used. Support is 40cm thick and consists of C30 concrete and 14 I-beam; take its modulus of elasticity as $E=30\text{GPa}$, Poisson's ratio as $\nu=0.2$ and specific weight as $\gamma=27\text{KN/m}^3$.

In this study numerical calculation is performed using strength reduction method. The reduction factor is determined by median method and expressed up to three decimal places.

2.2. Model and boundary conditions
The front slope is 15m high, slope ratio is 1:1 and portal is 9m high. Create a model with 2D solid elements. Constrains are shown in the Figure1, with DOF constraints in X direction on left and right sides and DOF constraints in Y direction at the bottom. Full-face excavation method is adopted.

3. Analysis of Calculation Results

3.1. Safety factor when tunnel is excavated to different lengths
Front slope failure is modeled for unexcavated ground, 3m, 6m, 9m, 12m and 15m excavation and support, and excavation followed by no support installation using the strength reduction method. Figure 2 displays surrounding rock displacement at different safety factors with 12m excavation.
followed by no support installation. When reduction factor \( F = 1.45 \), the crown displacement rises sharply to 16mm and the front slope failure is believed to have occurred.

![Surrounding rock displacement at different safety factors with 12m excavation followed by no support installation.](image)

Figure 2. Surrounding rock displacement at different safety factors with 12m excavation followed by no support installation

In this simulation the determination of front slope failure is based on the abrupt rise in crown displacement. Figure 2 displays the relation between crown displacement and safety factor at different excavation lengths. In unexcavated ground, when safety factor \( F \) exceeds 2.875 the crown displacement sharply rises. Therefore, when the safety factor \( F \) is 2.875 the front slope is considered to be in an ultimate equilibrium state; when this value is exceeded, the front slope failure has occurred. Therefore, safety factors for unexcavated ground, 3m excavation, 6m excavation, 9m excavation, 12m excavation and 15m excavation are taken as 2.875, 2.525, 2.25, 1.928, 1.425 and 1.1. The safety factor linearly correlates to tunnel excavation length.
3.2. Front slope sliding surfaces at different excavation lengths

Some simulation results show the distribution of plastic zones as displayed in Figure 3.

Figure 3. Crown displacement vs. safety factor at different excavation lengths

![Graph showing crown displacement vs. safety factor at different excavation lengths](image)

(a) Distribution of plastic zone at 6m excavation
(b) Distribution of plastic zone at 9m excavation
(c) Distribution of plastic zone at 15m excavation

Figure 4. Distribution of plastic zones in some simulation results
Prior to excavation to 6m, the plastic zone appears at the bottom of the tunnel face. As strength is reduced, the plastic zone propagates from the bottom of the face toward the top of slope in parallel to the surface of front slope. Front slope instability occurs when the plastic zone extends to the top of slope. Maximum plastic deformation concentrates at the bottom of the face. As the plastic zone propagates toward the top of slope, its width gradually decreases.

When excavated to 9m without support, a plastic zone appears at the top of tunnel face and develops vertically upward toward the slope surface. When it extends to the slope surface, the front slope fails in the form of a cantilever. As excavation proceeds, the failure develops from the top of tunnel face toward slope surface. With support installed, the plastic zone may be mitigated by tilting toward the ground ahead of the face.

When excavated to 12m, the plastic zone at the top of the face extends toward the middle of front slope before propagating toward the top of slope. The sliding surface is almost in parallel with the advancing direction, leading to front slope instability and failure.

3.3. Support effect
Calculation results suggest support has little effect on safety factors, but it can improve the shape of the front slope sliding surface, as illustrated in Figure 5. When excavated to 9m followed by support installation, the front slope sliding surface is in the previous stage of failure without support. As excavation advances, loading of the front slope gradually transitions to that of cantilever. With support installed, the sliding surface tilts in advancing direction and the width of the plastic zone decreases.

![Figure 5](image.png)

(a) Distribution of plastic zone when excavated to 9m without support
(b) Distribution of plastic zone when excavated to 9m followed by support installation

4. Conclusions
(1) We have analyzed tunnel crown displacements in different conditions. If the crown displacement abruptly changes, then front slope failure is deemed to have occurred. The previous strength reduction factor is taken as the safety factor. The safety factor linearly decreases as the tunnel is advanced.

(2) We have compared front slope sliding surfaces under different conditions. During tunnel excavation, the front slope sliding surface undergoes three stages: (1) it extends from the bottom of tunnel face toward the top of slope in parallel with the surface of front slope; (2) it extends normal to the advancing direction from the top of tunnel face toward the surface of front slope; (3) it extends from the top of tunnel face toward the top of slope and in the meantime, propagates toward the middle of the surface of front slope in parallel with the advancing direction. As the tunnel progresses, the failure moves from the first stage to the third stage.

(3) We have analyzed the effect of support structure and found the support structure has little effect on the safety factor and has some impact on the shape and development stage of the sliding surface.
The support structure has a relatively big impact on the sliding surface in the second stage by making it tilt toward the advancing direction.

Acknowledgments
The authors appreciate the funding of National Key Research and Development Program of China (Grant no. 2018YFC0809600, 2018YFC0809603), Science and technology projects of Tibet autonomous region (XZ201801-GB-07).

References
[1] Li Chen. Dissertation Submitted to Hebei University of Technology for The Master Degree of Geotechnical Engineering [D]. [Place of publication unknown]: Hebei University of Technology, 2015.
[2] Tang Yuan. Study on Stability and Support Measures of Side-slope-upward in Tunnel Section of a Shallow Buried Unsymmetrical Pressure Tunnel [D]. [Place of publication unknown]: Chongqing Jiaotong University, 2018.
[3] Yang Qingsong. Discusses the Calculation of Slope Safety Soeefficient by Fem Double Coefficient Reduction Method [J]. Shanxi architecture, 2019, 45(16): 56-58.
[4] HAN Lu, MIAO Li-chuan. Slope Stability Analysis Based on Strength Reduction Method——Taking the Abutment Slope of the Right Bank of Tailings Reservoir as an Example [J]. World nonferrous metals, 2019, Loss of volume (16): 267-268.
[5] Zhang Yu, Zhang Shumao, CUI Xuan Zhou Hanmin. Seepage stability analysis tailings dam based on strength reduction method [J]. Non-ferrous metals (mines), 2019, 71(5): 72-77.
[6] He Y and Xu D F, Research on Security Warning and Instability Criterion of Slope Based on StrengthReduction Method. Geology and Mineral Resources of South China [J].2019,35(3): 343-347.
[7] Hong Wei,Liu Daiguo,Lin Zhongxin. Slope stability analysis based on 3D strength reduction method [J]. Engineering Investigation, 2019, 47(9): 18-23.
[8] Dong Yong. Research on the Slope Stability of the Tunnel Entrance [D]. [Place of publication unknown]: TJU, 2008.
[9] Zhang Youli, Liu Shengchun, Zhou Peng. Stability analysis of excavation of tunnel openingsoil high heading slope based on strength reduction method [J]. Journal of Beijing jiaotong university, 2013, 37(3): 68-72.