OPTIMIZATION OF THE ROUND LENGTH IN DESIGN STAGE FOR TUNNEL EXCAVATION IN WEAK ROCK

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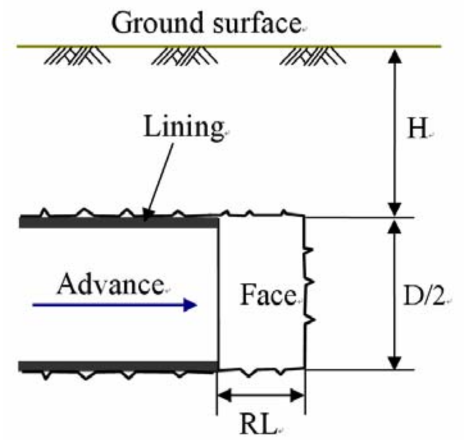
The paper deals with the determination of the optimum round length for weak rock tunneling in shallow or medium depth. The behaviour modes of the face and unsupported span were investigated by small scale model tests and PFC3D analyses. Using the concept of relative shear stress, FDM analyses were performed to formulate the safety factor for the face stability. This safety factor is also adopted as an indicator for the behaviour modes of the unsupported span. A conditional chart was established to determine the behaviour modes as the round length varies. By use of this conditional chart and detail construction information, the optimization of the round length can be performed in the design stage.

Keywords: Weak rock tunneling, Round length, Behaviour mode, Safety factor, Face stability, Optimization

1. Introduction

Although the round length has a major technical and economical impact in conventional tunneling, no coherent procedure is available for its determination. Research conducted so far in most cases has concentrated on the face stability, rather than on the combined region of the face and the unsupported span. The behaviour modes of the tunnel face and unsupported span was investigated for weak rock tunneling and total five types of behaviour modes were suggested as shown in figure 1 (Lee & Schubert, 2005).



H = overburden, D= tunnel diameter, RL= round length

Behaviour mode	Description
I (stable)	No overbreak with stable face
II (overbreak)	Overbreak with stable face
III (collapse)	Collapse with stable face
IV	Overbreak with unstable face
V	Collapse with unstable face

Fig. 1. Definitions of parameters and behaviour modes (Lee & Schubert, 2005).

The face stability and the behaviour modes were analyzed in this study by PFC3D analysis and FDM analysis and the determination of the behaviour modes can be carried out by use of the 'Conditional chart for excavation plan in weak rock tunneling'. For the optimization of round length, the construction cost and time was investigated with various round lengths and the behaviour modes.

2. Numerical Simulation for the Determination of Behaviour Modes

2.1. *PFC3D analysis*

2.1.1. *Simulation of the behaviour modes*

The face stability of a 10m diameter tunnel was investigated with 10m overburden by PFC3D analysis. The input parameters of PFC3D were calibrated by the numerical triaxial test which is provided by the code manufacturer (Itasca 1999). It was found that the results of PFC3D analyses correspond well to Vermeer's equation (Vermeer, Ruse and Marcher 2002) as shown in table 1.

Table 1. The estimation of the face stability by PFC3D analysis and Vermeer's safety factor.

CASE	D1	D2	D3	D4
C (kPa)	5.1	9.8	15.5	29.1
φ(o)	32.2	32.1	32.0	31.8
PFC3D analysis	collapse	stable	stable	stable
Vermeer's FoS	0.72	1.16	1.65	2.88

The unsupported span stability of a 10m diameter tunnel was also investigated with 10m overburden and 32^o friction angle to identify the behaviour modes as round length and cohesion varies. These results from PFC3D analysis are used as the reference models for the FDM analyses.

Table 2. The estimation of the unsupported span stability by PFC3D analysis.

CASE		D2a	D2	D3	D3a	D3b	D4
Sn (N)		8900	9000	11000	12000	15000	20000
C (kPa)		8.5	9.8	15.5	17.0	18.5	29.1
Round length (m)	1	Overbreak	Stable	Stable	Stable	Stable	Stable
	2	Collapse	Overbreak	Overbreak	Stable	Stable	Stable
	3	Collapse	Collapse	Overbreak	Overbreak	Overbreak	Stable
	4	Collapse	Collapse	Collapse	Overbreak	Overbreak	Overbreak
	5	Collapse	Collapse	Collapse	Overbreak	Overbreak	Overbreak

2.1.2. *Shape and volume of overbreak*

While the behaviour mode was investigated with different cohesion values in PFC3D analyses, the shape and volume of overbreak is affected by the friction angle. This has been reported also by the other researchers using model tests (Feder 1981). According to the small-scale model tests, PFC3D analyses and 40 cases from construction sites, the initial overbreak is less than 1.5m high. For the estimation of overbreak volume, it is assumed that overbreak has an elliptical shape in the cross section and the height of overbreak is related to the friction angle. Failure angle (θ) is assumed to be 45^o-$\varphi/2$ in behaviour mode-II and increases to approximately 45^o just before collapse occurs. Finally, the failure angle becomes $45^o+\varphi/2$ in behaviour mode-III of excessive overbreak. The volume of overbreak can be calculated by Eq. (1).

$$V = \frac{\pi}{16} D \cdot \tan\theta \cdot RL^2 \tag{1}$$

2.2. *FDM analysis*

2.2.1. *Methodology*

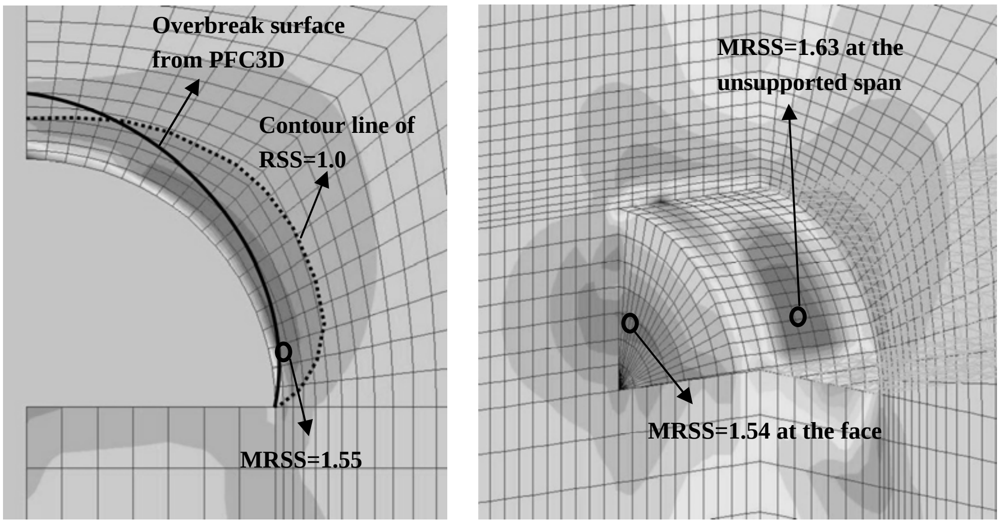
FDM analysis of an elastic model was adopted for an extensive parametric study with the concept of relative shear stress (RSS). Compared to the numerical methods such as PFC3D or elasto-plastic models, RSS analysis can provide a simple and quick solution so that the parametric study can be carried out efficiently. Relative shear stress is the ratio between the maximum elastic stresses and ground strength and can be considered as the reciprocal of the conventional safety factor at a specific location as shown in Eq. (2).

$$RSS = \frac{\frac{\sigma_1 - \sigma_3}{2}}{\cos\varphi \cdot C + \sin\varphi \cdot \left(\frac{\sigma_1 + \sigma_3}{2}\right)} \text{ (compression only), } RSS = -\frac{\sigma_t}{T} \text{ (tension exists)} \tag{2}$$

Positive RSS indicates a higher probability of shear failure and negative RSS indicates higher probability of tensile failure.

2.2.2. *Behaviour modes simulated by RSS analysis*

The failure mechanism cannot be realistically simulated by the RSS analysis because overbreak and collapse are progressive failures. However, it is found that the maximum relative shear stress (MRSS) has a relation to the behaviour mode. An example of an evaluation of RSS (case-D3 in table 1 & 2) is shown in figure 2.



(a) Behaviour mode-II with 3m round length (b) Behaviour mode-III with 5m round length

Fig. 2.Behaviour modes simulated by RSS analysis

It was found that with a MRSS value in the unsupported span higher than 1.55 with 3m round length, a potential for overbreak exists. Collapse potential exists with 5m round length if MRSS at the unsupported span is higher than 1.63. The face was stable in case-D3 as shown in table 1, thus the MRSS at the face indicating the face collapse should be higher than 1.54.

2.2.3. *Sensitivity study*

A Sensitivity study has been performed to identify the key factors influencing the behaviour modes and the important results are as below:

- Tensile strength is not playing a major role for the failure mechanism and does not have an influence on the MRSS.
- The assumption of 0.5 Ko (lateral earth pressure coefficient) is conservative for weak rock tunnel.
- Young's modulus of ground has an insignificant influence on the face stability while it has a great influence on the lining stress.
- The assumption that Young's modulus of shotcrete is 3GPa is conservative for the unsupported span stability as far as the stability of lining is not considered.

3. The Estimation of the Face Stability

3.1. *Definition of the safety factor for the face stability*

Since Vermeer's equation corresponds well to the results of the PFC3D analyses, MRSS at the face was calculated by FDM analysis with the Mohr-Coulomb parameters which are selected to obtain a safety factor of 1.0 with Vermeer's equation. This reference MRSS at the face indicating the face collapse was formulated by fitting the results of the FDM analyses. Assuming that the reference MRSS at the face is constant with various overburdens, the safety factor is defined in this study by use of the concept of 'critical cohesion' as shown in Eq. (3).

$$FoS = \frac{C}{C_{critical}} \tag{3}$$

Where, $C_{critical}$ is the critical cohesion corresponding to the reference MRSS.

For instance, the face of a 10m diameter tunnel collapses with 30^{o} friction angle, 8.2 kPa cohesion and 10m overburden according to Vermeer's equation. In this case, the MRSS at the face was calculated to be 1.73. If the overburden changes to 50m and the other parameters are unchanged, Vermeer's equation still provides the safety factor of 1.0. However, the MRSS at the face increases and exceeds 1.73 as the overburden increases. To keep the MRSS at 1.73 with 50m overburden, the cohesion must be increased accordingly. Therefore the safety factor of Eq. (3) can consider the influence of overburden on the face stability, which Vermeer's method disregards.

3.2. *Formulation of the critical cohesion*

The critical cohesion was formulated by fitting the results of the FDM analyses for various overburdens and tunnel diameters as shown in Eq. (4).

$$C_{critical} = \frac{\sigma_1}{\cos\varphi}\left[\frac{\alpha_2}{\alpha_1 \cot\varphi + \beta_1} - \beta_2 \sin\varphi\right] \tag{4}$$

Where, $\sigma_1 = m\gamma(H+D/4)$: the maximum principal stress of the MRSS at the face

m = 1.14 (for D = 5m),1.23(for D = 10m), 1.19(for D = 15m)

α_1 = 0.009D+0.522, β_1 = 0.013D+0.539, α_2 = 0.445+0.0045D, β_2 = 0.555-0.0045D

(unit : kN, m)

For the diameters which are not mentioned in Eq. (4), ‘m’ can be approximated by assuming that ‘m’ is linearly proportional to the diameter from 5m to 10m or from 10m to 15m. For example, ‘m’ is 1.214 for 12m tunnel diameter.

4. The Estimation of the Unsupported Span Stability

4.1. *FDM analysis of the reference models from PFC3D analysis*

The reference models of PFC3D analysis in table 2 were analyzed by FDM. The cohesion causing overbreak or collapse can be determined for each round length with the MRSS at the unsupported span as shown in figure 3. With this cohesion, the safety factor for the face stability can be calculated according to the Eq. (3).

For example, the critical cohesion is 8 kPa for the reference models according to Eq. (4) and tunnel collapses with 3m round length if the cohesion is 14.5kPa. In this case, the safety factor for the face stability is 1.81. This implies that the round length should be less than 3m to avoid the collapse if the safety factor for the face stability is not higher than 1.81. If the cohesion is higher than 26 kPa, overbreak does not occur with 3m round length. In this case the safety factor for the face stability is 3.25. Therefore the behaviour mode-II (overbreak) occurs with 3m round length if the safety factor for the face stability is 1.81-3.25.

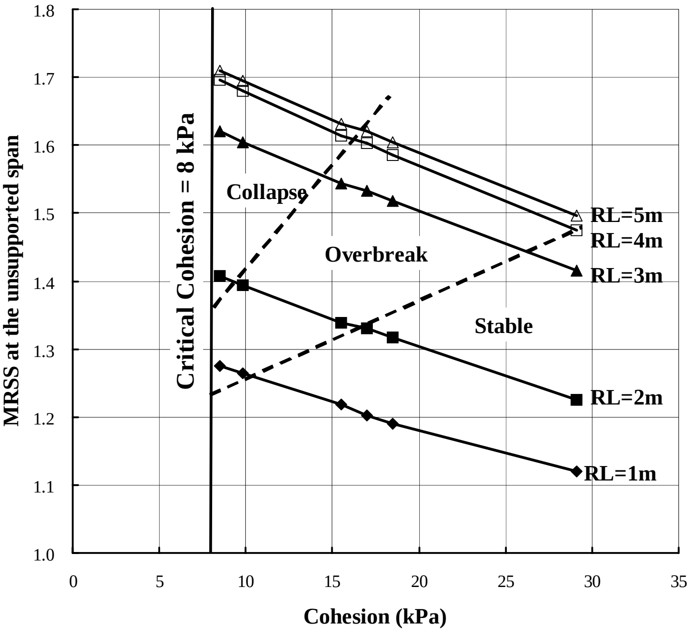


Fig. 3. Determination of the behaviour modes for the reference models.

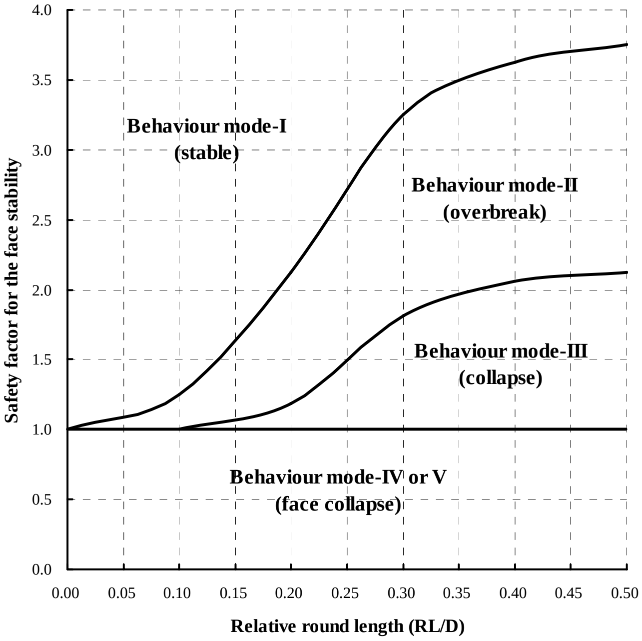
As described above, the safety factor for the face stability can be adopted as an indication for the behaviour modes of the unsupported span.

4.2. *Establishment of the conditional chart*

The reference models from PFC3D analysis are based on the assumption of 10m tunnel diameter, 10m overburden and 32^{o} friction angle. However, the safety factor for the face stability is adopted as an indicator for the behaviour modes and the correlations in chapter 4.1 can be applied for the other conditions based on the assumption as below:

The same behaviour mode of the unsupported span occurs with the same relative round length and the same safety factor for the face stability.

Correlating the safety factor for the face stability with the behaviour modes, the conditional chart can be established as shown in figure 4. For example, the safety factor for the face stability is 1.4 according to the Eq. (3) and (4) with 13m diameter, 45m overburden, 60kPa cohesion, 28^{o} friction angle and 23kN/m^{3} unit weight. The round length causing overbreak is 1.5m and the round length causing collapse is 3.0m according to the conditional chart.



Conditions:
Overburden (H) < 150m
Tunnel diameter (D) = 5-15m
1< H/D < 15
Ko = 0.5 – 1.0
Friction angle (φ) = 20^{o} - 40^{o}
Cohesion (C) > 10 kPa
Round length < 5m
Top heading excavation (tunnel height is half of diameter).

Fig. 4. The conditional chart for excavation plan in weak rock tunneling.

It should be emphasized that the conditional chart is established based on some assumptions and conditions as specified in the chart. Especially, the round length shown in this chart should be considered as the maximum value for each behaviour mode because the lining stability is not considered in this study.

5. Optimization of the Round Length

To optimize the excavation cost and time in terms of the round length, detailed construction information is required such as unit price of material, cycle time and so on. The round length has more influence on the construction time than the material quantity. The construction time is related to the indirect cost such as labor, maintenance of site, equipment etc., which are usually dependent on the specific site and contractual conditions. Therefore only direct costs of shotcrete and excavation are considered in this study. Cycle time, excavation and shotcrete time per unit volume are required to evaluate the construction time. For the construction cost, the unit prices of excavation and shotcrete are required.

Assuming one example tunnel, the simulation of construction time and cost is described as the round length varies. The behaviour modes of an example tunnel are shown in table 3.

Table 3. Calculation results for an example tunnel.

Condition	**Calculation results**
D = 14m, H=40m	Critical cohesion = 47.1 kPa
Length = 100m	Safety factor for the face stability = 1.27
C = 60 kPa, φ = 25°	Overbreak occurs with 1.5m round length
γ = 25 kN/m^3	Collapse occurs with 3.1m round length

Based on the results above, the construction time and the additional cost can be estimated with various round lengths as shown in figure 5.

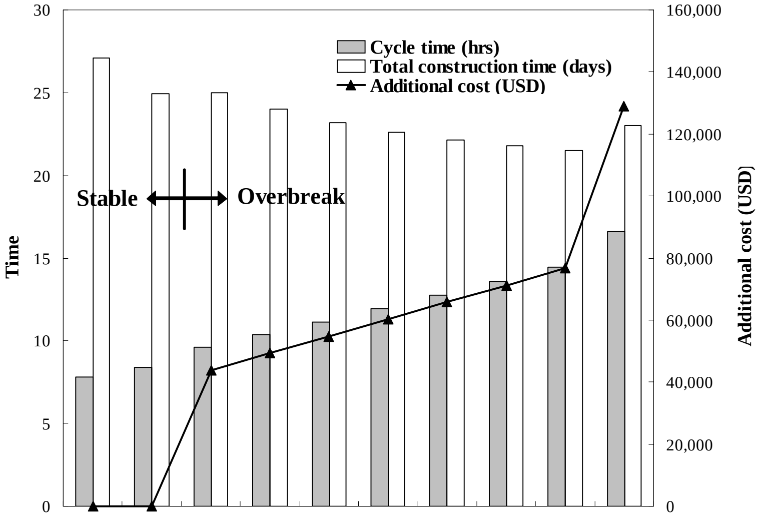


Fig. 5. Specific cycle times, total construction time and additional cost for an example tunnel with a length of 100m

With 1.4m round length, the behaviour mode-I (stable) is observed and overbreak does not occur. With 1.6m round length, the behaviour mode-II (overbreak) occurs and its volume is approximately 4.5m^3 per round according to the Eq. (1). Its volume increases as the round length increases. With 3.0m round length, overbreak almost reaches the collapse level and its volume is approximately 24.7m^3 per round. This amount of overbreak causes an excessive increase of cycle time and additional costs. Approximately 130,000 USD are additionally required to compensate for the overbreak for the total length of tunnel. Compared to the case of 1.2m round length, approximately 4 days of construction time can be saved with 3.0m round length and 130,000 USD. With 2.4m round length, the total construction time is approximately 5 days shorter than with 1.2m round length which causes no overbreak. In this case, the additional cost to compensate for the overbreak is approximately 66,000 USD.

As shown above, the round length can be optimized by the simulation of the construction time and cost. The final decision can be made in consideration of the specific site and contractual conditions.

6. Conclusions

The behaviour mode of the face and unsupported span was investigated in this study for weak rock tunnels in shallow to medium overburden depth. Total five types of behaviour modes are suggested for the planning of excavation and support. Based on the results from the PFC3D analysis, the equivalent models were analyzed by a FDM code, using elastic material behaviour. Using the relative shear stress (RSS) concept, a correlation between the maximum relative shear stress (MRSS) and the different behaviour modes was found.

The safety factor for the face stability is defined by the concept of the ‘critical cohesion’ and it is formulated by fitting the results of FDM analyses. This safety factor can consider the influence of overburden, which Vermeer’s equation disregards. The stability of the unsupported span was investigated based on the reference models of PFC3D analysis and FDM analysis. The safety factor for the face stability is adopted as an indicator for the behaviour mode. The results are illustrated in the ‘Conditional chart for excavation plan in weak rock tunneling’ which shows the relation of the safety factor and relevant behaviour mode as the round length varies.

With detailed construction information such as cycle time, unit price of materials etc., the optimization of excavation can be carried out in the design stage. According to the conditional chart, the behaviour mode can be determined with the applicable range of round length. Depending on the site conditions, round lengths causing a limited volume of overbreak can be considered in the excavation plan.

Although the proposed method in this study has some restrictions, this method can provide useful information for the optimization of the excavation planning.

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