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Determination of the round length for tunnel excavation in weak rock

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Abstract

Although the round length has a major technical and economical impact in conventional tunnelling, no coherent procedure is available for its determination. In this study, the determination of the round length was investigated for tunnels in weak rock, where the behaviour is not governed by discontinuities. This study focuses on shallow or medium depth tunnels so that squeezing or rock burst is not concerned. The behaviour mode of the face and unsupported span was investigated by a series of small scale model tests and PFC3D analyses. Total five types of behaviour modes are suggested for the planning of excavation and support. Based on the results from the PFC3D analyses, 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 investigated. The safety factor for the face stability is defined by the concept of the 'critical cohesion' and this 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 tunnelling' 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 deterministically and probabilistically in the design stage. Depending on the site conditions, round lengths causing a limited volume of overbreak can be considered in the excavation plan. Although the proposed method has some restrictions, it can provide useful information for the optimization of the excavation, especially in design stage.

Keywords: Round length; Weak rock tunnel; Behaviour mode; Safety factor; Optimization

1. Introduction

Most engineers recognize that the round length has a considerable influence on the potential for collapse of the face and unsupported span and also on the primary lining stability close to the face (Baudendistel, 1997; Chang, 1994). In addition the costs and time for tunnel construction are strongly influenced by the choice of the round length. In spite of the technical and economical importance of this issue, no reasonable procedure to determine suitable round lengths has been developed up to now. Some researchers have focused on the stability of the face only and the other approaches, which consider the unsupported span, disregard the relation of the face and unsupported span stability.

In this study, the stability of the face and unsupported span was investigated for tunnel excavation in weak rock by small scale model tests and numerical analyses. For the identification of behaviour modes of the face and unsupported span, small scale model tests and PFC3D analysis were adopted. FDM analysis was also performed to identify the behaviour modes quantitatively so that the safety factor for the face stability has been developed as an indicator of the behaviour modes of not only the face but also the unsupported span.

Assuming weak rock in this study, ground behaviour is not governed by discontinuities such as joints, bedding or foliation. The focus of this study is on highly to completely weathered rock or poorly cemented sedimentary rock.

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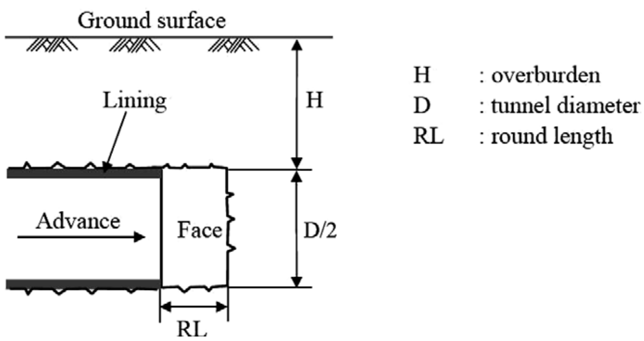


Fig. 1. Definitions of parameters.

Overbreak or collapse mainly results from stress-related failure, not from the geometry of discontinuities or blasting damage. Regarding the depth of tunnel, this study focuses on shallow and medium depth tunnels so that squeezing or rock burst is not concerned.

As shown in Fig. 1, round length (RL) is defined as the length of unsupported span which is excavated at once before support is installed. Overburden (H) is the distance from the crown to the ground surface and the tunnel height is a half diameter of tunnel (D) because a top heading excavation is assumed in this work. Rock bolts and pre-support such as pipe roof or forepoling is not considered either.

2. Behaviour modes of the face and unsupported span

2.1. Small scale model tests

Small scale model tests were performed to observe the behaviour modes of the face and unsupported span as round length increased. Although, the behaviour modes were observed qualitatively in these tests, many researchers have adopted this method to investigate the failure mechanism and behaviour of tunnel (Vavrovsky, 1987). However, most of works focused only on the behaviour of the face or have not considered the actual sequence of the excavation (Chambon and Corte, 1994).

The scale for the models is 1:40 and tunnel lining is modelled by a plastic plate and ground is modelled by sand classified as SW (well-graded sand) according to Unified Soil Classification System. The chosen water content was 1.6–2.0%, which results in an apparent cohesion. Its friction

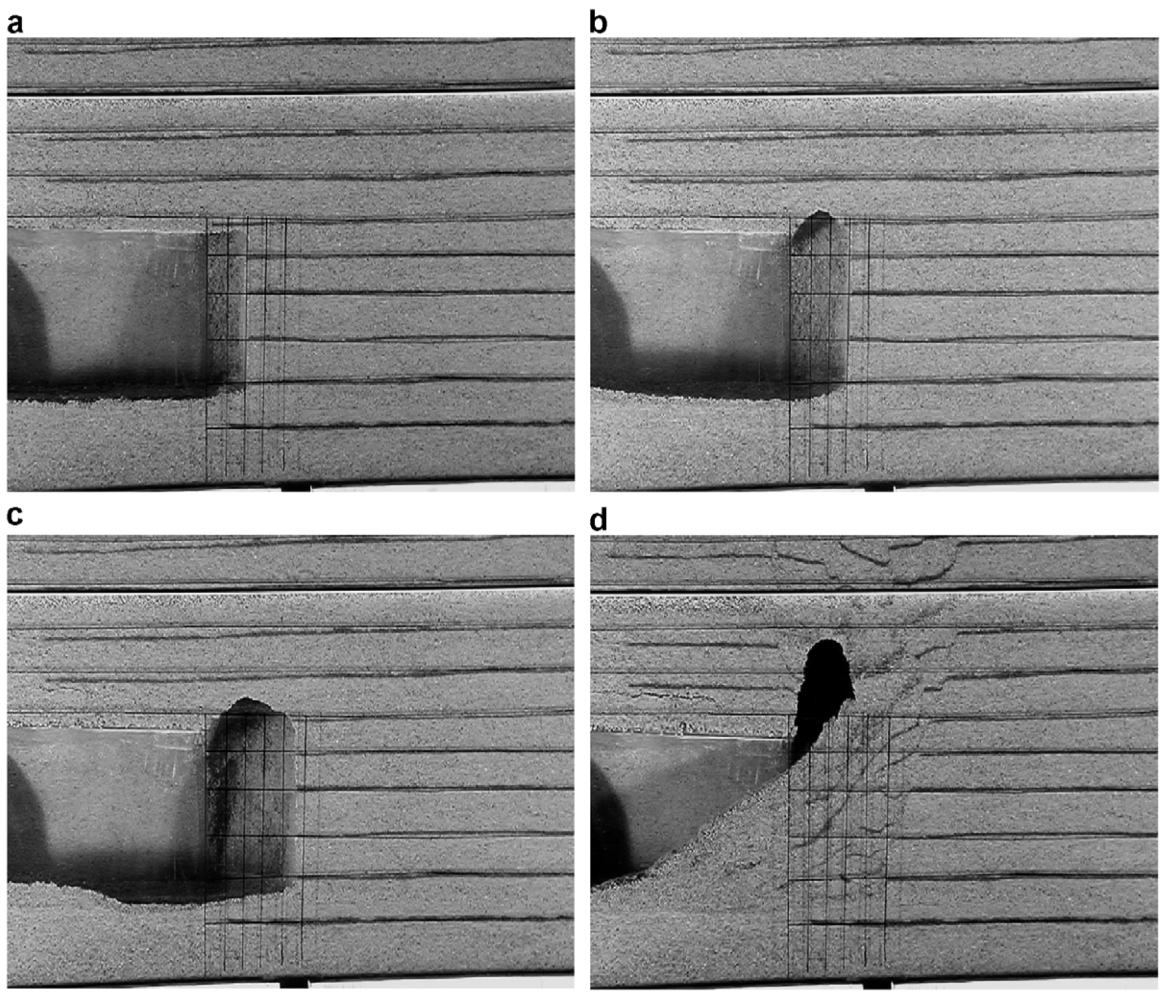


Fig. 2. Behaviour modes of the face and unsupported span in small scale model tests. (a) 'Stable' with 2 m round length. (b) 'Overbreak' with 3 m round length. (c) 'Excessive overbreak' with 4.5 m round length. (d) 'Collapse' with 5 m round length.

Table 1
Suggested behaviour modes of the face and unsupported plan for the excavation plan

Nos.	Behaviour mode	Possible excavation plan
I	Stable: No overbreak occurs in the unsupported span. The face is stable	The round length could be increased
II	Overbreak: Limited volume of overbreak occurs in the unsupported span. The face is still stable	Pre-support such as forepoling could be required to avoid this behaviour. Depending on the specific site conditions, the construction time can be saved with additional costs by adopting this behaviour
III	Collapse: Excessive overbreak or (day-light) collapse occurs in the unsupported span. The face is partly collapsed	The round length should be determined to avoid this behaviour. Pre-support such as pipe roof could be required if the round length is chosen close to this limit
IV	Face overbreak: The face is not stable and collapses even without excavation, leading to a small scale overbreak	Practically, excavation can be continued without significant interruption in this case and face supports such as face bolts can be applied to guarantee a stable face
V	Face collapse: The face is collapsed in excessive volume and usually results in day-light collapse	Excavation is practically impossible without pre-support and face support such as pipe roof and face bolts

angle is approx. 30°–32° and apparent cohesion is approx. 0.5–1.5 kPa, measured by indirect method. Tunnel diameter is 25 cm (10 m) and overburden is 50 cm (20 m) and half space is modelled. The excavation was carried out in 1.25–2.5 cm (0.5–1.0 m) interval to investigate the influence of the round length on the stability of the face and unsupported span.

The representative results are shown in Fig. 2. The face was stable initially in order to commence the excavation and excavation continued until the collapse happened. If the chosen round length did not cause the overbreak in unsupported span, the face was also stable (see Fig. 2a). It was also clearly observed that the face was still kept stable although overbreak occurs in unsupported span (see Fig. 2b and c). The excessive round length caused the collapse of unsupported span and the face also collapsed partly in this case (see Fig. 2d).

This observation implies that the round length has no influence on the face stability as long as the face is initially stable and the chosen round length does not cause the collapse in unsupported span.

2.2. Suggested behaviour modes for the excavation plan

As describe in chapter 2.1, the behaviour modes of the face and unsupported span can be identified as the round length varies. In this study, total five types of behaviour modes are suggested for the excavation plan as shown in Table 1, which is established based on the results of small scale model tests and experience of field observations. Naturally, the behaviour modes can be classified more precisely, but these five modes are enough for the purpose of the excavation plan.

3. Numerical analyses for the determination of the behaviour modes

3.1. PFC3D analysis

PFC3D analyses were performed to simulate the behaviour modes of tunnel face and unsupported span quantitatively since the observation was qualitatively made in the small scale model tests. The input parameters of PFC3D (contact bond strength and contact bond stiffness) were calibrated to elastic constants (Young's modulus and Poisson's ratio) and Mohr–Coulomb strength parameters (friction angle and cohesion) in order to simulate the behaviour modes which are similar to the results of the small scale model tests. For this purpose, the numerical triaxial test provided by the code manufacturer was carried out (Itasca, 1999).

3.1.1. Simulation of the behaviour modes

The face stability of a 10 m diameter tunnel was investigated with 10 m overburden and 32° friction angle by PFC3D analysis. Young's modulus and Poisson's ratio of ground is 130 MPa and 0.30, respectively. By adjusting input parameters of PFC3D based on the numerical triaxial test, cohesion can be varied with the other ground parameters fixed. Therefore the face stability was investigated with different cohesions under the same conditions and compared to the results of Vermeer's safety factor (Vermeer et al., 2002).

Although PFC3D analysis is one of the most reliable methods for the simulation of ground failure, it is not suitable for the investigation with a large range of parameters. It was found that the results of PFC3D analyses correspond well to Vermeer's safety factor as shown in Table 2. For this reason, Vermeer's method was chosen for the reference method of FDM analysis for the face stability.

The unsupported span stability of a 10 m diameter tunnel was also investigated with 10 m overburden and 32° friction angle to identify the behaviour modes as round

Table 2
The estimation of the face stability by PFC3D analysis and Vermeer's safety factor ($H = 10$ m, $D = 10$ m, $\varphi = 32°$)

CASE	*D*1	*D*2	*D*3	*D*4
C (kPa)[a]	5.1	9.8	15.5	29.1
φ (°)[a]	32.2	32.1	32.0	31.8
PFC3D analysis	Collapse	Stable	Stable	Stable
Vermeer's FoS[b]	0.72	1.16	1.65	2.88

[a] These parameters were determined by numerical triaxial tests.
[b] $\mathrm{FoS} = \frac{0.9\tan\varphi + 18C/\gamma D}{2+3(RL/D)^{6\tan\varphi/\mathrm{FoS}}}$ (after Vermeer et al., 2002.

Table 3
The estimation of the unsupported span stability by PFC3D analysis ($H = 10$ m, $D = 10$ m, $\varphi = 32°$)

CASE		*D*2a	*D*2	*D*3	*D*3a	*D*3b	*D*4
Sn (N)[a]		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

[a] Sn is called "normal contact bond strength between balls" as an input parameter of PFC3D.

length and cohesion varies. The results are shown in Table 3 and the behaviour modes are quite similar to the observed in the model tests. Although, Vermeer's formula includes the round length, it cannot distinguish the stability of the face and the unsupported span, thus the influence of the round length on the face and the unsupported span cannot be considered separately. In this study, the results of PFC3D analysis are used as the reference models of the FDM analyses for the unsupported span stability.

3.1.2. Shape and volume of overbreak

While the behaviour mode was investigated with different values of cohesion 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 1.5 m 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 as shown in Fig. 3.

Failure angle (θ) is assumed to be $45° - \varphi/2$ in behaviour mode-II and increases to approximately 45° just before collapse occurs. Finally, the failure angle becomes $45° + \varphi/2$ in behaviour mode-III of excessive overbreak. The volume of overbreak can be calculated by Eq. (1).

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

3.2. FDM analysis

3.2.1. Methodology

FDM analysis of an elastic model was adopted for an extensive parametric study with the concept of relative shear stress (RSS). The commercial code FLAC3D developed by ITASCA (USA) has been used for this study. Compared to other 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).

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

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

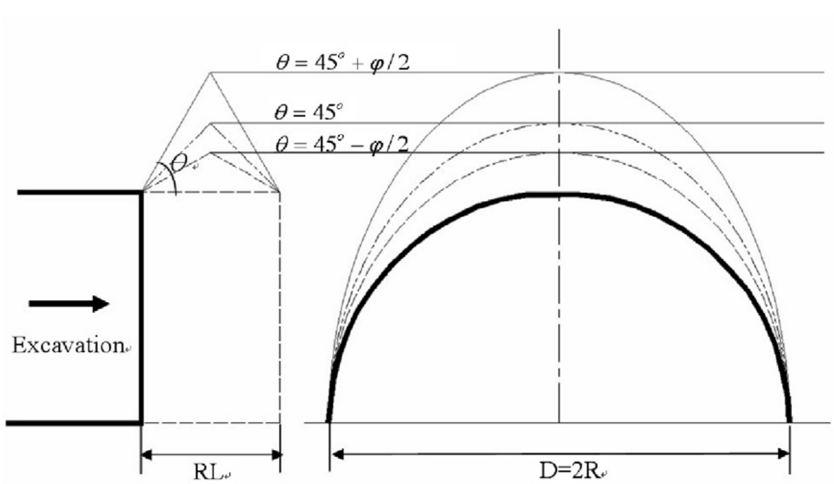


Fig. 3. Assumption of overbreak shape for the calculation of overbreak volume.

3.2.2. Behaviour modes evaluated by RSS analysis

The failure mechanism cannot be realistically simulated by the RSS analysis because overbreak and collapse are the phenomena of progressive failures as shown in Fig. 4. For instance, the overbreak surface from PFC3D does not correspond to the contour line of 1.0 RSS. However, it was 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 Tables 2 and 3) is shown in Fig. 4. Overbreak occurs with 3 m round length and collapse occurs with 5 m round length while the face is stable. It was found that with a MRSS value in the unsupported span higher than 1.55 with 3 m round length, a potential for overbreak exists. Collapse potential exists with 5 m round length if the value of MRSS at the unsupported span is higher than 1.63. The MRSS at the face indicating the face collapse should be higher than 1.54. As a result, MRSS can indicate the behaviour modes of the face and unsupported span although RSS analysis cannot simulate realistically the failure mechanism.

3.2.3. Sensitivity study

A Sensitivity study has been performed to identify the key factors influencing the behaviour modes. The variety of concerned parameters in this study is:

– Tensile strength $= 0 \sim C \cdot \cot(\varphi)$.
– Ko (lateral earth pressure coefficient) = 0.5, 1.0, 1.5.
– Young's modulus of ground (E) = (200–500) × (uniaxial compressive strength of ground, qu).
– Young's modulus of shotcrete (Es) = 1, 2, 3 GPa for young shotcrete.

The important results are summarized 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 in its range of 0.5–1.0 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 ratio of Young's modulus of ground and lining stiffness has an influence on the MRSS at the unsupported span. The higher stiffness of lining, the less potential for the behaviour mode-III of collapse.
- The assumption that Young's modulus of shotcrete is 3 GPa is conservative for the unsupported span stability as far as the stability of lining is not considered.

3.3. Estimation of the face stability

3.3.1. 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).

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

Where, C is cohesion of ground and C_{critical} is the critical cohesion corresponding to the reference MRSS indicating the face collapse.

For instance, according to Vermeer's equation the face of a 10 m diameter tunnel collapses, when the ground has 30° friction angle, 8.2 kPa cohesion and the overburden is

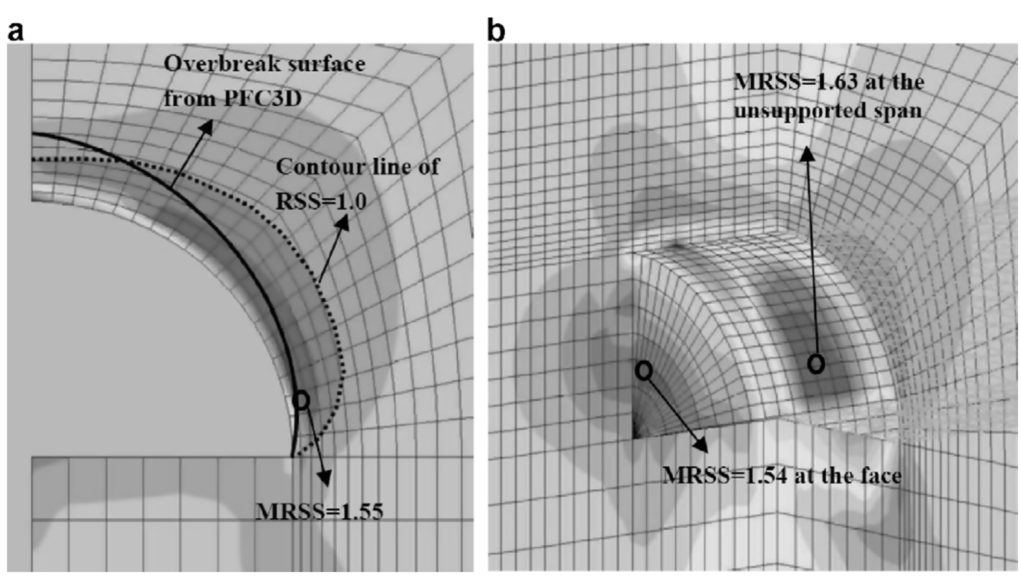


Fig. 4. Behaviour modes simulated by RSS analysis. (a) Behaviour mode-II with 3 m round length. (b) Behaviour mode-III with 5 m round length.

10 m. In this case, the MRSS at the face was calculated to be 1.73. If the overburden changes to 50 m 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 50 m overburden, the cohesion must be increased accordingly. In this case, 46.8 kPa cohesion is the critical cohesion. Therefore the safety factor of Eq. (3) can consider the influence of overburden on the face stability, while Vermeer's method disregards the influence of overburden.

3.3.2. 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).

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

where,

$\sigma_1 = m\gamma(H + D/4)$: the maximum principal stress of the MRSS at the face
$m = 1.14$ (for $D = 5$ m), 1.23 (for $D = 10$ m), 1.19 (for $D = 15$ m)
$\alpha_1 = 0.009D + 0.522, \quad \beta_1 = 0.013D + 0.539$
$\alpha_2 = 0.445 + 0.0045D, \quad \beta_2 = 0.555 - 0.0045D$ (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 5 m to 10 m or from 10 m to 15 m. For example, 'm' is 1.214 for 12 m tunnel diameter. Combining Eqs. (3) and (4), the face stability can be estimated quantitatively as tunnel diameter, overburden, friction angle and cohesion varies.

3.4. Estimation of the unsupported span stability

3.4.1. FDM analysis of the reference models from PFC3D analysis

The reference models of PFC3D analysis in Table 3 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 Fig. 5. With this cohesion, the safety factor for the face stability can be calculated according to the Eqs. (3) and (4), which indicates the behaviour modes of the unsupported span.

For example, the critical cohesion is 8 kPa for the reference models according to Eq. (4) and tunnel collapses with 3 m round length if the cohesion is 14.5 kPa. In this case, the safety factor for the face stability is 1.81 (=14.5/8). This implies that the round length should be less than 3 m 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 3 m round length. In this case the safety factor for the face stability is 3.25 (=26/8). Therefore the behaviour mode-II (overbreak) occurs with 3 m round length if the safety factor for the face stability is 1.81–3.25.

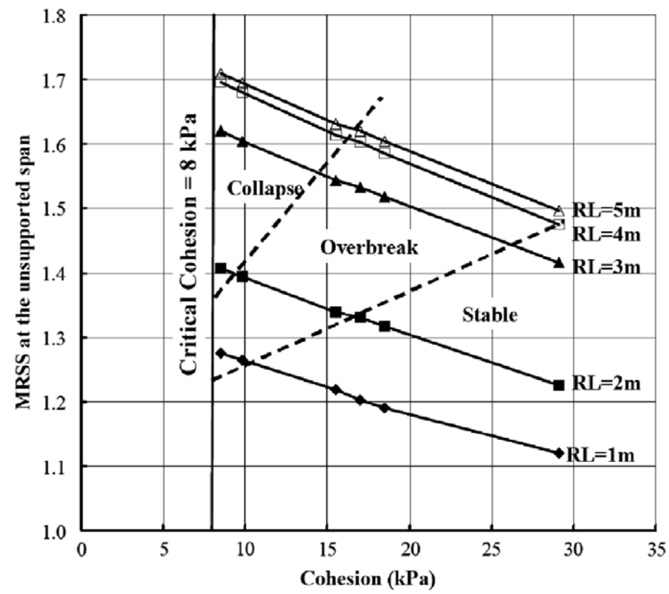


Fig. 5. Determination of the behaviour modes of the unsupported span by FDM analysis.

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

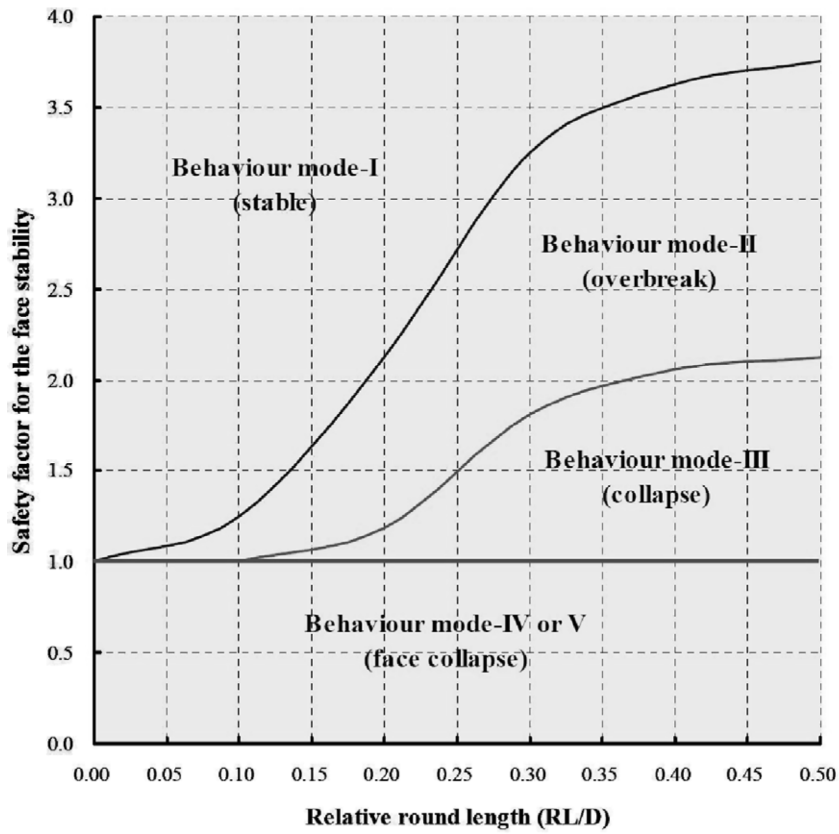
3.4.2. Establishment of the conditional chart

The reference models from PFC3D analyses are based on the assumption of 10 m tunnel diameter, 10 m overburden and 32° friction angle. However, the safety factor for the face stability is adopted as an indicator for the behaviour modes and the correlations in chapter 3.4.1 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 Fig. 6. For example, the safety factor for the face stability is calculated to be 1.4 according to the Eqs. (3) and (4) with 13 m diameter, 45 m overburden, 60 kPa cohesion, 28° friction angle and 23 kN/m^3 unit weight. The round length causing overbreak is 1.5 m and the round length causing collapse is 3.0 m according to the conditional chart.

Many researchers adopt the concept of stability number (N_s) for the definition of the safety factor (Terzaghi, 1943; Ellstein, 1986; Anagnostou and Kovari, 1996). It was found that the relation of the critical cohesion and overburden pressure can be considered as linearity according to the fitting results of the values calculated by Eq. (4). Therefore



Conditions:

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

Fig. 6. The conditional chart for excavation plan in weak rock tunneling.

the critical cohesion of Eq. (4) can be re-expressed as Eq. (5).

$$C_{\text{critical}} = \frac{\gamma H}{N_s} \tag{5}$$

where, N_s = stability number, unit = kN, m

It is recommendable that the Eq. (4) is used for the shallow depth tunnel instead of Eq. (5) while the calculation of the safety factor by the Eq. (5) is relatively quick and simple. The reason is that the fitting error is bigger for the shallow depth tunnel. Based on Eq. (5), the determination of the behaviour modes and round lengths can be carried out easily and quickly with the conditional chart as shown in Fig. 7.

It should be emphasized that the conditional chart is established based on some assumptions and conditions as specified in the chart of Fig. 6. 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. The behaviour modes were investigated without the effect of pre-support or face support. However, the excavation method can be decided based on the expected behaviour modes. The applicable excavation plan according to the conditional chart is presented in Table 4.

4. Application in design and construction stage

4.1. Application in design stage

The round length should be determined for the optimization of construction time and cost in addition to the stability of the tunnel. In this study, the construction cost and time were simulated with various round lengths and behaviour modes by deterministic and probabilistic approaches.

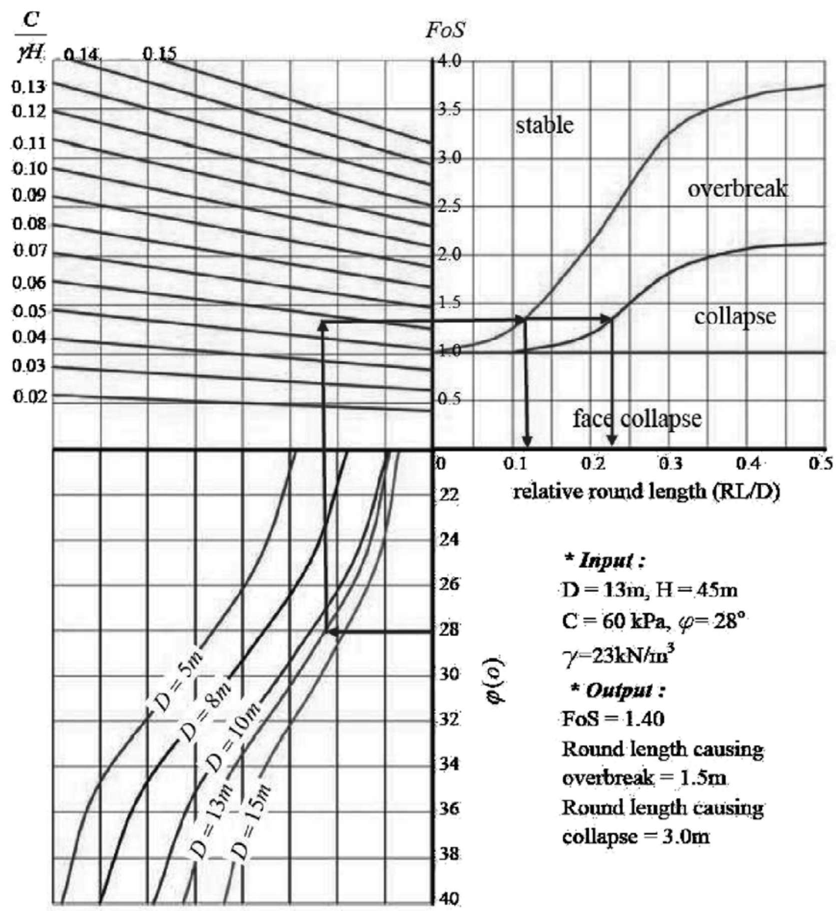


Fig. 7. The determination of the round length by use of the conditional chart.

Table 4
Applicable excavation plan according to the conditional chart

FoS	Behaviour mode	Excavation method
> 3.3	No overbreak occurs with 0.5D round length	Overstressing of lining must be checked with a large round length
2.2–3.3	No collapse occurs with 0.5D round length Overbreak occurs with a round length larger than 0.2D	Overstressing of lining must be checked with a large round length Forepoling would be required for a round length larger than 0.2D
1.5–2.2	Collapse occurs with a round length larger than 0.25D Overbreak occurs with 0.15D–0.2D round length	Overstressing of lining must be checked with a large round length Forepoling would be required for a round length larger than 0.15D
1.25–1.5	Collapse occurs with a round length larger than 0.22D Overbreak occurs with 0.1D–0.15D round length	Forepoling would be required for 0.1D–0.15D round length Pipe roof is necessary for a round length larger than 0.15D
1.0–1.25	Collapse could occur with a round length larger than 0.1D Overbreak could occur as soon as excavation begins	Without pre-support such as forepoling or pipe roof, excavation is risky. Pipe roof is necessary for a round length larger than 0.1D
<1.0	Face collapse	Face support like face bolt or pipe roof or ground improvement like grouting or freezing is necessary to commence the excavation. Possibly other method such as compressed-air or EPB shield tunnelling can be considered

4.1.1. Deterministic procedure

If ground strengths and boundary conditions can be determined singularly, the construction time and cost can be estimated deterministically as round length varies with detail information such as cycle time, unit prices of materials etc.

Fig. 8 shows the results of simulations for two different example tunnels. They have different ground strengths, overburdens and total tunnel lengths with the same tunnel size and construction ability. As round length increases, behaviour mode-I (stable) changes to behaviour mode-II (overbreak). Accordingly, cycle time and additional cost

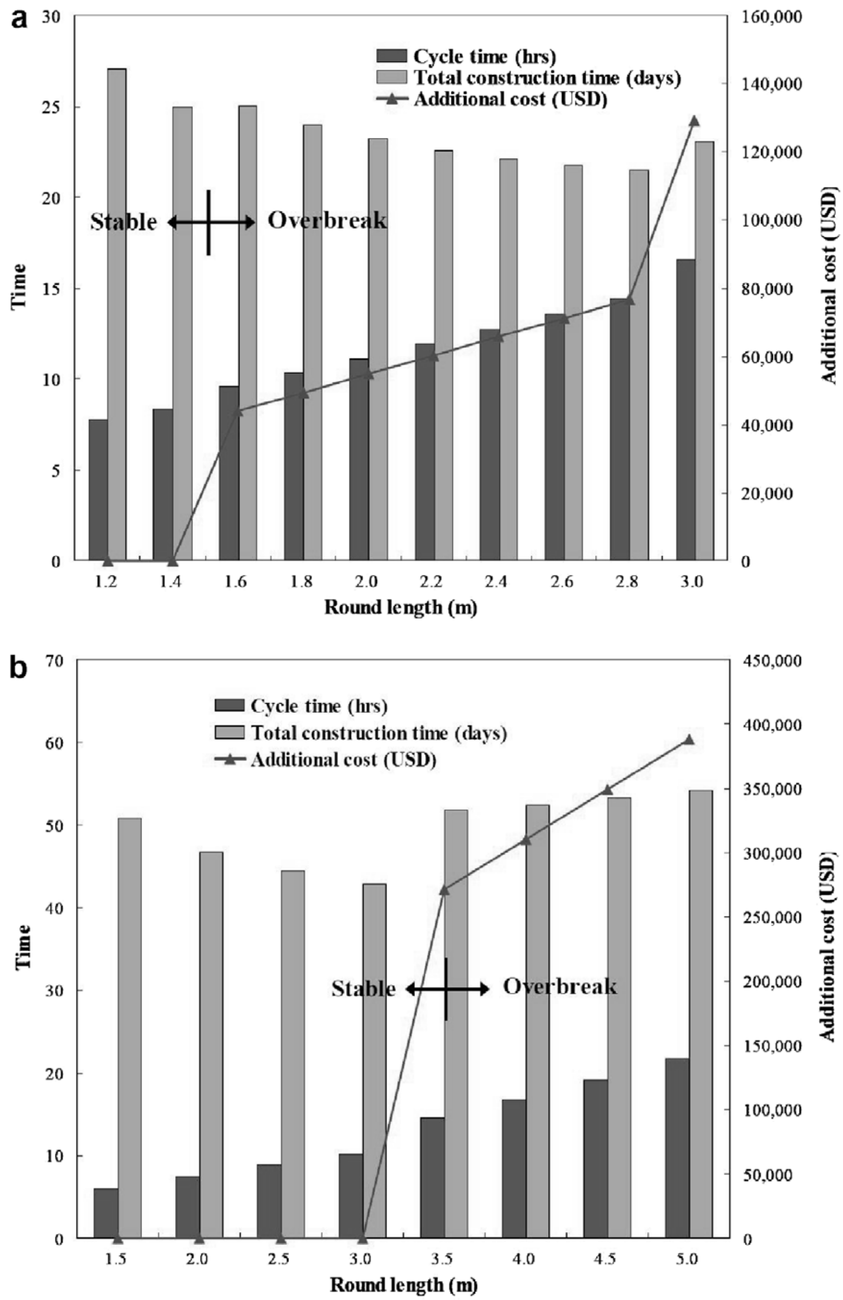


Fig. 8. Deterministic simulation of construction cost and time for the optimization of the round length. (a) Construction cost and time for example tunnel-A. (b) Construction cost and time for example tunnel-B.

increase as overbreak volume increases. However, total construction time can be reduced due to the large round length as shown in Fig. 8a. But any cases of overbreak are not favourable for the construction time and cost as shown in Fig. 8b. Therefore, the optimum round length should be determined in consideration of the specific site condition.

4.1.2. Probabilistic procedure

Due to the scatter of geotechnical data, a statistical evaluation can provide useful information in design stages. Assuming that cohesion has a normal distribution and its average is 60 kPa and standard deviation is 20 kPa, the safety factor for the face stability is also distributed with probabilities as shown in Fig. 9. With these probabilities, the excavation plan can be established probabilistically. For example, tunnel face collapses with 26% probability and 26% length of total tunnel length should be designed to be constructed with face support.

4.2. Application in construction stage

Regarding the determination of round length, monitoring results are hardly available prior to the decision. Therefore, the decision is mainly dependent on the observation of rock mass type and behaviour during excavation. How-

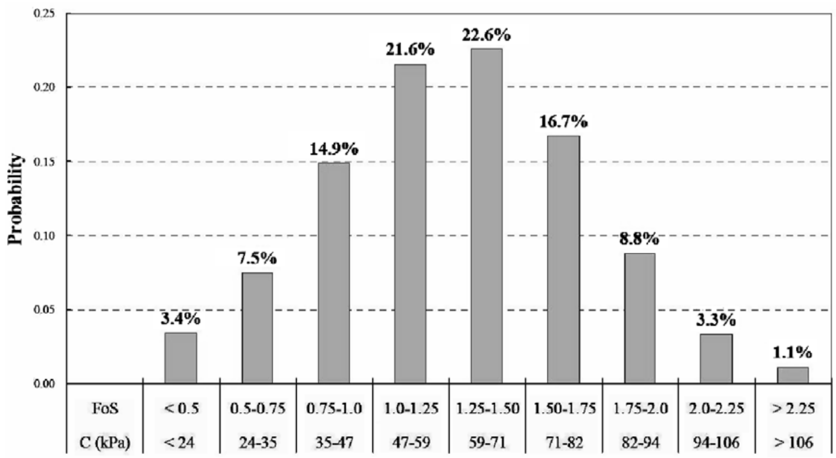


Fig. 9. Probability of the safety factor for the face stability.

ever, the round length also affects the system behaviour such as the deformation of tunnel, the surface settlement and the stress development of lining (Chang, 1994). This topic is not included in this study, thus the application in construction stage were performed relying on the site information of rock mass type. Two cases for the estimation of face stability are presented in Fig. 10. Tunnel diameter is 15 m and ground is mainly composed of extremely weak, medium beded, fine to medium grained, slightly silty sandstone. Its uniaxial compressive strength is approx. 0.5 MPa and friction angle is approx. 28° and cohesion is approx. 71.4 kPa, based on the field and laboratory tests. The groundwater condition is dry to damp. Tunnel was excavated by back-hoe and shotcrete, steel rib, wiremesh with rockbolts and forepoling were sequentially installed as excavation was continued.

As described before, the face stability is affected by overburden while Vermeer's safety factor disregards. In Fig. 10a, the face was stable with 49 m overburden and its safety factor for the face stability is 1.4 according to Eqs. (3) and (4). As excavation was continued, overburden increased and the tunnel face collapsed with 72 m overburden as shown in Fig. 10b. Its safety factor is 0.97. Especially, this kind of collapse often results from the ignorance of overburden impact.

5. Conclusions

Although, the round length has a major technical and economical impact in conventional tunnelling, no coherent procedure is available for its determination. In this study, the determination of the round length was investigated for tunnels in weak rock, where the behaviour is not governed by discontinuities. This study focuses on shallow or medium depth tunnels so that squeezing or rock burst is not concerned.

The behaviour mode of the face and unsupported span was investigated by a series of small scale model tests and PFC3D analyses. Total five (5) types of behaviour modes are suggested for the planning of excavation and support.

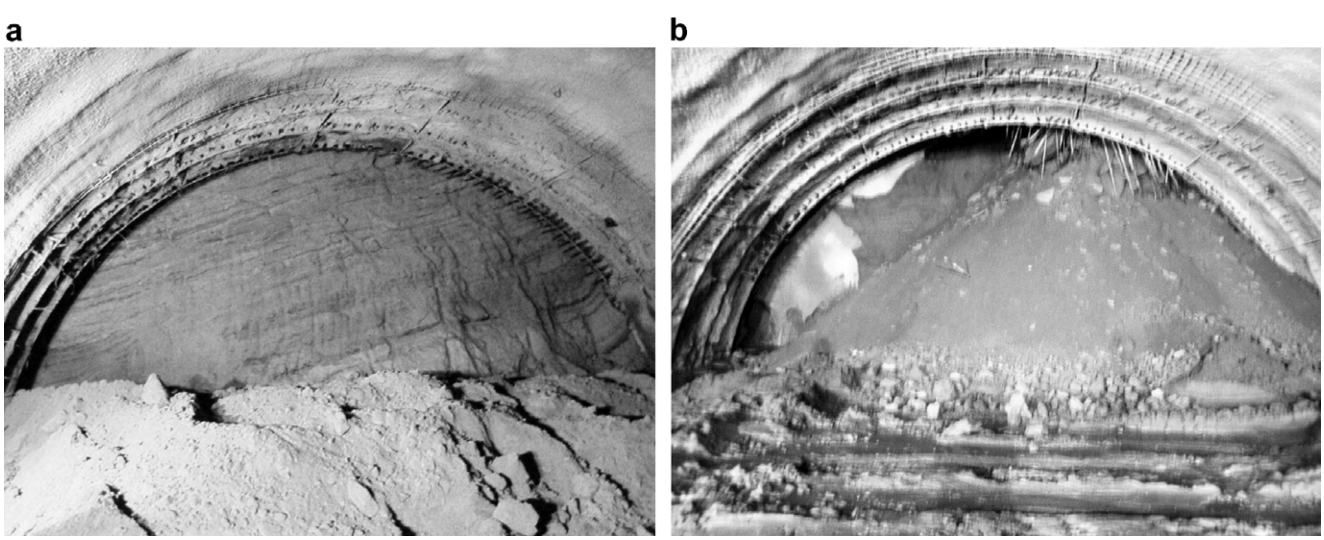


Fig. 10. Application in construction stage for the estimation of the face stability. (a) Stable face with low overburden. (b) Face collapse with high overburden.

According to the results of the small scale model tests and PFC3D analyses, it is clearly found that the stability of the unsupported span does not affect the stability of the face as long as the face is initially stable and the chosen round length does not cause excessive overbreak or day-light collapse.

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 investigated. The reference MRSS indicating the face stability was determined in comparison to the reference models of PFC3D analyses and Vermeer's method with several assumptions. The safety factor for the face stability is defined by the concept of the 'critical cohesion' and it is formulated by fitting the reference MRSS calculated by 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 tunnelling' which can show 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 deterministically and probabilistically 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, the round length causing a limited volume of overbreak can be considered in the excavation plan. For the practicable application during the construction stage, the prediction of system behaviour is required in consideration of the round length.

Although, the proposed method has some restrictions under some conditions, this method can provide useful information for the optimization of the excavation, especially in design stage.

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