The Influence of the Round Length on the Stability of Tunnel Face and Unsupported Span

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ABSTRACT: A number of research projects on the face stability of tunnels have been carried out in the past. However, the influence of the round length has not been thoroughly investigated, although it is an essential factor for the stability and excavation costs. This paper presents typical failure mechanisms of the face including the unsupported span in relation to the round length in weak rock tunnels, whose behavior is not governed by discontinuities. A series of small-scale model tests and numerical analyses by PFC-2D (Particle Flow Code, Itasca) were carried out to define failure modes at the face and unsupported span. Five failure modes according to its shape and extent are suggested for excavation planning. The influence of the lining stiffness and overburden on the overbreak and round length has been investigated in the model tests. Failure mechanisms, their initiation and propagation have been also investigated by PFC analyses and compared to the results of the model tests. Overbreak in the unsupported span does not affect the face stability as long as the face is initially stable and the round length is small enough not to cause excessive overbreak or daylight collapse. Therefore, the decision on the round length should be made in consideration of the interaction of overbreak and support rather than the face stability itself.

1 INTRODUCTION

Conventional excavation for tunnels requires the determination of each round length in consideration of the ground condition, support capacity, construction cost and time, etc. (Baudendistel 1997). Presently most of the decisions in the design and construction stage are based on personal experience. Although the round length has a considerable influence on the stability of excavation and construction cost, most of research has focused on the stability of face itself and the influence of round length has not been thoroughly investigated.

In this paper, failure mechanisms at the face and unsupported span are investigated by small-scale model tests and numerical analyses using Particle Flow Code (PFC 2D, Itasca, USA). Weak rock or rock-like soil, whose behavior is not governed by discontinuities such as joint, bedding or foliation are considered in this study. Therefore, overbreak mainly results from stress-related failure, not from the geometry of discontinuities or blasting damage. Regarding the depth of tunnel, overbreak is more dominant in low or medium stress environments than associated with squeezing or rock burst. Therefore, this paper focuses on shallow and medium depth tunnels.

1.1 *Terminology*

To avoid confusion of, ‘Round length’ is defined as the length of unsupported span which is excavated at once before support is installed. ‘Unsupported span’ is composed of crown, shoulder and sidewalls, and ‘face’ is a vertical plane perpendicular to the tunnel axis. ‘Overbreak’ has a limited volume in underground and ‘collapse’ means overbreak reaching the ground surface (so-called ‘Daylight collapse’).

2 SMALL-SCALE MODEL TESTS

2.1 *Modeling in small scale*

Small-scale model tests were carried out to simulate the overbreak and collapse as round length is increased. The overbreak shape and its propagation were observed and recorded by digital video camera at each round. The influence of overburden and lining stiffness on the failure mechanism was also investigated in model tests. The scale for these models is 1:40 and various cases were simulated. Sand material used for tests is classified in SW (well-graded sand) according to Unified Soil Classification System (ASTM D2487-83).

- $D_{max} = 2.0mm$, $D_{10} = 0.2mm$
- $Cu = D_{60} / D_{10} = 7.5$
- $Cc = D_{30}^2 / (D_{60}\text{-}D_{10}) = 1.63$

Water content is 1.6~2.0% and apparent cohesion can be calculated as below (Terzaghi 1954).

$$C_{apparent} = \frac{H \cdot \gamma}{4\sqrt{K_p}} = 1.5 \text{ kPa} \qquad (1)$$

where H = 0.2m = height; γ = unit weight; K_p= passive earth pressure coefficient using friction angle (φ) = 32°.

The primary lining is made of vinyl sheet and small steel wires for the flexible lining, while for stiff linings a 2mm thick plastic plate is used. Tunnel diameter is 10m and rock bolts are not modeled. After the excavation of each “1m” round, the behavior was observed for at least 15 minutes before continuing with excavation. Once first overbreaks occurred, the round length was reduced to “0.5m”.

2.2 *Results of model tests*

The results of model tests are summarized in Table 1. ‘Stable round length’ is a round length without overbreak and ‘collapse round length’ is round length causing daylight collapse. ‘Maximum round length’ is the maximum length with overbreak before daylight collapse.

Table 1. Results of small-scale model tests.

Cases	Stiff lining		Flexible lining	
overburden	1D	2D	1D	2D
Stable R/L	1.0	2.0	1.0	2.0
Max. R/L	3.5	4.5	3.0	3.5
Collapse R/L	4.0	5.0	3.5	4.0

* R/L=round length in meter; D = tunnel diameter; 1D and 2D are overburden.

Most of overbreaks are cone-shape and extended to the ground surface at the collapse round length, forming a so-called ‘chimney-shape collapse’, forming a crater at the surface. In all cases, the face was stable before daylight collapse occurred. It showed that excessive overbreak or collapse can affect the face stability, but the round length is not key factor for the face stability (Figs 1-4).

2.2.1 *Influence of overburden*

The model test showed that with increasing overburden also the stable round length increases. In addition, the collapse at low overburden occurs more abruptly, due to the low confining pressure.

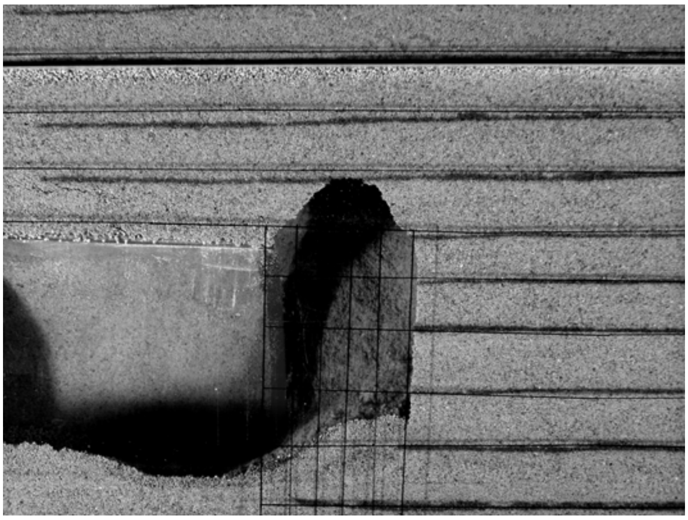

Figure 1. Typical overbreak at unsupported span in model test

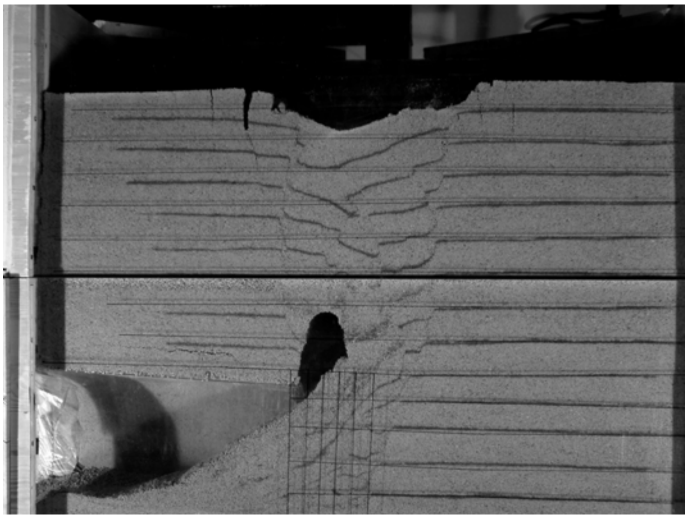

Figure 2. Daylight collapse in stiff lining case with 2D overburden in model test

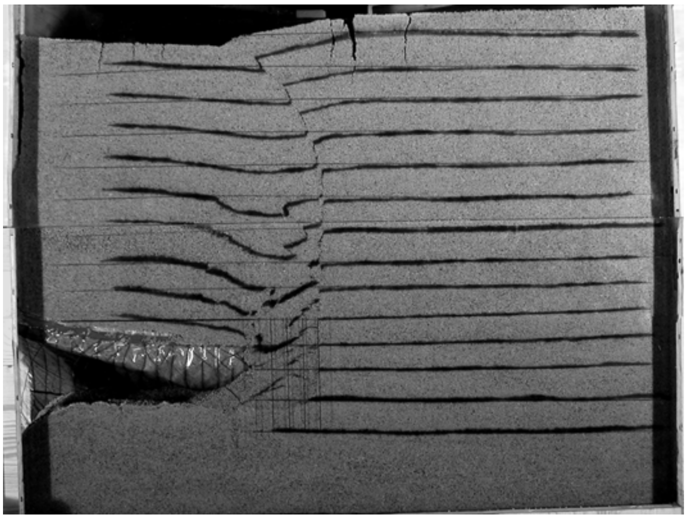

Figure 3. Daylight collapse in flexible lining case with 2D overburden in model test

2.2.2 *Influence of lining stiffness*

Larger round lengths are possible with stiff linings than with flexible linings. Considering stable round length, both cases do not show significant difference, however maximum and collapse round length are different. It means that the first overbreak mainly depends on the ground strength but its propagation and collapse can be affected by the lining stiffness.

The test results suggest that the initial strength and stiffness of shotcrete linings are very important factors controlling the overbreak and thus should influence the decision of round length.

2.2.3 *Relationship of overburden and lining stiffness*

While with an overburden of 1D and a flexible lining a distinct chimney develops and the lining damage is minor, in the case with an overburden of 2D the lining suffers heavy damage, causing also a longer crater at the surface (Figs 2-4).

This means that in case of collapse with an overburden of 2D the load on the lining is considerably higher. For the safety of laborers, high stiffness and strength of lining is necessary to minimize the consequences of a chimney type failure in the unsupported span.

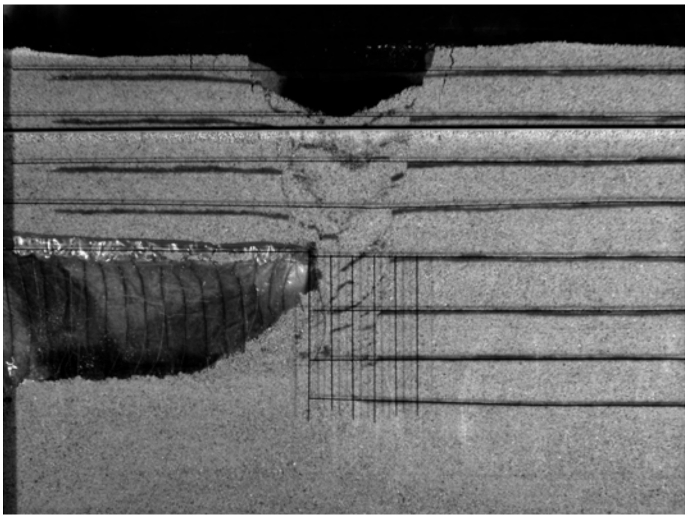

Figure 4. Daylight collapse in flexible lining case with 1D overburden in model test.

3 NUMERICAL ANALYSES USING PATICLE FLOW CODE (PFC)

To investigate the failure mechanism and the propagation of failure, as well as the stress distribution during overbreak and collapse a particle flow code (PFC, Itasca, USA) was used. Although the problem is clearly 3-dimensional, characteristic phenomena can be shown also in the 2-dimensional model.

The contact force plots show clearly the stress flow and the formation of arching stress. Analyses were performed as well longitudinally, as also in cross sections. The bond strengths between the particles were varied, while the friction angle was kept constant. The reason for this procedure is that cohesion is more important for the stability of face and unsupported span in shallow or medium depth tunnel than the friction angle.

3.1 *Longitudinal section analysis*

This analysis can show the development and changes of arching stress around the face during the occurrence of overbreak and collapse. The lining is modeled by a 'wall' element, therefore the lining is assumed to be a rigid boundary, similar to the 'stiff lining' in the model tests.

The first step is to simulate the failure mechanism without excavation as bond strength is gradually increased from zero. The properties and analysis conditions are as below;

- Tunnel diameter(D) = 10m
- Overburden (H) = 20m (2D)
- Ball size = 25.4~38.1cm
- Normal stiffness (Kn) = 1e8 N/m
- Shear stiffness (Ks) = 1e8 N/m
- Friction angle (*f*) = 30^{o}
- Normal bond (Sn) = 0, 84000, 85000 N
- Shear bond (Sb) = 0, 84000, 85000 N

If ground is cohesionless (zero bond strength), the face starts to ravel, resulting in a daylight collapse. However, a limited volume of overbreak occurs at the face, if ground is a little cohesive as shown in Figure 5 and other small-scale model tests (Vavrovsky 1987). With sufficient cohesion the face is stable and the excavation can be commenced (85000N bond strength).

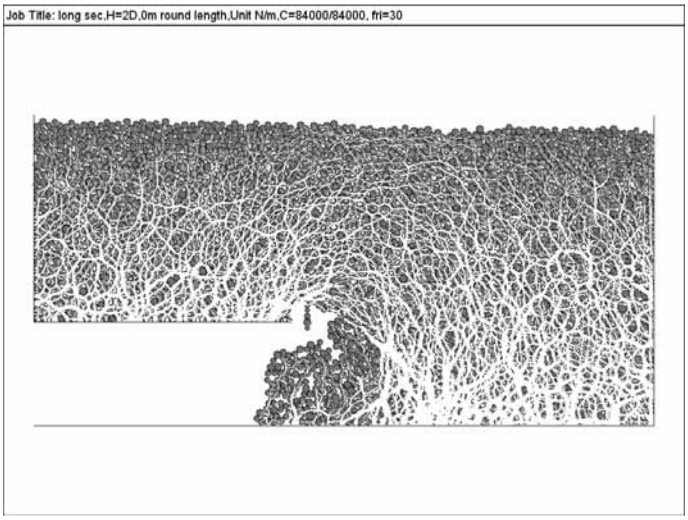

Figure 5. Longitudinal section of PFC analysis showing overbreak at the face before excavation with contact force chains (bond strength is 84000N).

In a next step the failure mechanism is investigated as round length is increased, beginning with the stable face without unsupported span (85000N bond strength). Excavation is carried out at "1m" steps until the collapse occurs.

At "4m" round length, the first overbreak occurs in the unsupported span, while the face is still stable (Figs 6-7). Although the ground at the face is loosened, it does not ravel and overbreak always occurs at the unsupported span. The same behavior was observed in the model tests.

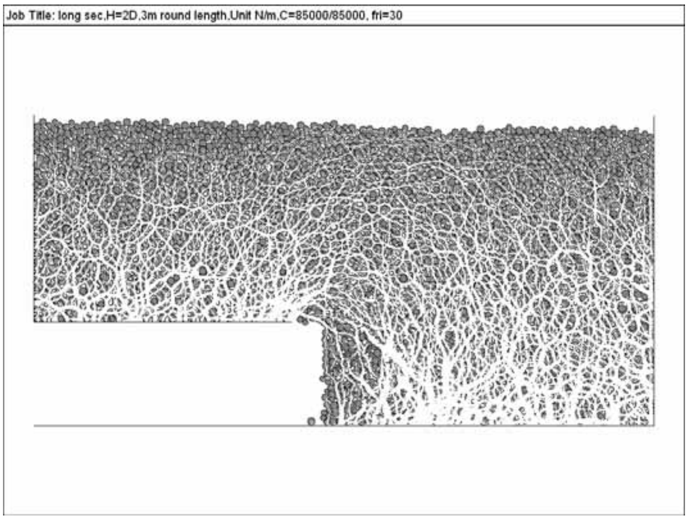

Figure 6. Longitudinal section of PFC analysis showing no overbreak with stable face after 3m excavation.

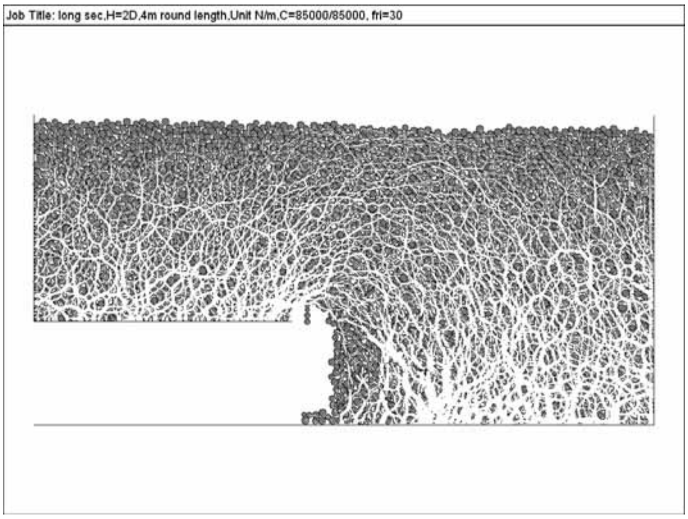

Figure 7. Longitudinal section of PFC analysis showing overbreak in the unsupported span after 4m excavation.

At 5m round length, the overbreak extends to the surface and a daylight collapse develops. In the beginning an overbreak occurs in the unsupported span, followed by the development of a natural ground arch. Eventually also the arch fails and partially the face. As overbreak progresses, the arching stress decreases (Figs 8-9).

Concerning the stress on the lining, it has been reported by many researchers that the larger the round length, the higher the lining stresses are (Chang 1994). However, it was found in model tests and PFC analysis that lower stresses act on the lining near to the face at the moment of overbreak because of the arching effect above the overbreak (Fig 7). Afterwards, higher stress acts on the lining at the moment of collapse, as shown in the model tests and PFC analyses, because arching stress is disturbed and ground load acts as a dead load (Fig 8).

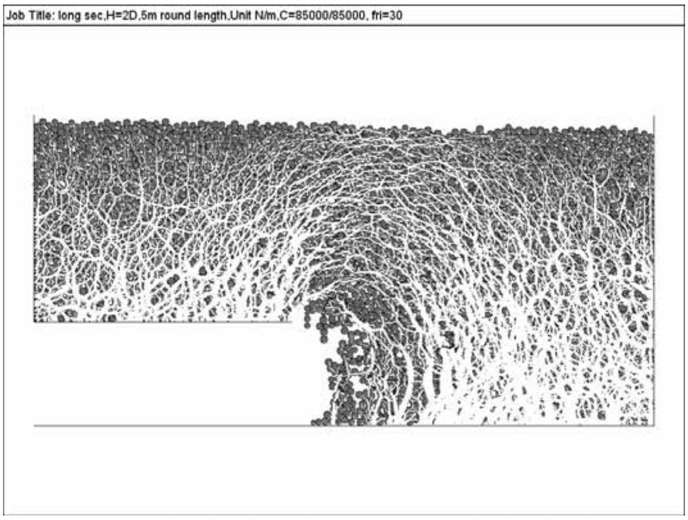

Figure 8. Longitudinal section of PFC analysis showing overbreak propagation after 5m excavation.

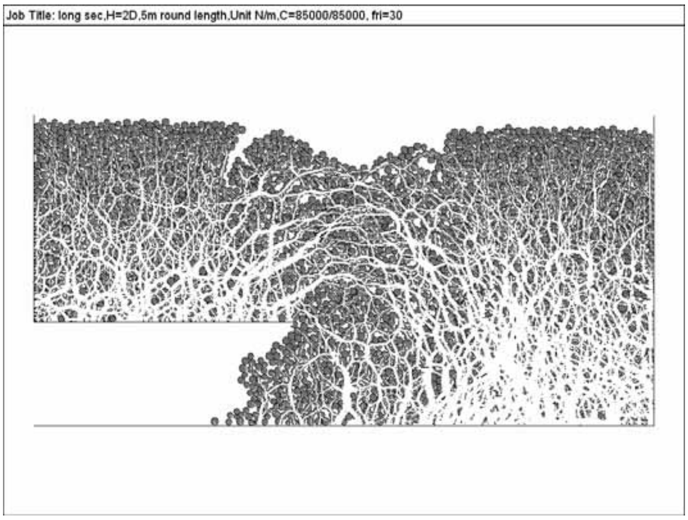

Figure 9. Longitudinal section of PFC analysis showing daylight collapse after 5m excavation.

3.2 *Cross section analysis*

It is reported that most of overbreak is triggered at the shoulder of the unsupported span and extends to the crown (Shin & Lee 2001). This phenomenon could also be observed in the small-scale model tests. Very rarely the overbreak begins at the sidewalls. Basically, it is the same reason why overbreak always occurs at the unsupported span rather than at the face, even if stress concentration is higher at the face.

Overstressing induces the loosening of the ground at the sidewall, before overbreak occurs at the shoulder. However, the material at the sidewalls keeps in place because of kinematical conditions and this loosening triggers a change of the arching stresses (Fig 10). This change results in stress relief at the shoulder, which triggers the overbreak. Afterwards, the overbreak changes the arching stress again and it triggers stress relief again at the crown (Fig 11). In this way, overbreak occurs at the shoulder and propagates to the crown. If ground is weak enough or confining pressure is low, overbreak extends to the surface and results in a daylight collapse (Fig12).

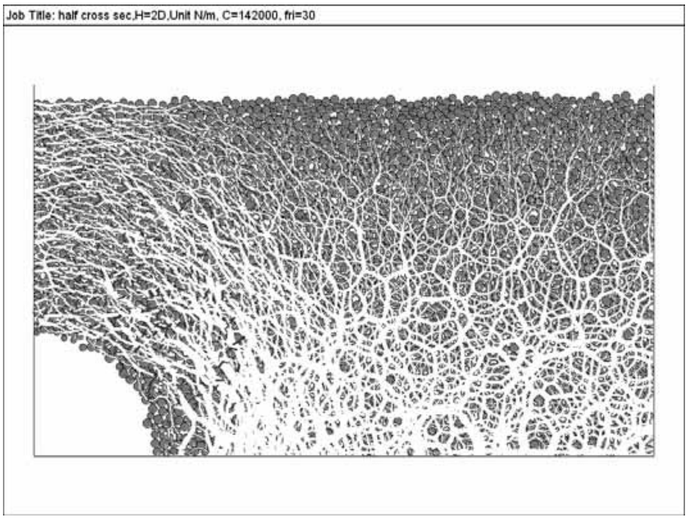

Figure 10. Cross section of PFC analysis showing stress relief at the sidewall with contact force chains.

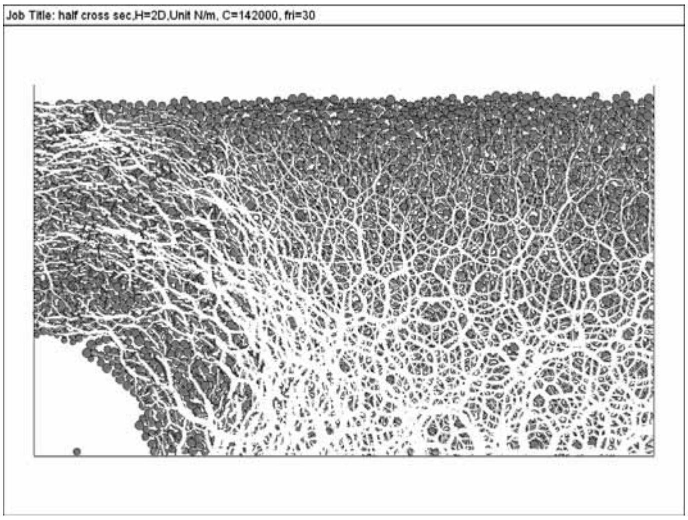

Figure 11. Cross section of PFC analysis showing the initiation of overbreak at shoulder with contact force chains.

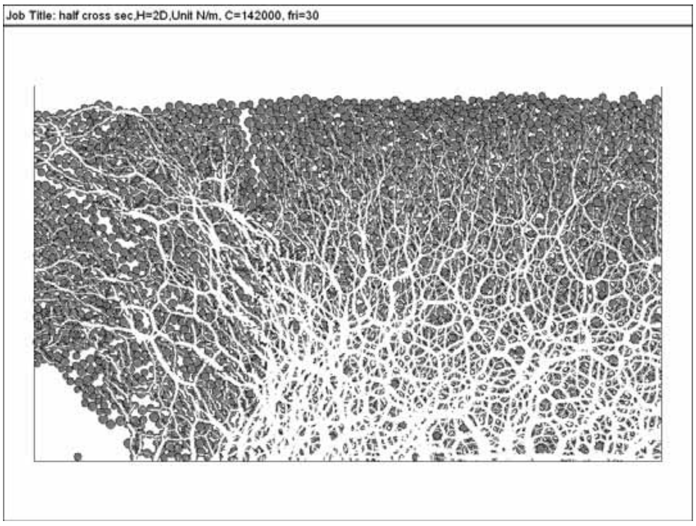

Figure 12. Cross section of PFC analysis showing the propagation of crack to crown from shoulder with contact force chains.

Researchers using FEM models obtained similar results but these do not cover the detailed procedure from the initiation of overbreak to the collapse because of the restriction of the method (Shin & Lee 2001, Vermeer et al 2002).

4 SUGGESTED FAILURE MODES

According to model tests and PFC analyses, 5 types of failure modes can be suggested for the decision of round length and support method. With decreasing cohesion the failure modes change. Those modes are described in chapters 4.1 to 4.5 for the same overburden and lining condition.

4.1 *No Overbreak with stable face*

In this case, an increase of the round length can be considered. However, the decision should be made carefully to avoid overstressing of the lining, excessive volume of overbreak and daylight collapse.

4.2 *Overbreak with stable face*

In this case, the optimization of the round length is essential for the excavation plan and safety. Overbreak starts at the shoulder of the tunnel and it propagates to the crown. However, it does not result in a daylight collapse and the face and sidewall are still stable during this failure. The increase of the round length leads to increase an of overbreak volume and construction costs, but also to a reduction of construction time. Therefore, the round length should optimized to achieve a minimum in the construction costs with an acceptable safety level. A safety margin should be maintained to avoid a daylight collapse.

4.3 *Daylight collapse with stable face*

In this case, excessive round length results in a daylight collapse. During the propagation of overbreak to the ground surface, the face could also partially collapse, depending on the support and ground conditions. The round length should be kept well below the critical value to avoid excessive stresses in the shotcrete lining.

4.4 *Overbreak with unstable face*

In this case, the unsupported face is not stable and collapses even without excavation, leading to a small scale overbreak. However, the overbreak does not propagate to the ground surface because of the ground strength. 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.

4.5 *Daylight collapse with unstable face*

In this case, the face is unstable and collapses before excavation is commenced and it leads to a daylight collapse. Cohesionless ground typically shows this failure mode and excavation is practically impossible without pre-support and face support such as pipe roof and face bolts.

5 CONCLUSIONS

According to the results of small-scale model tests and PFC analyses, it is clearly found that the overbreak in 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 daylight collapse.

The initiation of overbreak occurs at the shoulder of the unsupported span and extends to the crown. This initiation is governed by the ground condition, round length and initial stress, rather than the lining stiffness. However, the lining stiffness plays an important role when the failure propagates, eventually leading to a daylight collapse.

Stress acting on the lining is increased as the round length is increased. However, stress is relieved at the lining near to the face, if overbreak occurs in small scale so that arching stress is not significantly disturbed. During the development of daylight collapse, excessive ground loads act on the lining like a dead load because the ground arch fails. Therefore the stiffness of the lining is important for the safety of workers in case of a daylight collapse.

A large round length leads to failure when the overburden depth is not enough for the development of a natural arch above the overbreak. However, daylight collapse does not necessarily lead to the distortion of the lining in shallow tunnels because of low ground loads.

Regarding the determination of round length and support method, five failure modes are suggested, which should be considered for optimization of the construction. The round length should be decided to avoid overstressing of the lining and daylight collapse, and limit overbreak to acceptable limits. As the stiffness and strength of the lining plays a certain role in the propagation and extent of failure, also the advance rate should be optimized in case of shotcrete linings.

Various parametric studies and evaluations of case histories are planned to arrive at a kind of "rule" for the determination of the optimum round length for design and construction purposes.

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