Tunnel face stability in slurry shield tunnelling

La stabilité du front d'un tunnel percé par bouclier et bentonite

H.BALTHAUS, Philipp Holzmann AG, HN Düsseldorf, FRG

SYNOPSIS: For slurry shield tunnelling machines the stability of the tunnel face depends on the geometrical and soil conditions and the prevailing support pressure. This support pressure at the tunnel face has to be adjusted to a value that gives as well sufficient safety against a collapse of the tunnel face as against uplifting. In this paper a new method for the determination of the support pressure and the related safety level is discussed. It is compared to others and an example is used to illustrate its application in practice.

1 INTRODUCTION

Shield tunnelling with slurry-supported tunnel face has had an increasing importance during the last decade, particularly in near surface tunnelling below the water table in soft and granular soils. Supporting the tunnel face with clay-water or bentonite slurries in mechanical shield advances has a number of advantages compared to traditional compressed air support:

- no time for opening and closing air locks
- higher safety level
- better stability of the tunnel face due to affinity between supporting pressure and acting earth and water pressure
- additional support effect due to formation of a filter cake
- reduced hazard of blow-out due to lower pressure at the tunnel roof and lower permeability of the soil for the supporting slurry
- slurry can be used for muck removal

Tunnel face stability for slurry shield drives depends on the geometrical and geological boundary conditiones, the mechanical properties of the prevailing soils, the properties of the supporting slurry and the support pressure.

The slurry properties have to be adjusted to the grain size distribution and the chemical properties of the soil to be cut.

For the proper adjustment of the support pressure, stability computations have to be carried out for all relevant cross-sections along the tunnel line. A new method for the determination of the support pressure will be outlined in the following.

2 TUNNEL FACE STABILITY AND SUPPORT PRESSURE

2.1 Possible stability problems

Only little has been published about the practical problem of determining the tunnel face stability along a tunnel line. Following a systematic comparison of methods published to date a new method shall be introduced that is tailored to the needs of tunnelling practice.

A certain similarity exists between the stability problem of open slurry-filled diaphragm wall trenches and slurry supported tunnel faces. For diaphragm walls usually the following factors of safety have to be examined:

- safety against intrusion of groundwater
- safety against movement of single grains (local stability)
- safety against too low support pressure (global stability)
- safety against formation of slip surfaces (collapse of the tunnel face)

In West Germany, German standard DIN 4126 regulates the required calculations and safety levels.

For slurry support of tunnel faces additionally have to be examined:

- safety against heaving of the overburden (uplift)
- safety against blow-out failure

The first three factors of safety can be determined according to DIN 4126. The support pressure should be at least 1,05 times the water pressure. Local grain stability is governed mainly by the adjustable yield point of the supporting slurry.

The determination of safety against the formation of slip surfaces and against uplift require special methods that satisfy the particular boundary conditions of tunnelling.

The formation of blow-out channels depends not only on the level of support pressure but also on possible preferred seepage or air flow channels in the overburden. A generalised safety concept can therefore not be applied.

2.2 Safety against formation of slip surfaces

The factor of safety against formation of slip surfaces can be defined by

$$\eta = \frac{S - W}{E} \qquad (1)$$

Where S ist the supporting force, W the water pressure and E the earth pressure. DIN 4126 requires a factor of safety of η = 1,3 near structures. This factor of safety is suggested here for slurry shield drives as well.

2.3 Calculation models for the support pressure

Only few methods for the calculation of the required support pressure for slurry shield drives are documented in the literature (Broms et al. 1967, Atkinson et al. 1977, Davis et al. 1980, Krause et al. 1987). In a summarised and tabulated form the main characteristics of these methods are outlined and compared in Fig.2. Fig.1 explains the symbols used. It will be shown to which degree the different methods are able to take into account the stratification of soil, position of groundwater table, additional loads at or below the surface, depth of overburden above the tunnel roof, spatial earth pressure effects, and the soil strength parameters.

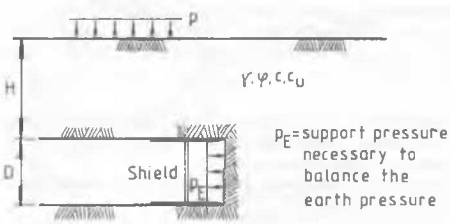


Figure 1. Explanation of symbols in Fig. 2

2.4 Practical methods for the determination of support pressure and factor of safety

2.4.1 General

A calculation model (suitable for application in tunnelling practice) should allow for the following features:

- friction angle φ' and cohesion c' as input parameters
- soil stratification
- surcharges as area and line loads
- groundwater level
- depth of overburden
- spatial earth pressure effects
- dependence of support pressure on tunnel depth
- level of safety depending on support pressure

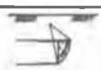
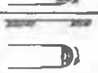
Advantageous is the possibility of accounting for arching effects above the tunnel roof (Terzaghi/Jelinek, 1954).

An additional safety check for risk of uplift (overburden heaving) should be possible. Thereby a threshold value can be established that forms an upper limit for the support pressure.

Fig. 3 shows how important it is to introduce the soil stratification into the calculation model. It is shown how an unstable layer can initiate a successive failure of the tunnel face. A method that allows for layered soil profiles and renders a safety profile over the tunnel height could have revealed the hazard.

2.4.2 Safety against collapse of the tunnel face

A method that satisfies the requirements outlined before can be derived from the numerical

Calculation method				characteristics					
description		source	formula	strati-fication sur-charge	internal friction φ	cohesion c (c_u)	spatial earth pres-sure	soil over-burden	ground water level
Log. Spiral		/6/	$p_E = f(\gamma, c, \varphi, p, H, D)$	−	+	+	−	+	+
upper and lower bounds		/2/	$p_E > \gamma(H+D/2)+p-Nc_u \quad N\approx 6$	−	−	+	+	+	−
		/3/	$\frac{\mu}{\mu^2-1}\gamma D < p_E < \frac{1/\tan\varphi+\varphi-\pi/2}{4\cos\varphi}\gamma D \Big/ \mu=\frac{1+\sin\varphi}{1-\sin\varphi}$	−	+	−	+	−	−
		/4/	$p_E = \gamma(H+D/2)+p-Nc_u \quad N=f(H/D)$	−	−	+	+	+	−
half circle ,2D		/5/	$p_E = (\gamma D/6-\pi c/2)/\tan\varphi$	−	+	+	−	−	−
quarter circle ,2D			$p_E = (\gamma D/3-\pi c/2)/(0{,}5+\tan\varphi)$	−	+	+	−	−	−
half sphere			$p_E = (\gamma D/9-\pi c/2)/\tan\varphi$	−	+	+	+	−	−
soil wedge with side friction		−	$p_E = f(\varphi, c, \gamma, p, H, D, \eta)$	+	+	+	+	+	+

/2/ Broms et al. 1967
/3/ Atkinson et al. 1977
/4/ Davis et al. 1980
/5/ Krause 1987
/6/ Murayama

Figure 2. Comparison of different methods for determination of slurry support pressures at the tunnel face

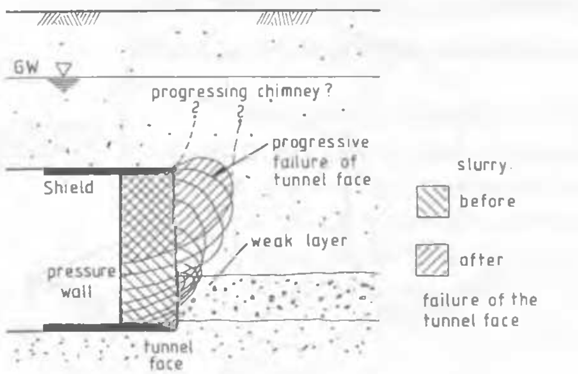


Figure 3. Process of tunnel face collapse due to a too weak layer

algorithm described by Walz and Pulsfort (1983) for the evaluation of open, slurry-filled diaphragm wall trenches.

Fig. 4 illustrates the main features of the method applied to a slurry shield tunnel. The tunnel cross-section is approximated by a conservative substitute rectangle. The tunnel face is regarded as an open slurry-filled trench and its stability is computed according to the above mentioned method. For that purpose a vertical pressure at the tunnel roof level is calculated that may take into account possible arching effects. Slurry pressure is defined by an assumed (fictitious) slurry level that lies above the tunnel roof.

The method now computes the stability (as a factor of safety) for different depths under variation of the angle of inclination for the slip surface of a sliding wedge. The computation renders a safety profile from tunnel roof to base and a lowest value for the factor of safety. The slurry level that correlates to the minimum required safety (e.g. η = 1,3) is found by an iterative computer procedure. This slurry level is related to the minimum support pressure at the tunnel cross-section under consideration.

2.4.3 Simplified methods

In practice less sophisticated methods are often used. Tho methods shall be mentioned here.

The first method calculates the support pressure at the tunnel roof as sum of the water pressure and the average horizontal active earth pressure between ground surface and tunnel base (Fig. 5).

The second method is based on an evaluation of results won by the more sophisticated soil wedge method described above and expressing the results in the form

$$p_S^F = u_F + k \ (\sigma_v' + p) \qquad (2)$$

k is an empirical earth pressure coefficient depending on soil layering and properties that is derived from the soil wedge method. k may only be applied for a limited tunnel length, where soil conditions do not change considerably. The vertical pressure σ_v' + p at tunnel roof level should be calculated using an arching reduction according to Terzaghi (1954).

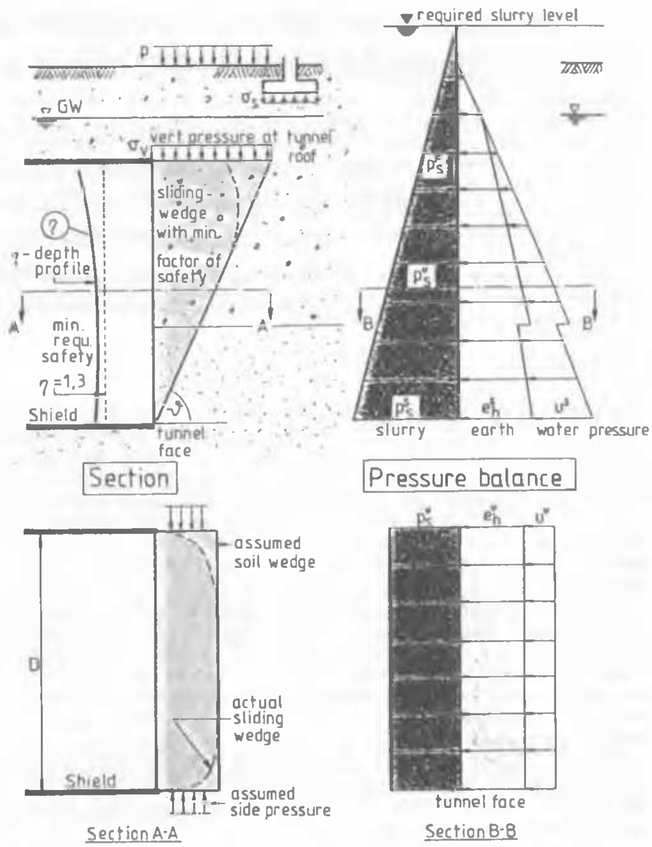
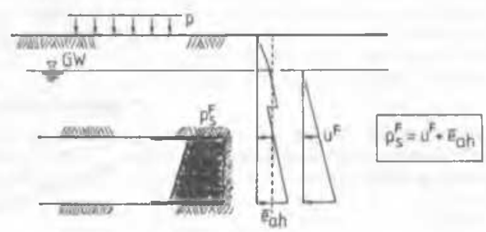


Figure 4. Calculation model for the safety against collapse of the tunnel face (soil wedge method)



$\bar{e}_{ah}$ = average active horizontal earth pressure between ground surface and tunnel base

Figure 5. Mean pressure method for support pressure determination

2.4.4 Safety against uplift of overburden

Increasing the support pressure leads to higher factors of safety against collapse of the tunnel face. However, too high support pressures increase the risk of blowout-failures and overburden uplift ahead of the tunnel face.

While the formation of blowouts mainly depends on possible preferred seepage channels, the factor of safety against uplift can be evaluated with a comparatively simple model.

For that purpose the force balance according to Fig. 6 at a soil obelisk is evaluated. Comparing the weight of the uplift soil body to the uplifting slurry force yields a safety definition (Fig. 6). α and B in the equations of Fig. 6 are constants independent of B.

Instead of looking at the factor of safety η which still contains the unknown length of action of the support pressure, at the tunnel roof, it is sufficient to take only the first term of the definition formula of η as a conservative safety definition ($\eta > \eta_1 > \eta_2$, Fig.6).

For very deep tunnels η_2 may be used as factor of safety.

The minimum factor of safety against uplift can be based on typical national requirements for safety against buoyancy.

2.5 Example

To determine the slurry support pressure and the span within which it may change without a risk for stability, for each charateristic point along a tunnel line the factors of safety against collapse of the tunnel face and uplift have to be determined. The depth of the tunnel, the soil layering and properties, the ground water level, and the surcharges influence the results.

If the slurry levels that belong to certain prescribed factors of safety against collapse of the tunnel face and uplift of overburden are plotted along the tunnel line, a safety profile results that may be used to define an optimum support pressure that lies between the upper and lower safety line.

Fig. 7 demonstrates the effect of overburden, surface surcharge, and groundwater level on the optimum slurry level. Vertical stress has the most dominant influence.

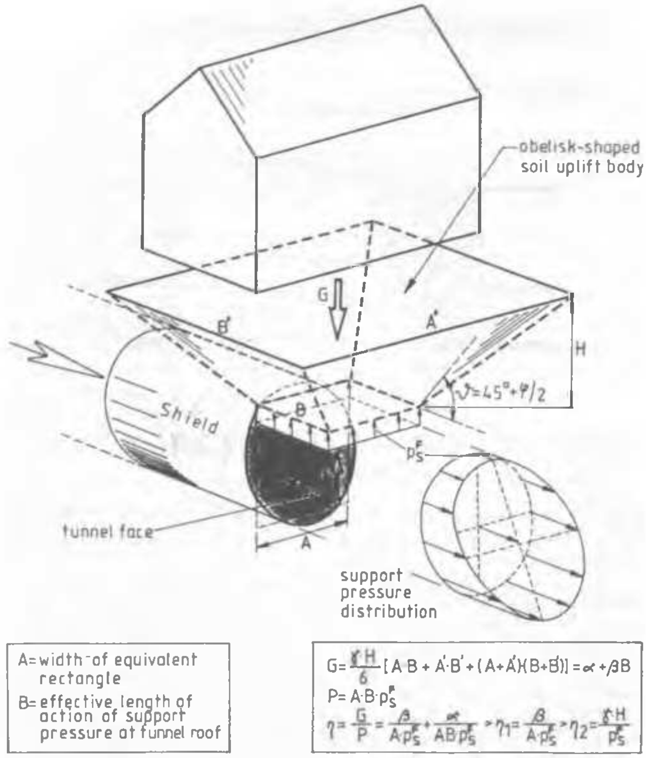


Figure 6. Calculation model für the safety against uplift of overburden

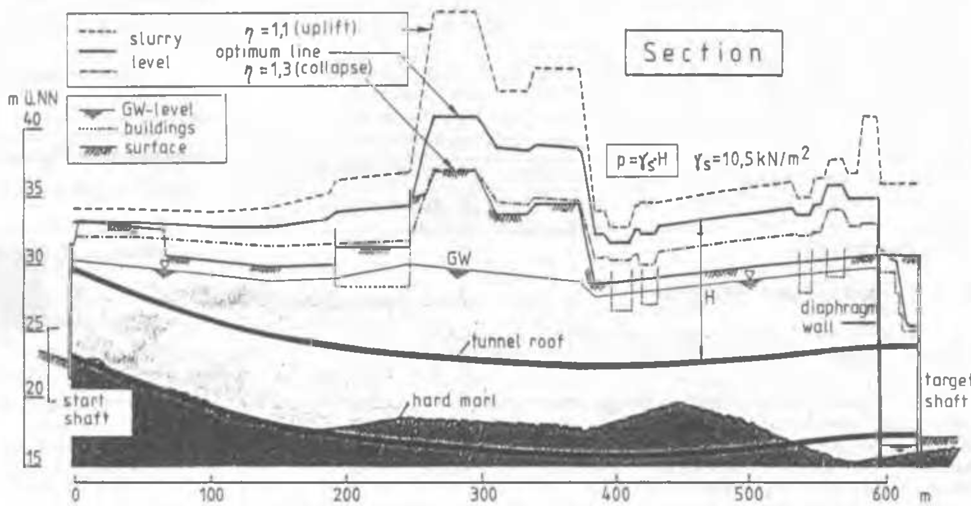


Figure 7. Support pressure and safety margins as slurry levels along a tunnel line (Mayer, 1987)

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