Tunnel Stability Factor – A new controlling parameter for the face stability conditions of shallow tunnels in weak rock environment

Facteur de stabilité de tunnel : Une paramètre nouveau qui contrôle les conditions de stabilité des fronts d' excavation pour les tunnels peu profonds dans un environment des roches tendres.

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ABSTRACT

The present paper justifies, on the basis of a significant number of parametric analyses, the use of Tunnel Stability Factor (TSF) in the preliminary assessment of tunnel's face stability conditions for low overburden heights in weak rocks.

The Tunnel Stability Factor is determined mathematically according to the following relationship:

$TSF=\sigma_{cm} / \gamma H^a D^{1-a}$

where : σ_{cm} & γ is the strength and the specific unit weight of the in-situ rockmass surrounding the tunnel,

$\sigma_{cm}=2c/\tan(45^0+\varphi/2)$, c is the cohesion and φ the angle of internal friction of the rockmass, respectively

H is the height of overburden soil

D is the equivalent diameter of the underground opening

The execution of all parametric analyses has been based on the use of 3-D wedge limit equilibrium model. The examined tunnel cases included circular tunnel cross – sections with diameter D=4m – 10m and overburden heights H=10m – 20m. The weak rock conditions were characterized by the following shear strength parameters: c=5KPa -20KPa, $\varphi=25^0$- 30^0. Groundwater conditions have been also included in the parametric analyses as an independent variable.

RÉSUMÉ

La présente communication, basée sur un nombre important d'analyses paramétriques, justifie l'emploi d'un Facteur de Stabilité du Tunnel (TSF) pour la détermination préliminaire des conditions de stabilité du front d'excavation, dans un environment des roches tendres de petit recouvrement. Le Facteur de Stabilité du Tunnel est défini mathématiquement selon la formule :

$TSF = \sigma_{cm}/ \gamma H^a D^{1-a}$

avec σ_{cm} et γ: La portance et le poids volumique de la masse rocheuse autour du tunnel

$\sigma_{cm} = 2c/\tan (45°+\varphi/2)$, c étant la cohesion et φ l' angle de frottement interne de la masse rocheuse

H : l' hauteur du sol de recouvrement

D : le diamètre équivalent d'excavation

Toutes les analyses paramétriques ont été basées sur l'utilisation d'un modèle eu dièdre tridimensionnel en équilibre limite. Les cas des tunnels examinés concernent des sections circulaires avec diamètre D=4m-10m et hauteur de recouvrement H=10m-20m.

Les conditions des roches tendres ont été caractérisées par les paramètres de cisaillement suivants : c=5 KPa-20KPa, φ=25°-30°.

La présence de la nape souterraine a été aussi prise en compte dans les analyses paramétriques comme une variable indépendante.

Keywords : tunnel, face stability, support pressure, weak rocks, tunnel stability factor

1 INTRODUCTION

During the excavation works for the construction of shallow tunnels in weak rocks, instability phenomena on the area of the tunnel face are often observed. In these cases, the favourable arch effect either does not take place due to geometrical constraints or its temporary duration is so small that does not contribute to the stability of the tunnel face.

This potential instability dictates the necessity for application of adequate support pressure on the tunnel face, active in the case of use of TBM or passive (for instance with fibre glass nails) in the case of NATM.

Absence of this necessary support pressure may result in excessive face extrusion. This may initiate the potential for partial or total failure of the tunnel face with the form of the chimney failure and in some case a crater, that reaches the ground surface introducing adverse effects on the structures located in the area.

The causes that lead to a potential instability and failure of the tunnel face are associated with the geometrical characteristics of the tunnel cross-section, the strength and deformability characteristics of the rockmass surrounding the tunnel, the in situ stress state in the area of excavation as well as the presence of underground water table above the tunnel crown.

2 FACE STABILITY

2.1 *Limit equilibrium model with side friction*

The face stability in homogenous soil can be assessed by considering the simple collapse mechanism presented in figure 1. This 3-D model, which was originally proposed by (Horn 1961), is based on the Silo theory from (Janssen 1895).

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The circular cross section of the tunnel is approached by a square with side length the diameter D of the tunnel. The collapse mechanism comprises a wedge and a prism that extends from the tunnel crown to the ground surface. The soil/rockmass is considered to behave as elastic- perfectly plastic material according to the Mohr-Coulomb failure criterion, with shear strength characteristics the cohesion c and the angle of internal friction φ. Hence, at every point along the slide surfaces, the shear strength is given by the following expression (1):

$$\tau = \frac{c}{F} + \sigma \frac{\tan\phi}{F} \tag{1}$$

where σ and F are the normal stress and the safety factor, respectively.

The wedge of the collapse mechanism is subjected to the following actions: (a) the self weight, (b) the resulting normal and shear forces along the failure surfaces ADE, BCF and ABFE, (c) the support force applied on the tunnel face and (d) the vertical force due to the weight of the overlying prism in the interface DEFC.

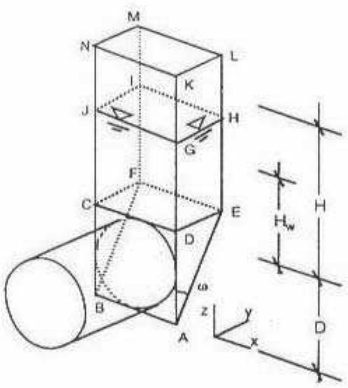

Figure 1 Collapse mechanism (after Horn, 1961)

The support pressure for a given failure mechanism characterised by a specific slope ω of the slide surface ABFE is derived through the solution of the limit equilibrium equations for the wedge. The critical slope ω_{cr} is determined through an iterative procedure until the maximisation of the necessary support pressure for a given safety factor or until the minimisation of the safety factor for a given support pressure.

In case of presence of underground water table above the tunnel crown, all the calculations are performed on the basis of effective stresses while it is considered that the distribution of the water pressures along the slide surfaces has a hydrostatic pattern.

The shear stresses depend essentially on the horizontal stresses that act perpendicular to the vertical slide surfaces. However, the horizontal stresses can not be determined without consideration of the deformability characteristics of the ground. Following the silo theory of (Janssen 1895), a constant coefficient λ of the horizontal to the vertical stresses is adopted. (Terzaghi and Jelinek 1954) suggested the use of λ=1. In the present work, the value λ=0,8 was adopted based on the experiments conducted by (Gudehus and Melix 1986) and (Melix 1987).

The vertical force on the interface CDEF is determined through the application of the silo theory of Janssen first on the part of the prism above the ground water table and then on the remaining part between the ground water level and the tunnel crown, in order to take into account the different specific unit weights of the soil above and below the ground water table.

The mean effective vertical stress σ' on the surface CDEF is given by the following expression (2):

$$\sigma_v = \frac{\gamma' r - c}{\lambda \tan\phi}\left(1 - e^{-\lambda \tan\phi Hw/r}\right) + \frac{\gamma d r - c}{\lambda \tan\phi}\left(e^{-\lambda \tan\phi Hw/r} - e^{-\lambda \tan\phi H/r}\right) \tag{2}$$

where H, Hw, γd and γ' are the height of the overburden soil, the height of the ground water table above the tunnel crown (see figure 1), the dry unit weight and the effective unit weight under buoyancy of the soil, respectively. The parameter r denotes the ratio of the volume to the periphery of the prism and is defined as:

$$r = 0{,}5D \tan\omega / (1 + \tan\omega) \tag{3}$$

Equation (2) is valid for safety factor F equal to 1. Other values of the safety factor may be considered by replacing the cohesion c and tanφ through c/F and tanφ/F, respectively as shown in equation (1).

Regarding the distribution of stresses σ on the slide surfaces ADE and BCF of the wedge the linear approach suggested in (DIN 4126 1986) is adopted, as depicted in figure 2. Consequently, the vertical stress σ_z increases linearly with depth due to the weight of the soil, while the contribution of the interface stress σ_v decreases.

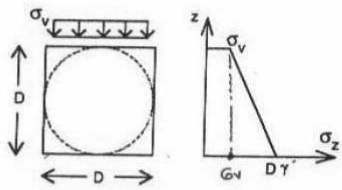

Figure 2 Distribution of vertical stresses on the slide surfaces of the wedge

Hence, the mean friction resistance τ_φ is calculated through the integration of the term $\lambda\sigma_z\tan\varphi$ on the slide surfaces ADE and BCF:

$$\tau_\phi = \lambda\left(\frac{1}{3}\gamma' D + \frac{2}{3}\sigma v\right)\frac{\tan\phi}{F} \tag{4}$$

(Anagnostou and Kovari 1994) performed numerical analysis in order to examine and verify the accuracy of the approach presented in figure 2. In these analysis, the equilibrium of the wedge was analysed according to the silo theory and the wedge was divided in horizontal slices. The analysis showed that the approach proposed in DIN 4126 overestimates the vertical stress σ_z and hence the shear resistance. However, the uncertainties associated with the linear approach of figure 2 can be eliminated by choosing a lower value of λ in equation (4). In the present work, the value λ=0,4 was adopted, namely half of the value that was adopted for the part above the tunnel.

3 TUNNEL STABILITY FACTOR

As it has already been mentioned, the general stability of the tunnel face depends on the in situ strength of the soil/rockmass surrounding the tunnel, the geometrical characteristics and the excavation depth of the tunnel.

(Mihalis et al. 2001) have proposed the use of the Tunnel Stability Factor (TSF) for the assessment of the behaviour of underground openings in weak rock conditions, which combines all the above influence factors and can be considered as an important parameter for the initial assessment of the overall behaviour of tunnel cross sections.

The Tunnel Stability Factor (TSF) is defined through the following mathematical expression:

$$TSF = \frac{\sigma_{cm}}{\gamma H^{a} D^{1-a}} \tag{5}$$

where:

σcm & γ are the strength and the specific unit weight of the in-situ rockmass surrounding the tunnel, respectively

$\sigma cm = 2c/\tan(45^0+\varphi/2)$ with c the cohesion and φ the angle of internal friction of the rockmass, respectively

H is the height of overburden soil and

D is the equivalent diameter of the underground opening

The exponent a is a parameter that depends on the type of tunnel behaviour assessment under consideration, such as assessment of tunnel stability in relation to radial convergence and potential squeezing problems, assessment of tunnel face stability etc.

4 PARAMETRIC ANALYSIS

4.1 *Variable parameters*

In the framework of the parametric analysis of the present work, the following case combinations where examined:

- Circular cross section with diameters D=4, 6, 8 and 10m
- Overburden height H=10, 12.5, 15, 17.5 and 20m
- Weak rock with cohesion c=5, 10, 15 and 20 KPa and angle of internal friction $\varphi=25^o$ and 30^o
- Height of ground water column H_w=H/2, H/4 and 0m.

4.2 *Safety factor considerations*

In the parametric analysis, the support pressure P that must be applied on the tunnel face of a shallow tunnel for the achievement of a given factor of safety was determined. Support pressures P were calculated for safety factors of SF=1, 1.1, 1.2, 1.3 and 1.4.

It was considered that when the support pressure is such that a safety factor of 1 and 1.1 can be achieved, the face has a high failure probability, also due to the various inherent uncertainties associated with the estimation of the geomechanical properties of the surrounding rockmass and the simplifying assumptions adopted in the failure model. When the applied support pressure on the face results in safety factors of 1.2 and 1.3, it can be considered that the face is temporarily safe, under the geotechnical notion of the term. When the safety factor is in the order of 1.4, it can be considered that the support pressure applied on the tunnel face is sufficient to achieve permanent stability. The terms temporary and permanent stability are more appropriate for the case where the tunnel is conventionally excavated and the face support takes place for instance with the use of fibreglass anchors. When the tunnel is excavated with a TBM these terms denote in a way the escalation of the safety factor, except for the case of interventions.

5 RESULTS

5.1 *Definition of TSF*

According to the results of the parametric analysis, the analytical form of the Tunnel Stability Factor was defined as:

$$TSF = \frac{\sigma_{cm}}{\gamma H^{0,35} D^{0,65}} \tag{6}$$

(Mihalis et al. 2001) have proposed the value 0,75 for the exponent a, for the case where the TSF is used for the assessment of tunnel stability in weak rocks in relation to the radial convergence of the tunnel walls, the evolution of plastic zone around the excavation and the potential for evolution of squeezing problems. In this case, the relative contribution of the overburden height H is higher in comparison to the tunnel diameter, since the potential for evolution of squeezing problems is in direct conjunction with the ratio of the in situ strength of the rockmass to the overburden pressure (Hoek 1999).

On the other hand, in the assessment of tunnel face stability in weak rock with low overburden height, where the evolution and activation of the arch effect is questionable, the predominant contribution comes from the tunnel diameter, namely the area where the tunnel face extrusion shall evolve. The bigger the diameter of the tunnel, the higher the radial pre-convergence and axial face extrusion and higher the potential for evolution of failure mechanisms on the face.

5.2 *Support pressure on the tunnel face*

For each safety factor, a diagram was produced (see diagrams 3 to 7) that correlates the dimensionless parameters P/c and TSF for various values of the groundwater table level Hw. In addition, the associated mathematical expressions with the highest correlation of the results of the parametric analysis were derived.

5.2.1 *Dimensionless diagrams*

(1) Safety factor 1.0

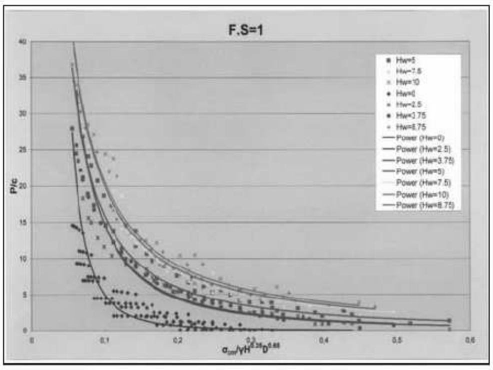

Figure 3 Support pressure on the tunnel face for limit equilibrium

(2) Safety factor 1.1

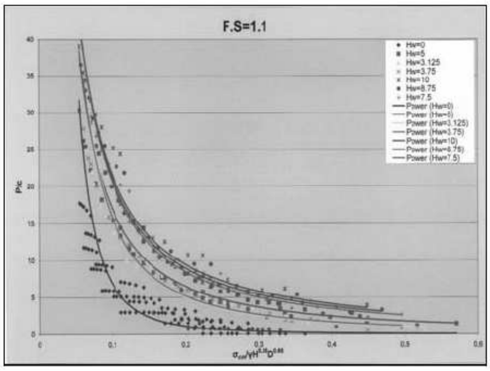

Figure 4 Support pressure on the tunnel face for safety factor 1.1

(3) Safety factor 1.2

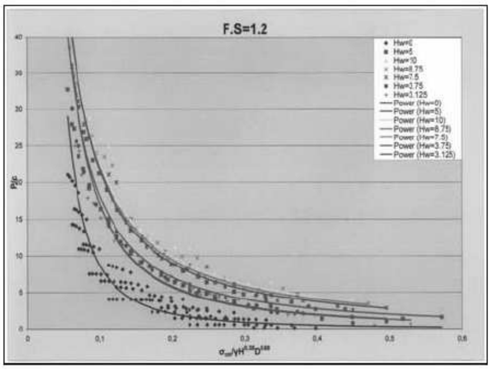

Figure 5 Support pressure on the tunnel face for safety factor 1.2

(4) Safety factor 1.3

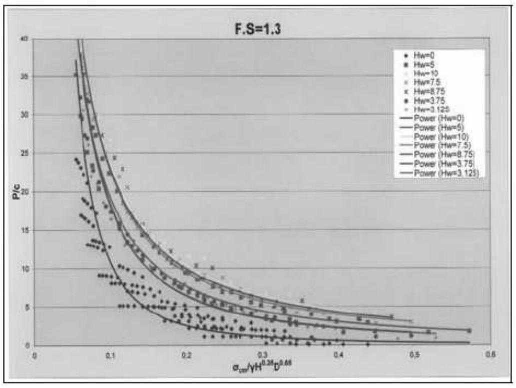

Figure 6 Support pressure on the tunnel face for safety factor 1.3

(5) Safety factor 1.4

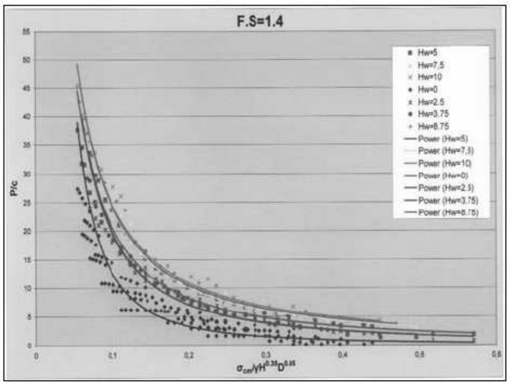

Figure 7 Support pressure on the tunnel face for safety factor 1.4

5.2.2 *Mathematical expressions*

All the above trend lines can be summarised in the following mathematical expression, with the values of A and B given in table 1:

$$P/c = A(TSF)^{-B} \tag{7}$$

Table 1 Values of A and B for mathematical expression (7)

	SF=1	SF=1.1	SF=1.2	SF=1.3	SF=1.4
A- Hw=0	0,0058	0,0161	0,0724	0,0846	0,1456
A- Hw≠0	a)	c)	e)	g)	i)
B- Hw=0	2,9344	2,6322	2,0797	2,1108	1,9394
B- Hw≠0	b)	d)	f)	h)	j)

a) $0,1502H_w-0,1583$, b) $2,3536\ H_w^{-0,2956}$
c) $0,1587H_w-0,1625$, d) $2,3978\ H_w^{-0,3068}$
e) $0,1525H_w-0,0347$, f) $2,148\ H_w^{-0,257}$
g) $0,1494H_w+0,0726$, h) $2,0275\ H_w^{-0,2328}$
i) $0,1465H_w+0,1844$, j) $1,9025\ H_w^{-0,2056}$

6 CONCLUSIONS

On the basis of the results taken from the performed parametrical analyses, a number of practical design charts with the associated mathematical expressions have been produced. These charts essentially provide an assessment of the support pressure P that needs to be applied on the tunnel face for the assurance of stability conditions (characterised by a certain value of safety factor) in conjunction to TSF values.

It is noted that, although the wide range of all the examined cases (in terms of ground, groundwater and tunnelling conditions), the aforesaid design charts provide a well determined trend of behaviour, due to the small degree of scattering of the calculation results. As a consequence of this, all the presented in this paper design charts and mathematical expressions could be safely used for preliminary design purposes, by providing the necessary face support measures of shallow tunnels in weak rock conditions.

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