11th ISRM Congress, The Second Half-Century of Rock Mechanics, July 9 – 13, 2007, Lisbon, Portugal

Design and analysis of yielding support in squeezing ground

G. Anagnostou & L. Cantieni
ETH Zurich, Switzerland

ABSTRACT: The only feasible method for dealing with extremely squeezing ground is providing sufficient space for accomodating rock deformations and installing a so-called yielding support, i.e. a support which can deform considerably without damage. This paper provides a critical overview of the flexible support systems proposed and applied in the past, and presents design nomograms for estimating the amount of convergence required in order to reduce rock load to a technically manageable level.

1 INTRODUCTION

The term "squeezing" refers to the phenomenon of large long-term rock deformations triggered by tunnel excavation. Squeezing may lead to the destruction of a temporary lining or even to a complete closure of the tunnel cross section. Two basic concepts exist for dealing with squeezing conditions (Kovári 1998). According to the so-called "resistance principle", a practically rigid lining is adopted, which is dimensioned for the expected rock pressure. In the case of high rock pressures this solution is not feasible. The so-called "yielding principle" is based upon the observation that rock pressure decreases with increasing deformation. By installing a flexible lining, rock pressure is reduced to a value that is structurally manageable. An adequate overprofile and suitable detailing of the temporary lining will permit the non-damaging occurrence of rock deformations, thereby maintaining the desired clearance from the minimum line of excavation. The rock load reducing effect of flexible supports, as well as various technical solutions, have been known - at least in principle - since the first decades of the 20th century (Fig. 1). Major progress was made in 1932 with the introduction of sliding connections by Toussaint-Heintzmann.

Typical design issues concern the feasibility of a rigid support in a given geotechnical situation (rock strength and deformability, depth of cover and magnitude of pore pressure), the amount of deformation required in order to reduce rock load to a technically manageable level and the structural detailing of a flexible support. The present paper addresses these questions by outlining and discussing the yielding support systems proposed and applied in the past (Section 2), and by presenting design nomograms for estimating the amount of deformation required to reduce loading (Section 3).

2 TYPOLOGY OF FLEXIBLE TUNNEL SUPPORTS

There are basically two technical options for accommodating deformation without damage to the lining (Fig. 2): (a) Arranging a compressible layer between the extrados of a stiff lining and the excavation boundary; (b) Installation of a yielding lining in contact with the rock face. In the first case, the rock may experience considerable convergence, while the clearance profile remains practically constant as the lining's stiffness limits deformations. Such a solution is therefore advantageous particularly in cases with slow and prolonged deformations during the service period of a tunnel. It is a standard solution for the final support of tunnels crossing highly swelling rock (Kovári et al 1988).

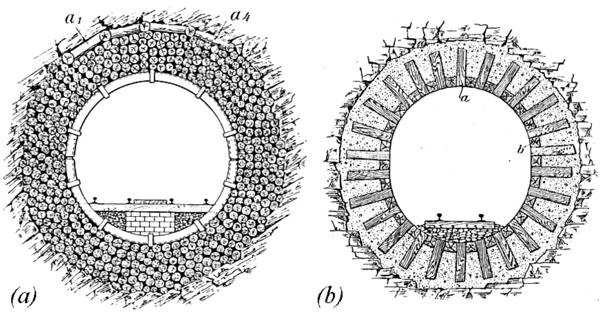

Figure 1. (a) Layer of wood between rock and U section steel sets; (b) Concrete with wood interlayers (from Heise & Herbst 1913).

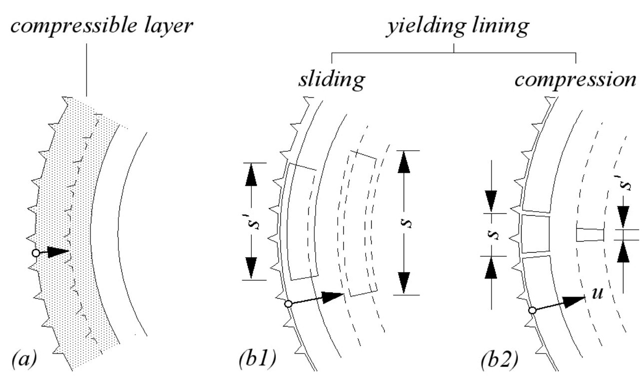

Figure 2. Basic types of flexible support.

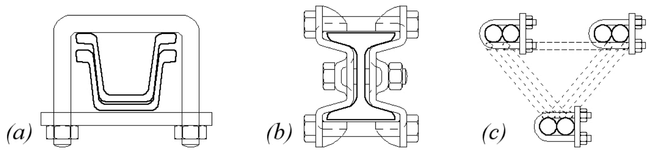

Figure 3. Sliding connections of (a) top hat section steel sets and (b) H section steel sets (from Fröhlich 1948); (c) lattice girders.

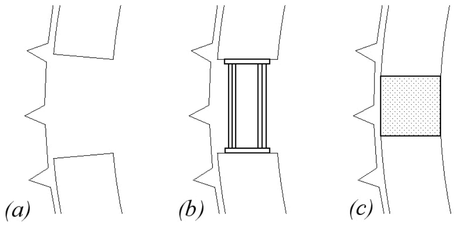

Figure 4. Shotcrete shell with (a) open slots, (b) steel cylinders (Schubert 1996), (c) ductile concrete elements (Thut et al. 2006).

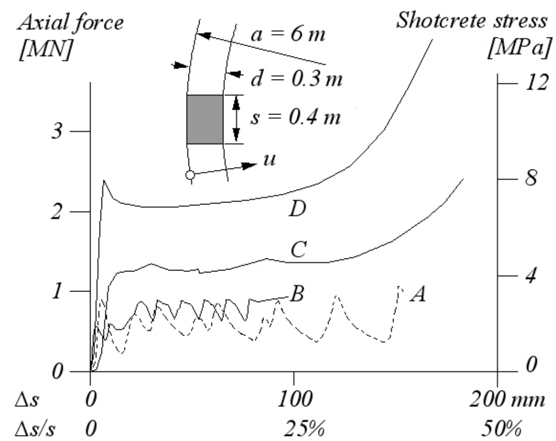

Figure 5. Load-deformation behaviour of compressible elements. Curves A and B: steel cylinders (4 elements per linear meter) after Schubert et al. (1996, 1999), respectively. Curves C and D: ductile concrete elements after Thut et al. (2006).

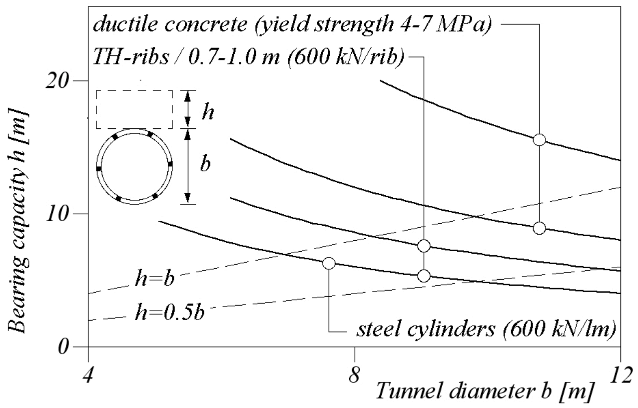

Figure 6. Bearing capacity of yielding support (solid lines) and height of loosening zone (dashed lines) as a function of tunnel diameter *b*.

In the second solution, the lining deforms with the rock and, consequently, its circumference shortens. This is possible by an appropriate structural detailing involving either steel sets with sliding connections (Fig. 2-b1) or deformable elements inserted into slots left between stiff lining segments (Fig. 2-b2). Thrust transfer occurs via friction in the first case and via compression in the second. The axial force in the lining is controlled by the frictional resistance of the connectors or by the yielding stress of the deformable elements, respectively.

The basic design parameters of a yielding support are the deformability Δs ($=s-s'$ in Fig. 2), the number n and the yielding load N of the flexible joints. The first two parameters are selected on the basis of the radial convergence u that must occur in order to reduce loading (for a circular tunnel cross section, $n.\Delta s=2\pi u$).

Depending on the strength and the structure of the rock mass, block detachment or loosening of an extended zone above the crown may occur - particularly when considering the larger deformations taking place with a yielding support. The yield load N of the joints must, therefore, fulfil two criteria: it must be, (i), lower than the design load of the lining segments or of the steel ribs but, (ii), higher than the resistance needed for safety against loosening. If the resistance of the flexible joints is not high enough, the support starts to yield under the weight of the rock. A low yield load (e.g., 50 kPa as indicated by Hoek et al. 2006) does not ensure safety against loosening, while solutions leaving the tunnel completely unsupported for a period of time (as proposed by Kolymbas 2003) should be obviously avoided.

Steel sets applied in squeezing ground have usually a top hat cross section and are connected by friction loops (Fig. 3a) offering a sliding resistance of up to 600 kN/set (4 loops x 150 kN) utilizing thus the high bearing capacity of TH-ribs (for a recent successful application of TH-ribs in a large cross section railway tunnel with up to 10% convergence see Kovári et al. 2006). Occasionally, H cross section ribs (Fig. 3b) are also used (cf. Sánchez Fernández et al. 1994, Wittke et al. 2005). Lattice girders with sliding overlapping bars (Fig. 3c) have even been proposed (Hindley et al. 2004) although their contribution to the support resistance is negligible (very low buckling load of the bars).

Various support layouts in past underground mining works incorporated wood extensively as a compressible element. Lenk (1931) reported about early applications in connection with prefabricated concrete elements. Recent, mainly experimental, attempts to increase the flexibility of precast segmental linings utilize neoprene elements (Croci 1986) or hydraulic devices (Tusch & Thompson 1996) which are arranged in the longitudinal joints. Particularly interesting from a mechanics point of view is the system described by Baumann & Zischinski (1994) as it can accommodate axial deformations of up to 30 cm under a very high yielding load of 3 MN – this nevertheless at a prohibitively high cost (expensive deformable jacks, time-consuming installation of the segments, heavy reinforcement due to shear forces).

A shell made of shotcrete can, due to the brittleness of the material, accommodate only small deformations without damage (maximum 1-2% convergence). Leaving longitudinal slots open in a shotcrete shell (Fig. 4a) was a method used for dealing with high rock pressures in conventionally driven alpine tunnels in the 1970s (see, e.g.,

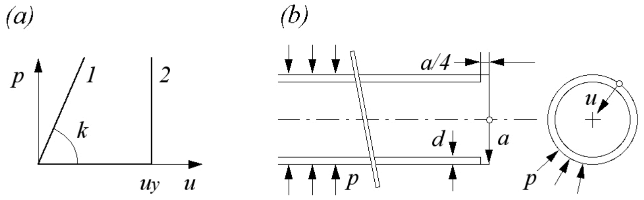

Figure 7. (a) Characteristic lines of support; (b) Problem layout.

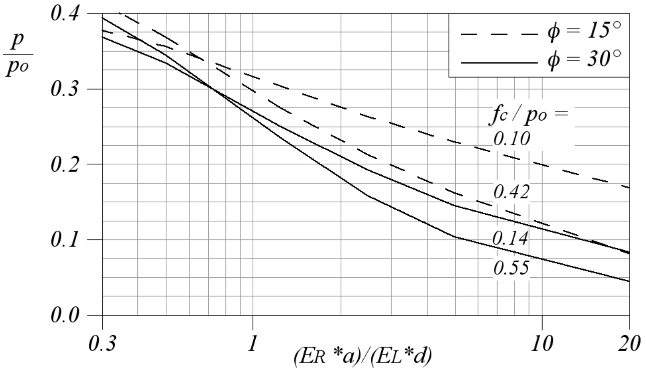

Figure 8. Pressure p (normalized by the intial stress p_o) acting upon a stiff support as a function of the stiffness ratio $E_R a/E_L d$, where E_R and E_L denote the Young's modulus of the rock mass and of the lining, respectively, a is the tunnel radius and d the lining thickness. The symbols ϕ and f_c denote the friction angle and the uniaxial compressive strength of the rock mass. The Poisson's number ν and the angle of plastic dilatancy ψ were taken equal to $\nu = 0.30$ and $\psi = \phi - 20°$ (or 0 for $\phi < 20°$).

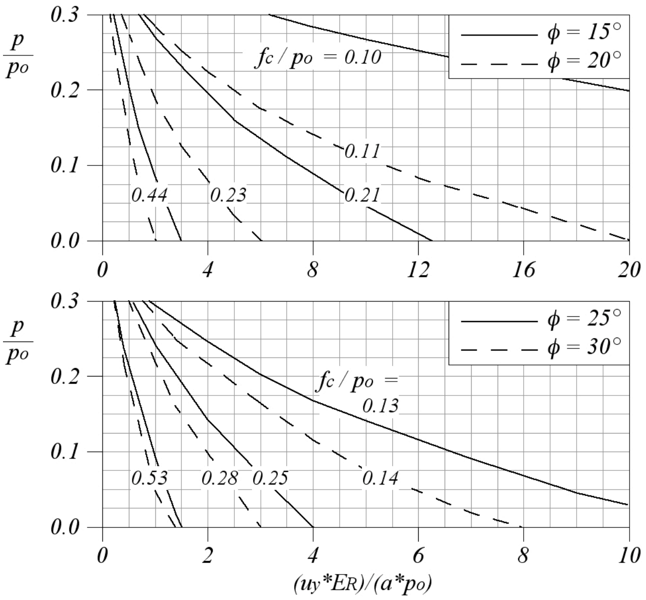

Figure 9. Pressure p (normalized by the intial stress p_o) acting upon a rigid support as a function of the normalized convergence u_y occurred during the preceding deformation stage (see Fig. 8 for the other parameters and notation).

Pöchhacker 1975). In this case, the high compressive strength of the shotcrete is not utilized, and its statical function degenerates to that of large anchor plates (Schubert 1996). Safety relies then solely upon bolting. A large quantity of long bolts may be needed in order to control rock deformation and for safety against loosening. Deformable rock bolts with an extremely low yielding load (70 kN, Wittke et al. 2005) are in this respect unsuitable as they do not offer sufficient safety against loosening.

Compressible elements incorporated into the slots of the shell increase safety by utilizing the shotcrete during the deformation stage. For this purpose, so-called "lining stress controllers" have been developed, and were applied first in the Galgenberg Tunnel (Schubert 1996). They consist of steel cylinders which are loaded in the axial direction (Fig. 4b), and which buckle in stages and shorten up to 200 mm at a load of 150 - 250 kN, thereby limiting the stress in the shotcrete shell (curve A in Fig. 5 refers to 4 elements/lm). An improved element with three co-axial cylinders (Schubert et al. 1999), similar to another device developed in the same period for yieldable anchors (de Souza 1998), reduced the force oscillations caused by uncontrollable and asymmetric buckling (Fig. 5, curve B). The cylindrical elements exert a concentrated pressure to the lining segments (Budil et al. 2004). Overstressing of the shotcrete can be avoided by appropriate, but costly and demanding, structural detailing.

Further progress in this field has been made recently with the introduction of compressible elements composed by a mixture of cement, steel fibres and hollow glass particles (Kovári 2005). The glass particles, which increase the void-fraction of the mixture, collapse at a pre-determined compressive stress, thereby providing the desired deformability. The elements yield up to 50% in a ductile manner, while the yield strength depends on the composition of the mixture and can be adapted to specific project conditions (Fig. 5, curves C and D). These elements have recently been applied in the Lötschberg Basetunnel and in the St. Martin la Porte site access tunnel of the Lyon Turin Ferroviaire (Thut et al. 2006). Easy handling and installation, complete incorporation into the shotcrete shell, uniform load transfer to the shotcrete segments and almost perfectly-plastic behaviour at high compressive stress are their advantages.

Figure 6 shows the bearing capacity of yielding supports (expressed by the rock column height h) as a function of the tunnel diameter b ($h=2N/b\gamma$, where N denotes the yielding load of the deformable elements and $\gamma = 25 kN/m^3$ is the unit weight of rock). With increasing tunnel diameter, the yielding support resistance decreases while the probable size of the loosening zone increases. High strength yieldable elements offer considerable safety-gains, particularly for large tunnel cross sections.

3 DESIGN NOMOGRAMS

The design of yielding support is based upon estimates of the amount of deformation needed in order to reduce rock load. The respective calculations usually assume plane strain conditions. The latter underestimate deformations as they do not consider correctly the stress-path dependence of the mechanical behaviour of the ground (Cantieni &

Anagnostou 2007). Furthermore, plane strain analyses necessitate additional assumptions concerning the deformations of the ground ahead of the tunnel face. Three-dimensional simulations do not have these disadvantages as they take into account the spatial stress re-distribution around the tunnel face. Step-by-step numerical modeling of tunnel excavation is very costly, however, and is carried out only for specific projects.

Using a numerically efficient technique which solves the advancing head problem in just one computational step, thereby making comprehensive parametric studies possible (Anagnostou 2007), design nomograms for yielding support have been derived. The calculations have been carried out assuming axisymmetric conditions (Fig. 7b, cylindrical tunnel, uniform and hydrostatic initial stress field) and a homogeneous ground with isotropic, linearly-elastic and non-associated perfectly-plastic behaviour obeying Coulomb's yield criterion.

Both stiff and yielding supports have been considered. In the first case (resistance principle, Fig. 7a, line 1) the lining deforms more or less in relation to stiffness k ($k=E_L d/a^2$, where E_L and d denote the Young's modulus and the thickness of the lining, respectively, and a is the tunnel radius). In the second case (yielding principle, Fig. 7a, line 2) the lining deforms under stress-free conditions up to a radial convergence u_y and is rigid afterwards (for simplicity, the yield load of the compressible elements or sliding connections was neglected in the rock-support interaction). Lining stiffness k (the resistance principle) or deformation u_y (the yielding principle), respectively, govern the rock pressure p. Figs. 8 and 9 show the numerical results in dimensionless form (cf. Anagnostou & Kovári 1993).

Fig. 8 can be used in order to assess the feasibility of a lining according to the resistance principle as it shows the load p (normalized by the initial stress p_o) developing on a stiff (but not rigid) support without yielding or sliding elements. Fig. 9 serves for the estimation of the convergence u_y that must occur during the deformation stage of a yielding support in order that the rock pressure decreases to a pre-determined, technically manageable load value p.

The nomograms are useful for making quick assessments of the conditions prevailing in a specific project, thereby assisting the Engineer in the decision-making process.

REFERENCES

Anagnostou, G. & K. Kovári 1993. Significant parameters in elasto-plastic analysis of underground openings. *ASCE, Journal of Geotechnical Engineering*, 119 (3), 401-419.

Anagnostou, G. 2007 (in press). Continuous tunnel excavation in a poro-elastoplastic medium. In Pande & Pietruszczak (eds.), *Tenth Int. Symp. on Numerical Models in Geomechanics (NUMOG X),* April 25 - 27, 2007, Rhodes, Greece.

Baumann, L. & U. Zischinski 1994. Neue Löse- und Ausbautechniken zur maschinellen "Fertigung" von Tunneln in druckhaftem Fels. *Felsbau,* 12 (Nr. 1), 25-29.

Budil, A., Höllrigl, M. & K. Brötz 2004. Strenger Tunnel – Gebirgsdruck und Ausbau. *Felsbau,* 22 (Nr. 1), 39-43.

Cantieni, L. & G. Anagnostou 2007. On the adequateness of the plane strain assumption in tunneling analyses. *11th Congr. of the Int. Soc. for Rock Mech.*, Lisbon, Portugal.

Croci, G. 1986. Progettazione, Costruzione e Sperimentazione del Rivestimento Prefabbricato della galleria Santomarco, nella zona interessata da terreni estremamente spingenti con ricoprimento di circa 1000 metri. *Int. Congr. On Large Underground Openings*, Firenze, vol. 1, pp. 137-146.

De Souza, E., Mottahed, P. & M. Molavi 1998. Field Testing of a Yielding Support System. *Int. J. of Rock Mech. & Min. Sci.,* Vol. 35, 4-5, Paper No. 087.

Fröhlich, K. 1948. Die Verbindung stählerner Streckenbögen, *Gluckauf*, pp. 543–555.

Heise, F. & F. Herbst 1913. *Lehrbuch der Bergbaukunde*. Berlin: Verl. V. J. Springer.

Hindley, G., Gibbons, P., Agius, M., Carr, B., Game, R. & K. Kashani 2004. Linking Past and Future. *Civil Engineering Magazine*, ASCE, May 2004.

Hoek, E., Marinos, P., Kazilis, N., Angistalis, G., Rahaniotis, N. & V. Marinos 2006. Greece's Egnatia Haighway Tunnels. *Tunnels and Tunnelling Int.,* Sept. 2006, 32-35.

Kolymbas, D. 2003. The role of time in NATM. In Natau, Fecker & Pimentel (eds), *Geotechnical Measurements and Modelling*, pp. 73 - 78, Swets & Zeitlinger, Liss.

Kovári, K., Amstad, Ch. & G. Anagnostou 1988. Design / Construction methods - Tunnelling in swelling rocks. In Cundall et al. (eds), *Proc. of the 29th U.S. Symp. "Key Questions in Rock Mechanics"*, Minnesota, 17-32.

Kovári, K. 1998. Tunnelling in Squeezing Rock. *Tunnel*, 5/98, 12-31.

Kovári, K. 2005. Method and device for stabilizing a cavity excavated in underground construction. *US Patent Appl*. 20050191138.

Kovári, K., Ehrbar, H. & A. Theiler 2006. Druckhafte Strecken im TZM Nord: Projekt und bisherige Erfahrungen. In Löw (ed), *Geologie und Geotechnik der Basistunnels*, pp. 239-252, Zürich: Vdf Hochschulverlag.

Lenk, K. 1931. *Der Ausgleich des Gebirgsdruckes in grossen Teufe beim Berg- und Tunnelbau*. Berlin: Julius Springer.

Pöchhacker, H. 1975. Gebirgsklassifikation bei Gross-Strassentunneln. Kritik und Anregungen. PORR-Nachrichten, Nr. 63.

Sánchez Fernández, J. L. & C. E. Terán Benítez 1994. Túnel de Trasvase Yacambú – Quibor. Avance Actual de los Trabajos de Excavación Mediante la Utilización de Soportes Flexibles Aplicados a Rocas con Grandes Deformaciones. In M. van Sint Jan (ed.), *IV CSMR / Integral Approach to Applied Rock Mechanics*, pp. 489-497, Santiago: Editec.

Schubert, W, Moritz, B., Sellner, P. & M. Blümel 1999. Tunnelling in Squeezing Ground – Recent Improvements. *Felsbau,* 17 (Nr. 1), 56-58.

Schubert, W. 1996. Dealing with Squeezing Conditions in Alpine Tunnels. *Rock Mech. Rock Engng*. 29 (3), 145-153.

Thut, A., Nateropp, D., Steiner, P. & M. Stolz 2006a. Tunnelling in Squeezing Rock - Yielding Elements and Face Control. In: *8th Int. Conf. on Tunnel Constr. and Underground Structures*, Ljubljana.

Thut, A., Piedevache & Prouvot 2006b. Projet Alptransit: Instrumentation et essais in-situ pour deux tunnels de base en contexte alpin. *Tunnels et ouvrages souterrains*, 198, pp. 331-336.

Tusch, K.N. & J.F.K. Thompson 1996. Method of connection. *US Patent* 5489164.

Wittke, W., Wittke-Schmitt, B. & D. Schmitt 2005. The 9 km long Kallidromo tunnel of the new highspeed railway line Athens-Thessaloniki, Greece, tunnel sections in squeezing ground. In Erdem & Solak (eds), *Underground Space Use: Analysis of the Past and Lessons for the Future*, 321-326. London: Taylor & Francis Group.