World Tunnel Congress 2009, Budapest, Hungary, May 23-28

DESIGN METHODS WITH YIELDING SUPPORT IN SQUEEZING AND SWELLING ROCKS

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Keywords: squeezing rock, swelling rock, yielding support

INTRODUCTION

Although the processes taking place in the ground around a tunnel in squeezing and in swelling rock differ from each other fundamentally, there is one common feature in both cases: with increasing rock deformation the rock pressure decreases. This fact is proved both by experience and theoretical investigations and was clearly recognized as early as at the beginning of the last century. “With each fraction of (a) millimetre with which the rock mass moves, the amount of pressure acting on the lining decreases”. (Wiesmann, 1914). Based on this observation a number of design methods are nowadays at the disposal of the engineer to control rock pressure even in heavily squeezing and heavily swelling rock. Both the temporary and the final lining can be constructed nowadays in such a way as to exert stabilizing pressure on the rock and at the same time allow the rock mass to deform. In many cases this combined action, i.e. rock support and letting the rock deform, not only presents the most economical solution, in some cases it is the only one that makes tunnel construction feasible. One must bear in mind that in modern traffic infrastructure projects (e.g. high speed rail connections), apart from stabilizing the opening also the limitation of deformations during the long operation life of the tunnel may become a formidable problem to be overcome. This is possible by limiting considerably the maximum pressure on the permanent lining that could develop in the long term and with it the maximum lining deformations or/and lining displacements. It is obvious that the differential displacements with respect to the tunnel lining are crucial rather than the absolute ones. It is well known that the squeezing and swelling potentials along a tunnel are not uniform and also that the development of the corresponding pressures in the long term may be extremely variable.

The need for yielding types of temporary or final support when tunnelling in squeezing and swelling rock has long been recognized. Recently Anagnostou and Cantieni (2007) have shown two historical examples for yielding support from mining in squeezing ground, which clearly demonstrate two conceptually quite different approaches (Fig. 1). On the one hand, a layer of sufficiently compressible material is inserted between the excavated rock surface and the lining and, on the other hand, the lining itself is made highly deformable (Heise & Herbst, 1913).
In both cases an adequate overexcavation is required to accommodate the expected rock deformations. According to Fig.1 (a) a wood back-packing of sufficient thickness serves as “yielding material “ whereas according to Fig.1 (b) compressible wood interlayers serving as “yielding elements” are inserted into the concrete lining allowing it to converge. Later, for both concepts much more practicable solutions were developed. For example,

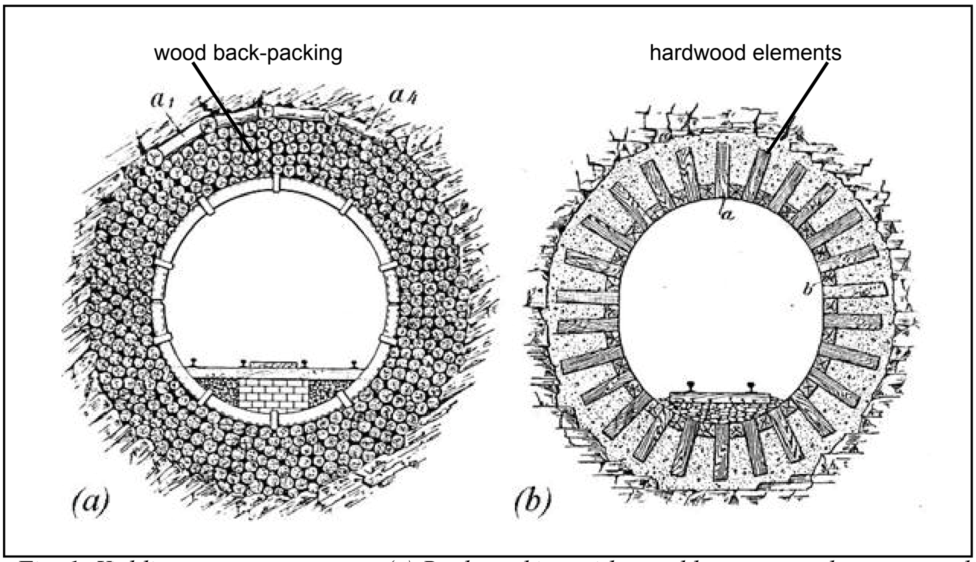

Fig. 1: Yielding support concepts. (a) Back-packing with wood between steel support and rock, (b) Interlayer of wooden panels in the concrete lining (Heise and Herbst, 1913)

in squeezing ground Mohr (1957) proposed applying highly compressible fuel ash between the lining and the rock of a deep shaft instead of wood. In this context, Mohr provided the first representation of the characteristic line of the rock mass together with that of the yielding support (Kovári, 2003).

In the 1930s Lenk (1931) reported on a patented method consisting of placing a limited number of yielding wooden elements between prefabricated concrete segments, in this way also providing joints almost free of bending moments (Fig. 2). The deformation characteristics of these wooden elements were determined experimentally.

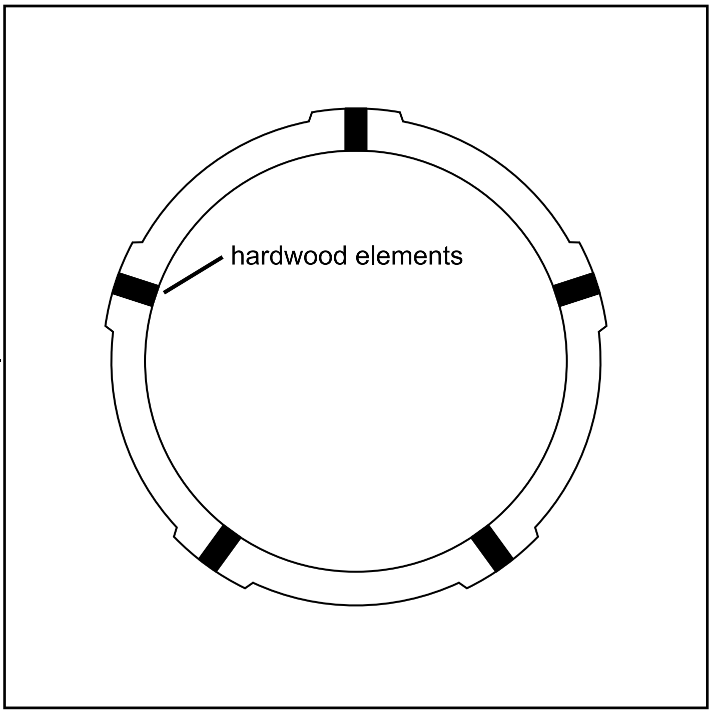

Fig. 2: Yielding hardwood elements between prefabricated concrete segments (Lenk, 1931)

The first type of yielding support of broad and continuous application, both in mining and in tunnelling, was provided by the so called Toussaint-Heintzmann steel ribs. This involved the design of new steel profiles (top hat cross-section) with friction connecting loops (Fig. 3) permitting the tunnel to withstand larger convergence with more or less constant lining resistance. This marked the beginning of the first industrially-produced supports in squeezing rock, by means of which ground pressure could be reduced with increased convergence (Fröhlich 1948). As the friction resistance in the joints is very limited with respect to the full load-bearing capacity of the ribs, the lining's resistance to rock convergence is also relatively small.

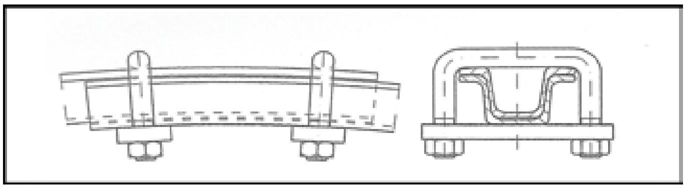

Fig. 3: Sliding steel rib connection (Fröhlich, 1948)

An early attempt to master tunnelling in heavily swelling ground by inserting a yielding medium between lining and rock was reported by Schächterle (1926).
As can be seen in Fig. 4, firstly the lining was founded on a compressible layer of rock debris and secondly in its upper part a compressible layer of the same material of 1 m thickness was placed. In fact, in the course of time the roof heaved by approx. 1.3 m, necessitating the reconstruction of the tunnel, which correctly involved the placement of an invert arch.

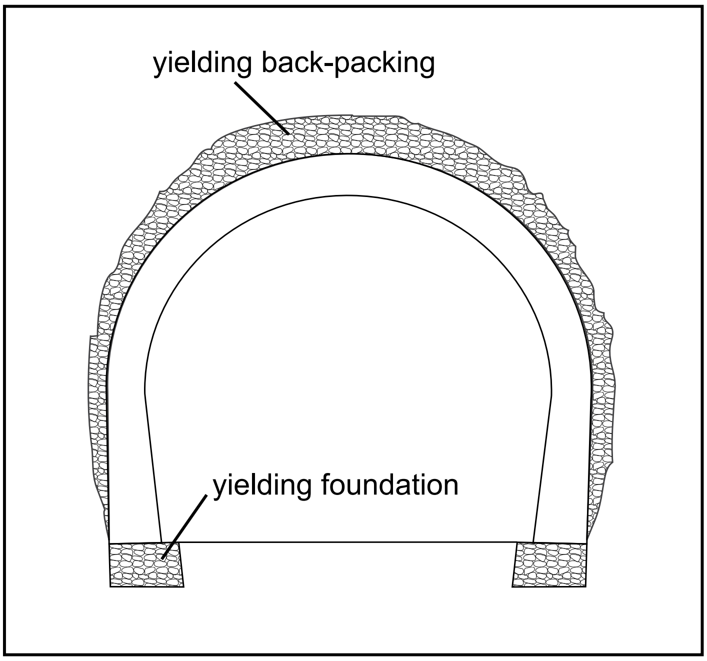

Fig. 4: Tunnel lining in swelling rock: yielding back-packing in the roof and yielding foundation (Schächterle, 1926)

YIELDING STEEL SUPPORT

The further development of the Toussaint-Heintzmann support system is shown in Fig. 5. In view of its planned large scale application in the base tunnels driven through the Swiss Alps and of the large tunnel diameter, large scale 1:1 in situ tests were carried out based on a concept proposed by the Author (Kovári et al, 2005). The diameter of the planned tunnel was Ø=13 m and the requested possible convergence 0.75 m (function of tunnel radius).
It was planned to place two complete sets of TH 44/70 - type ribs within each other to allow the large movements, involving in total 8 frictional sliding connections. Theoretical considerations indicated a maximum lining resistance of 2 MPa for the case of complete ring closure. The question was whether the system would really behave as predicted considering the extreme high loads combined with the unusually large displacements (sliding) of the individual ribs with respect to each other. To perform the test a niche of adequate dimensions was excavated in hard massive gneiss and two sets of ribs were erected with a spacing of 0.5 m and stabilized

to prevent movement out of the plane of the rings.
Liner plates were placed on the ribs to accommodate large inflatable rubber cushions using water as the pressurizing medium.

Fig. 5: Yielding steel support
(a) Details of the steel rib connection *(b) Example for application in mining*

Fig. 6 shows the test set up schematically, while Fig. 7 shows details of the ribs loaded up to their bearing capacity. The most important results of this test can be summarized as follows: During the sliding process in the joints there is only a very modest frictional resistance resulting in a lining resistance of less than 0.25 MPa as shown in Fig. 8. At a radial displacement (corresponding to convergence) of approx. 0.65 m, the lining resistance increases but does not exceed 30% of its theoretically expected value. Due to local buckling of the ribs, the bearing capacity of the double-rib only corresponds to about 50% of that of a single rib. However, the ability of the double-rib ring, with its connections, to allow a radial convergence of 0.7 m was well confirmed.

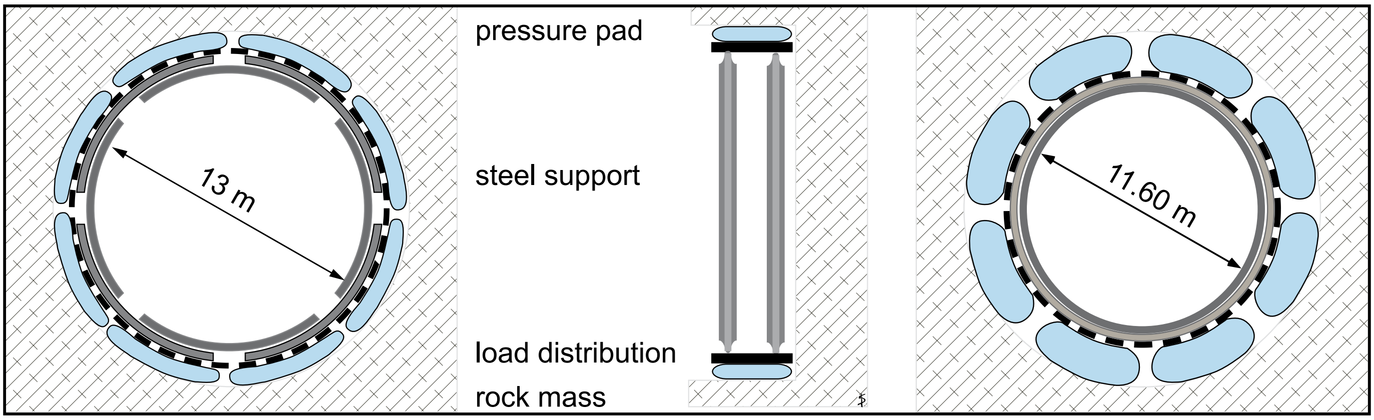

Fig. 6: Field test of a large diameter steel support executed in a hard rock niche with two complete steel sets, (a) The sets prior to loading, (b) The sets after loading by water-inflatable cushions and convergence up to 0.7 m (Kovári et al, 2005)

Fig. 7: Steel arches loaded up to local buckling of the ribs (TH44)

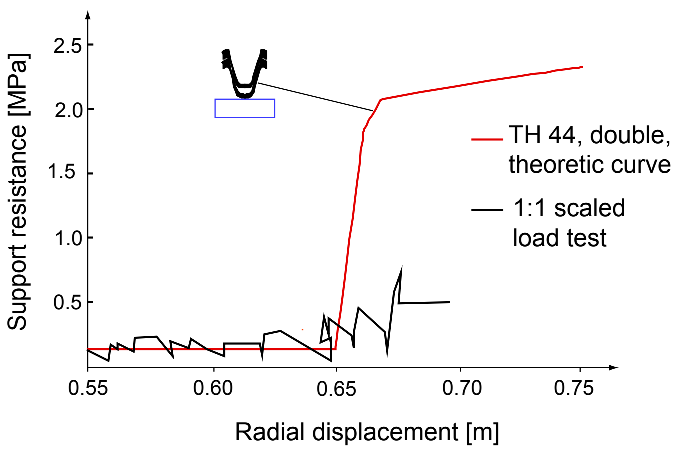

Fig. 8: Test results and theoretically expected diagrams for single and double ribs

YIELDING SPRAYED CONCRETE SUPPORT

An ordinary sprayed concrete lining exhibits a high lining resistance but an extremely low deformation capacity. If it is overloaded, it generally loses its load-bearing capacity due to brittle failure even it is reinforced by the customary steel mesh. Therefore, a sprayed concrete lining without special measures is not suitable in applications under the conditions of squeezing or swelling rock. However, if the "stiff" concrete lining is provided with a number of yielding elements, as proposed in Fig. 2, allowing the contraction of the profile and exerting at the same time resistance to rock deformation, the sprayed concrete lining becomes a particularly powerful means of controlling rock pressure.
Recently, new types of yielding elements have been proposed and applied successfully in practice. One such element consists of steel cylinders inserted into gaps in the shotcrete lining and loaded axially in the circumferential direction of the profile (Moritz, 1999). After a given initial critical load the cylinders start to buckle and continue to do so in successive steps, undergoing shortening and thus allowing at the same time a lining resistance to develop. The photo in Fig. 9 illustrates the application in one of the slots in a shotcrete lining.

Fig. 9: Steel cylinders inserted into slots of the shotcrete lining

Fig. 10: Highly compressible concrete elements inserted in the shotcrete lining

Further progress in this field was achieved by the development of highly compressible bulk elements on a cement basis. They are composed of a mixture of cement, sand, hollow glass particles, steel fibres and additives and are also provided with suitable steel reinforcement (Thut et al 2006). In Fig. 10 an application is shown in the 37 km long Lötschberg Base Tunnel (Switzerland) driven through highly deformable coal schist under a large overburden (Keller, 2005).
The compressibility of these "concrete" elements amounts to up to 40-50 %, depending on the selected yielding stress (4 ÷ 20 MPa). Fig 11 shows the results of laboratory tests carried out on such elements, illustrating the high reproducibility of their deformation properties. As can be seen, after reaching a given peak stress of approx. 10 MPa, there is a practically constant yielding state with a stress level of approx. 7.5 MPa, which after roughly 40% compression is followed by strain hardening. This type of element does not exhibit sudden brittle failure - on reaching the full deformation capacity, the strength of the element increases.

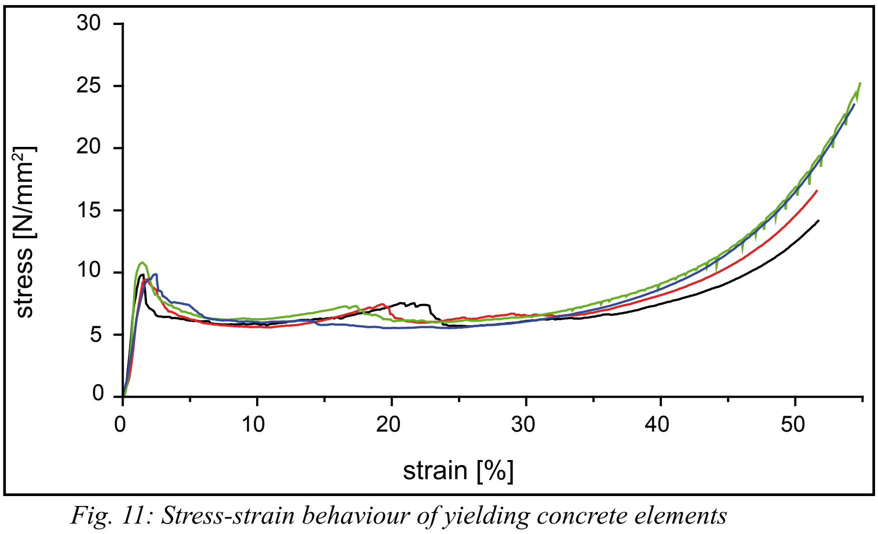

Fig. 11: Stress-strain behaviour of yielding concrete elements

APPLICATIONS IN SQUEEZING ROCK

In underground construction, it is frequently observed that the excavation of an opening leads in some circumstances to major short- or long-term rock deformations, which cause a progressive contraction of the opening (Kovári,1998). If the phenomenon develops completely, the rock penetrates the opening from all sides including the tunnel floor. In such cases the main task is to limit the rock deformations by means of a temporary support. Often this does not succeed because the temporary support is not able to withstand the rock deformations and is either damaged or completely destroyed. Without appropriate countermeasures the rock, so to speak, slowly pushes the destroyed lining in front of it until the movements come to a standstill or lead to a collapse of the opening. One of the countermeasures consists of introducing yielding steel ribs (Fig.5) together with rock anchors. Another concept consists of a yielding sprayed concrete lining support combined with a light yielding steel support. In the following, examples will be given for both types of application.

GOTTHARD BASE TUNNEL WITH YIELDING STEEL RIBS

In the central part of the 57 km long twin tube Gotthard Base Tunnel driven through the Swiss Alps a stretch of 1150 m of the so called TZM Formation was predicted to be highly squeezing (Fig. 12). In fact, a number of deep exploratory boreholes with lengths up to 1750 m have revealed a rock of very low strength and high deformability, consisting of schists and phyllites.
In this part of the tunnel (excavation diameter Ø=13 m) the overburden was approx. 800 m. From laboratory tests and comprehensive statical calculations it became clear that the tunnel could only be constructed if radial displacements up to 0.70 m were permitted (Kovári and Ehrbar, 2008).

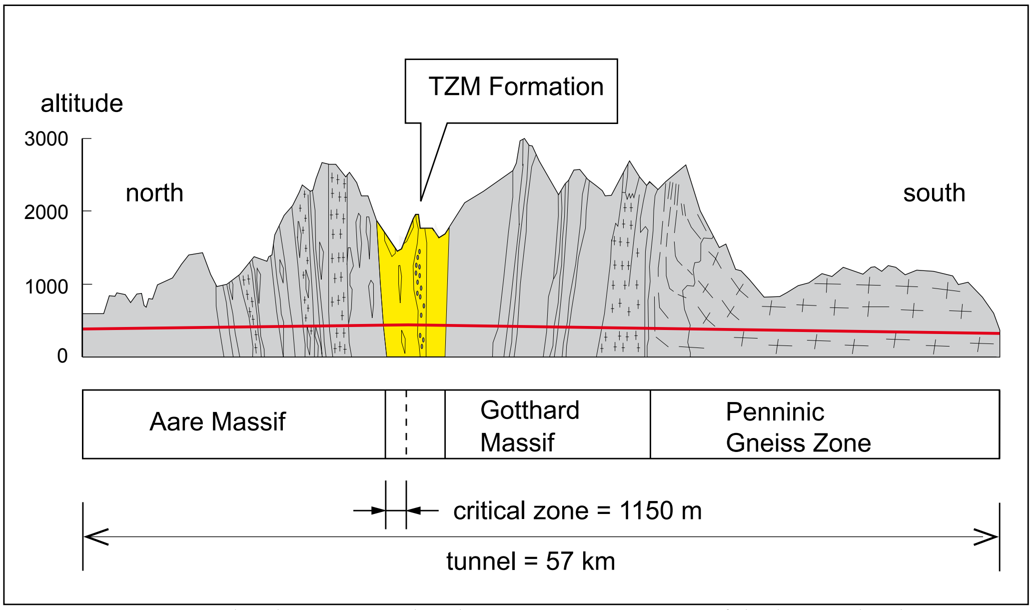

Fig. 12: Gotthard Base Tunnel: schematic representation of the longitudinal geological section with the squeezing TZM-Formation

In order to stabilize the opening, the corresponding lining resistance had to be increased to 2 MPa. Fig. 13 illustrates the relation between the overburden H, the radial displacements u and the lining resistance p for the representative rock mass parameters listed in the figure.

It can be seen that for an overburden of 500 m the radial displacements amount to 0.25 m (p = 1.0 MPa) and 0.15 m (p = 2.0 MPa), respectively. Doubling the height of the overburden to 1000 m the radial displacements at p = 1.0 MPa increase their value five-fold, i.e. 1.2 m. For a lining resistance of 2 MPa the displacements decrease to 0.6 m. The excavation-support system (Fig. 14) involved a nearly circular profile (Ø=13 m) excavated in full face (Lunardi, 1998) and systematically supporting the tunnel face by means of long fully-grouted steel anchors.

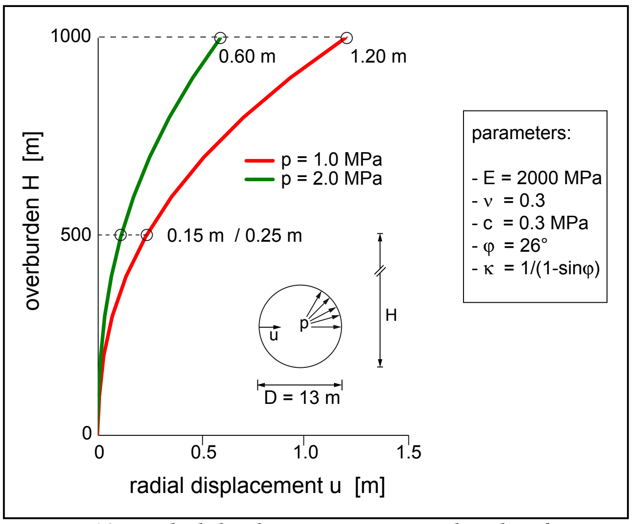

Fig. 13: Radial displacement u versus height of overburden H for two values of lining resistance p (Kovári and Ehrbar, 2008)

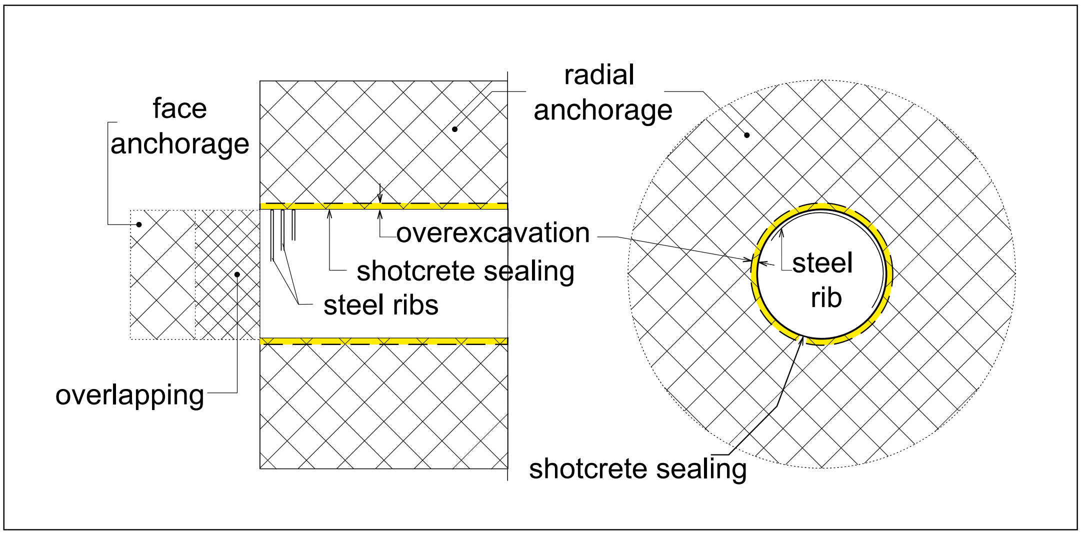

Fig. 14: Schematic representation of the excavation-support concept (Kovári and Ehrbar, 2008)

As to the support in the cross section, the emphasis was placed on yielding steel ribs of the heaviest type (TH44/58) with a spacing of 0.33-1.25 m. Additionally; fully-grouted radial rock anchors with a total length of up to 300 m were placed. A thin shotcrete lining applied immediately after an excavation step had the sole function of sealing the rock surface. This temporary lining concept permitted radial displacements up to 0.70 m in a regular manner. To accommodate this rock convergence, it was necessary to provide space by means of overexcavation. This most critical 1.1 km long stretch of the Gotthard base tunnel was completed without the necessity of re-profiling.

SAINT MARTIN LA PORTE ACCESS ADIT WITH YIELDING CONCRETE ELEMENTS

This adit - currently being excavated - will provide construction access to the 53 km long twin tube base tunnel of the new Lyon -Turin high speed rail link (Mathieu 2008). Exceptionally severe convergences have occurred in carboniferous formations with black schists, sandstones, clay-like shales interspersed with layers of coal, with an overburden of 250 to 350 m. The excavation profile is 77 m2 to 125 m2 for a final internal profile of 54 m2 to 63 m2. The temporary support consisted initially of dense radial bolting around the profile including the invert together with yielding steel ribs (TH44/58) and a 200mm thick shotcrete lining interrupted by 4 or 5 longitudinal slots. Due to these slots the shotcrete lining could not develop any support effect for the rock. The greatest convergence occurred after 145 days at a distance of 60 m from the working face and exceeded 2 m. Convergence rates varied from 30-50 mm/day at the face with 50% of total deformation taking place in the first 20 m (Mathieu 2008). In order to better control the rock deformations, i.e. to avoid the necessity of cumbersome, costly and time-consuming re-profiling a novel support system was implemented. This involved a near circular cross section with the insertion of the yielding concrete elements described above into 9 longitudinal slots in the sprayed concrete lining. The choice of this countermeasure was based on earlier experience made in the 37 km long deep Lötschberg base tunnel (Keller, 2005).

The beam-shaped elements (height 400 mm, length 800 mm and thickness 200 mm) were designed to yield at approx. 40% compression (Barla et al, 2008). It was verified, by means of an extensive field monitoring programme, that the elements incorporated into the lining were capable of shortening under a nearly constant tangential stress of 8.5 MPa. The system adopted in the Saint Martin La Porte access adit proved to be very successful.

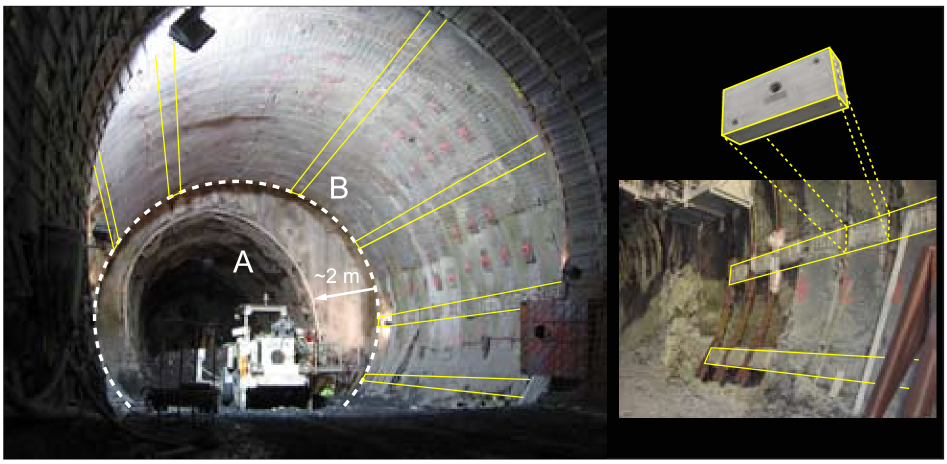

Fig. 15: Lyon–Turin high speed rail link, access adit: convergence up to 2 m (Profile A), Re-profiling and application of yielding concrete elements (Profile B

APPLICATIONS IN SWELLING ROCK

Rocks containing clay minerals or anhydrite increase in volume when they come into contact with water. This phenomenon is referred to as rock swelling. Tunnelling in swelling rock normally causes two different types of damage. The first type results in the failure of the invert arch due to the pressure from the surrounding swelling rock. The second type occurs under low overburden conditions, in which the tunnel lining results in heave of the entire tunnel and initially may remain only slightly damaged. The tunnel crown and floor experience an upward displacement which leads to limitations or even loss of serviceability (Kovári et al, 1998).
The 1.5 km long Chienberg Road Tunnel in Switzerland, penetrating a heavily swelling anhydrite formation (Gipskeuper), well illustrates this situation. It was designed with a circular cross section and a 1.0 m thick concrete final lining to resist high swelling pressure and excavated with the heading and bench method. As the heading was nearing completion in two individual stretches swelling caused the entire tunnel profile to heave by up to 100 mm. The overburden was modest and the rock located over the roof was very soft. Damage first affected a 60 m long tunnel section and another 370 m section of tunnel (Hofer et al, 2007). These two tunnel sections were redesigned according to the concept of "Modular Yielding Support" (Kovári and Chiaverio 2007). This involved the application of yielding concrete foundation elements placed under the lining pillars (Fig.16). Other yielding concrete elements were used for the heads of tie-back anchors mounted on the tunnel floor.

To implement this plan the concrete floor of the tunnel lining in the two affected sections had to be removed in stages. A 6 m deep trench had to be excavated below the original floor to build the new floor for the modified system. The new carriageway slab is 4m above the new floor and has bending-resistant connections to the remaining tunnel structure (In figure 16 the dashed line shows the original profile).

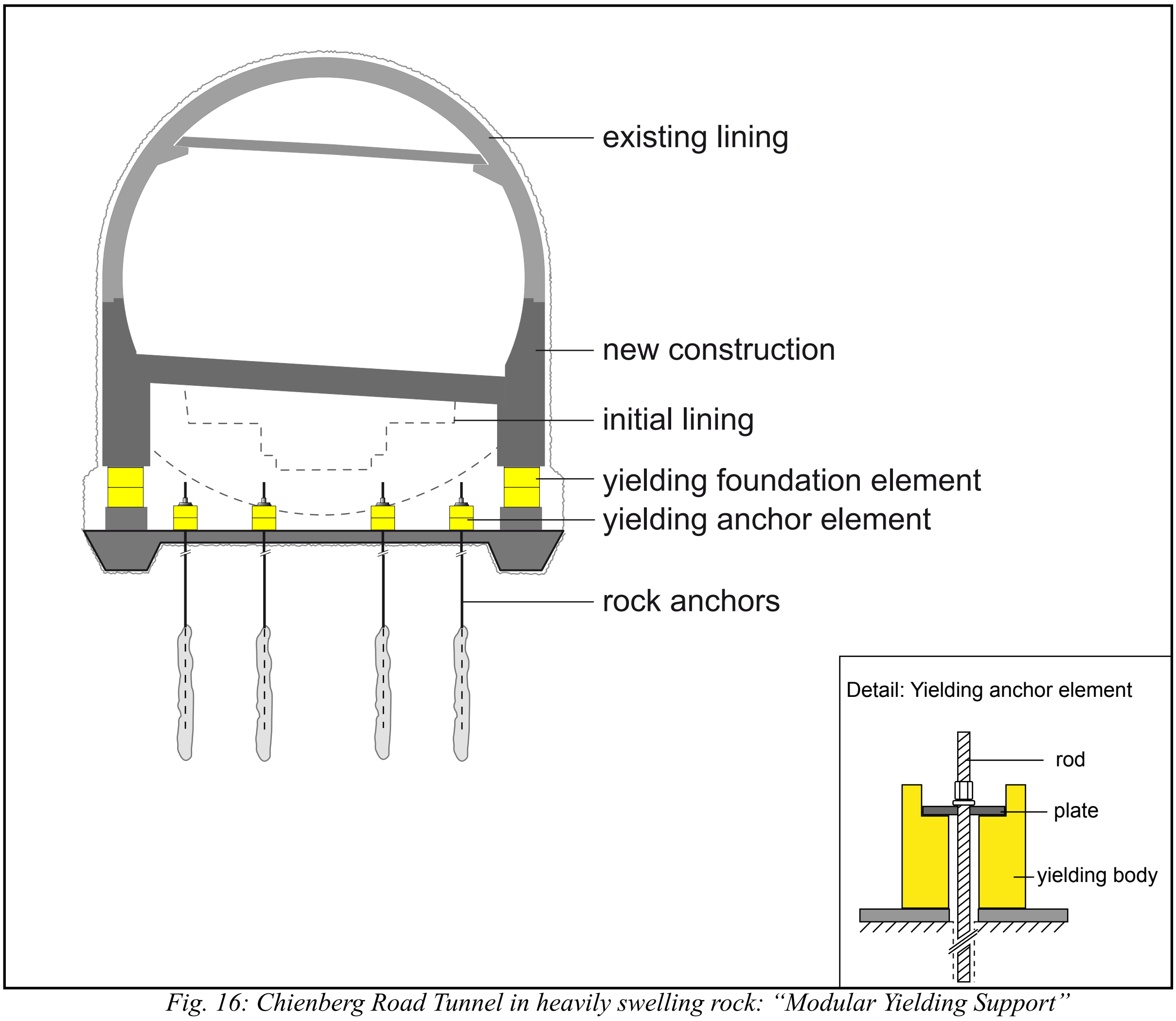

Fig. 16: Chienberg Road Tunnel in heavily swelling rock: "Modular Yielding Support"

The concept of "Modular Yielding Support" is based on the diminution of swelling pressure due to permitted floor heave. Figure 17 shows the qualitative relationship between floor heave ua and the lining resistance pa of swelling rock (Kovári et al, 1998). Permitting long term floor heave ua by using deformable elements results in less vertical stress p_a.

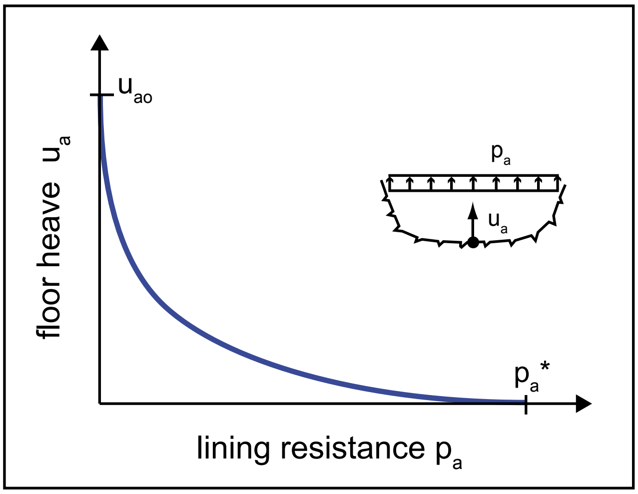

Fig. 17: Characteristic line of swelling rock

The foundation elements applied at Chienberg Road Tunnel having a height of 1000 mm and diameter of 900 mm were designed in 3 different load classes for the variable overburden along the two heavily swelling stretches. Each type has defined minimum and maximum levels of load resistance. The minimum level prevents tunnel settlements; the maximum level protects the tunnel against overstress and heave. Within the specified limits, a deformation range of 30-40 % of the original height of the elements can develop (depending on the selected yielding stress). The load capacity of each element type was customized by varying the constituents and the reinforcement within the elements.
To configure the different types of element for their design parameters, several tests had been conducted on a 20 MN load testing equipment. Figure 18 shows the results of uniaxial compression tests in the laboratory carried out at cylindrical foundation elements.

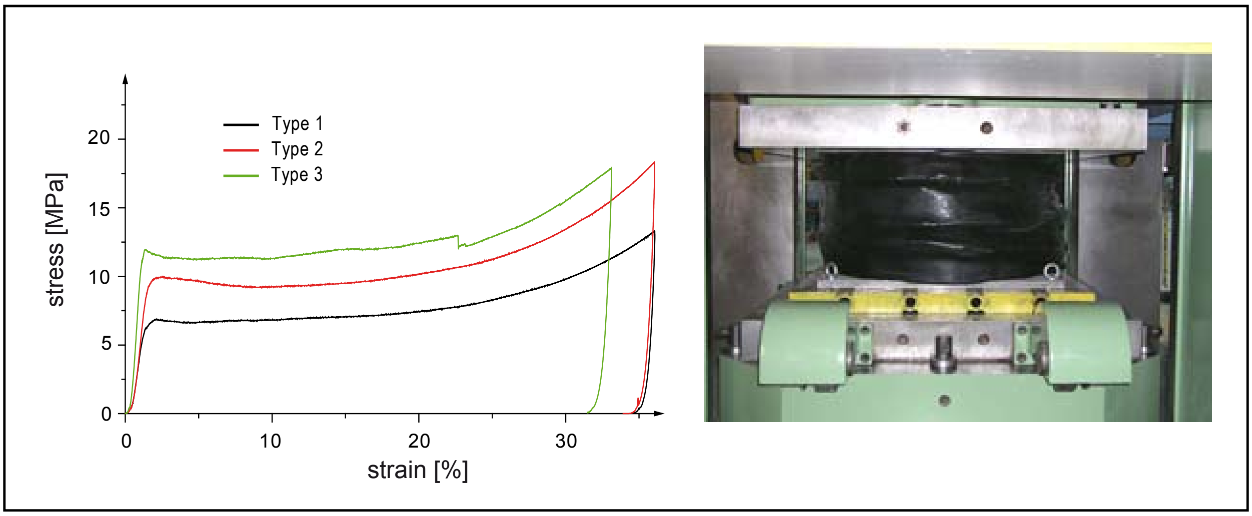

Fig.18: Laboratory tests of cylindrical foundation elements (height: 1000 mm / diameter 900mm)
(a) Elements with different strength levels *(b) An element compressed at 30 % (with rubber skin)*

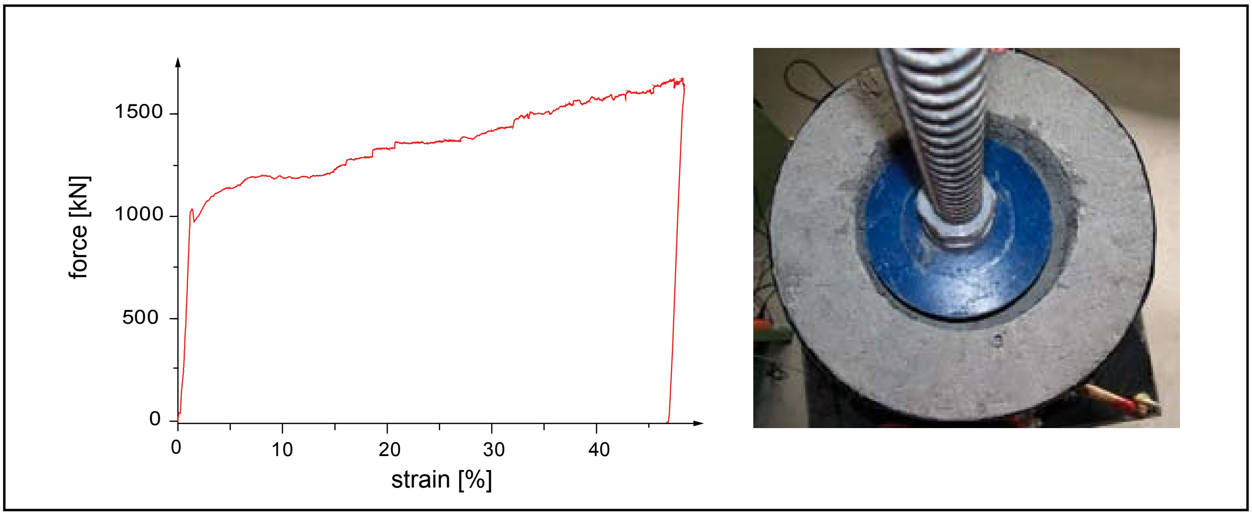

Fig.19: Laboratory test of a cylindrical anchor element
(height: 600 mm / diameter 600mm / diameter load plate 350 mm)
(a) Force-strain diagram of an anchor element *(b) An element compressed at 40 %*

The yielding anchor elements in the floor were installed in order to reduce the rate of the floor heave. The elements for the anchor heads are based on the principle of penetrating the anchor plate with a smaller diameter than that of the yielding element (see also the detail in fig. 16). This system also functions perfectly well if there is some eccentricity of the force transmission (anchor force). Figure 19 illustrates a test result carried out with such an anchor element.

The highly deformable concrete elements at the Chienberg Road Tunnel are designed for a deformation endurance of about 25 years. The advantage of the “Modular Yielding Support” system is that it enables observing and replacing the elements at any time without affecting the traffic in the tunnel. The elements can individually be replaced after reaching their deformation capacity.

Fig. 20: Chienberg Road Tunnel after completion: “Modular Yielding Support”

CLOSING REMARKS

Although the physical and chemical processes taking place in the ground around a tunnel in squeezing and in swelling rock differ from each other, there is one fundamental aspect in these two cases: with increasing rock deformation the rock pressure decreases. This is proved both by experience and theoretical investigations. Based on this fact, nowadays a number of design methods are at the disposal of the engineer to control rock pressure even in heavily squeezing and heavily swelling rock.
The need for the construction of long deep tunnels - as is the case under the Alps in Austria, France, Italy and Switzerland - has made the problem highly relevant. In fact, the heavily squeezing rock zones under high overburden in the 34 km long Lötschberg Base Tunnel and the 56 km long Gotthard Base Tunnel in Switzerland could recently be successfully overcome by introducing new design and constructional methods. The key element of the design of the temporary rock support was the fulfilment of the requirement to allow controlled radial displacements up to 0.7 m. The steel support is provided with sliding joints and yielding beam elements are inserted in the shotcrete lining. In this way the lining is capable of providing considerable rock support (so called lining resistance) and at the same time also permitting convergence leading to a reduction of rock pressure for the final lining.

In the case of swelling rock containing clay and/or anhydrite the problem stems from the capacity of these rock types to increase their volume by absorbing water and thus lead to heave of the base of the tunnel. The solution to the problem is provided again by designing a lining system that allows a given amount of base heave without violating operational requirements. Inserting highly compressible materials of a specified high resistance between rock and invert provides a satisfactory solution.

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