Convergency compatible support systems

E. Schneider, Institute of Construction and Material Sciences, University of Innsbruck, Austria and M. Spiegl of SSP BauConsult GmbH discuss yielding support systems and their possible applications

Convergency compatible yielding support systems are well established in conventional tunnelling. They were developed to take advantage of the fact that the load on a tunnel support is reduced when controlled convergencies are allowed. This principle not only applies for Drill and Blast tunnels but also for gripper type TBM tunnels where conventional support like steel ribs, shotcrete and anchors are used.

Recently proposals have been put forward by various parties to combine the idea of convergency compatible support with prefabricated concrete segmental linings, installed behind shielded TBMs. This paper overviews the current and future developments in this field.

Geotechnical background

It is generally accepted in tunnelling that controlled convergencies reduce the load on the tunnel support. This phenomenon can be visualised in a diagram showing the dependency between radial stress and radial deformation (figure 1 & 2).

The diagram has been published in various forms by different authors beginning with Fenner (1938) and Pacher (1964)[1]. Other prominent authors are Lombardi, Egger and Seeber. For practical use in the design of tunnel support and lining numerical solutions have been developed by some of these and other authors.

Convergency support-systems

The most popular application of the above mentioned principle is NATM (New Austrian Tunnelling Method). It was developed in the 1960's by Rabcewicz, Müller and Pacher. Their ideas have revolutionised the design and construction of tunnels the world over. It was only natural that such success has led to discussion of authorship, although there is a common understanding now that the development of NATM was mainly an Austrian achievement even if it was based on "inventions" made elsewhere and contributions from other countries.

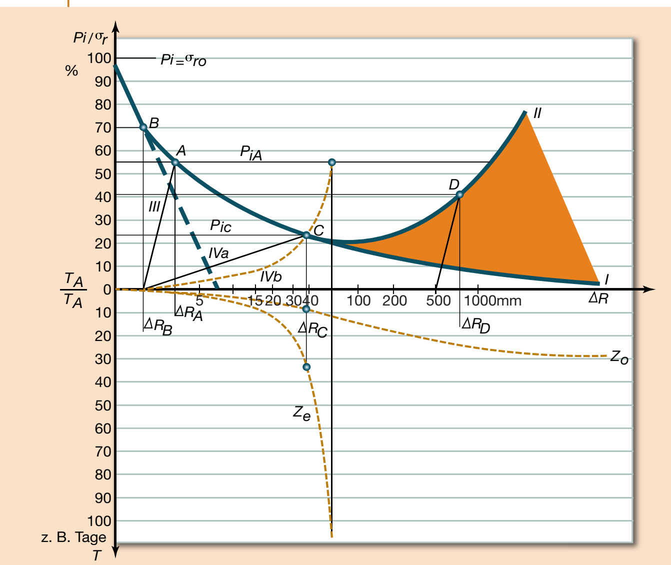
Obviously it is more productive to look ahead than to dig over the past and one way of doing this is to concentrate on finding solutions for a convergency compatible support for TBM-bored tunnels with a segmental lining.

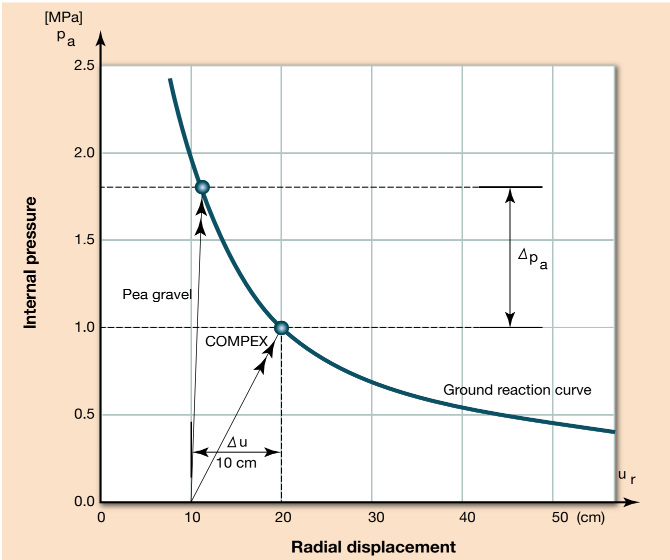
Before going further, the authors would like to remark on how the principles of NATM are applied in different countries. For tunnels in shallow depth the main support measure is nearly the same everywhere, namely reinforced shotcrete. For tunnels with higher overburden the Swiss use convergency compatible steel ribs as the main support, whereas the Austrians use mainly shotcrete and rockbolts. Longitudinal open slots in the shotcrete shell or compressible elements in various shapes, which help to prevent fractures in the shotcrete shell, have been common practice in Austria since the 1970's. Only recently engineers from other countries have begun to recognise their advantages.

A different development, which some consider a logical development of NATM – an interpretation the authors do not share – has taken place in Italy.

Lunardi, the inventor and promoter of the ADECO.RS system (Analisi delle deformationi controllate nelle rocce e suoli[2]) emphasises the importance of maintaining a three-dimensional stress-situation at the tunnel face. In contrast to

Left: Fig 1 – Ground and support reaction curves according to PACHER;
Right: Fig 2 – Reduction of load on segmental lining by use of COMPEX mortar





Austria, where this principle is less important and where the general method is to support a tunnel in squeezing rock by sequential steps, the ADECO.RS-method uses full face excavation under all conditions. This is made possible by controlling the deformations of the face using long fibre-glass anchors and by installing a full circle heavy, rigid support/lining immediately after opening the face. Apart from geotechnical doubts the authors have some reservations about the claimed cost-saving effects of this method.

Above, left: **Gotthard's Sedrun section;** Right: **Saint Martin-LA Porte access gallery**

Recent developments

A new support solution for conventionally excavated tunnels in severely squeezing rock has been developed at the Sedrun Lot on the Gotthard Base Tunnel. Inspired by ideas from Italy and by methods developed in German coal mines, where squeezing rock prevails, the Swiss engineers designed a convergency compatible steel support system, which combined with long face anchors successfully permitted full face excavation of the Tavetscher Zwischenmassiv, the most critical zone of the whole project[3].

A similar solution has been applied in the Saint Martin-La Porte access gallery of the Lyon-Turin Base Tunnel by Barla and Panet[4]. There, heavy steel ribs with sliding joints were combined with a 20 - 30cm thick shotcrete layer. Similar to solutions developed in Austria, where compressible steel elements intercept the rigid shotcrete shell, highly deformable concrete elements were installed. They helped to prevent cracks and fractures in the shotcrete shell, caused by overloading.

Convergency for gripper TBMs

In North America, where tunnelling with gripper TBMs has a long history of success, the preferred means of support is steel ribs with wooden lagging. In Europe, until recently, many engineers thought that steel bolts with wire mesh completed by shotcrete is the most appropriate measure behind a gripper TBM for all conditions, including squeezing. The problem with this is it will only work if the rock is not too sheared or squeezing. Many tunnel designers and contractors have now realised that in squeezing rock, full circle steel ribs are a much better solution. Tunnels in very difficult ground like the Walgau in Austria (1981-1984) or Evinos in Greece (1992-1995) have been driven successfully using a combination of rigid full circle steel ribs and shotcrete.

In the 1990s an even better solution - yielding steel ribs with sliding joints - was introduced at the Vereina Tunnel in Switzerland and became an immediate success[5]. Amazingly it took more than ten years before a further development of this system was made. There is little doubt that squeezing sections such as those at the start of the Faido-Sedrun heading of the Gotthard Base Tunnel could not have been constructed by open TBMs without this kind of yielding support. In both projects steel ribs with sliding joints were installed right behind the cutter head support and completed by an additional shotcrete layer some 50 - 60m behind. Depending on the local conditions systematic bolting and shotcrete were applied additionally right behind the cutterhead support.

Convergency for segmental lining

With the increasing application of shielded TBMs in rock-tunnels, ideas for convergency compatible segmental lining systems appeared. One of the first was a proposal by a British tunnelling contractor, who applied for a patent in the late 1970's[6]. Since then numerous have been published but so far none have come to fruition. The proposals can be classified into three categories (figure 3):

- Installation of compressible elements in the longitudinal joints
- Ribbed-segments with outer recesses
- Annular gap filled with compressible mortar

Compressible elements

The idea to install compressible elements in the longitudinal joints originates from conventional excavation. Long before such systems were applied in tunnelling they were used in coal mining in the shape of "Quetschhölzer". Today's deformable elements are made from steel or concrete. In order to provide an appropriate reaction against the load, they are designed so that the characteristics of their stress-deformation curve match the load-bearing capacity of the support.

Though this looks fine in theory, no one has as yet installed compressible elements in combination with a segmental lining erected behind a shielded TBM.

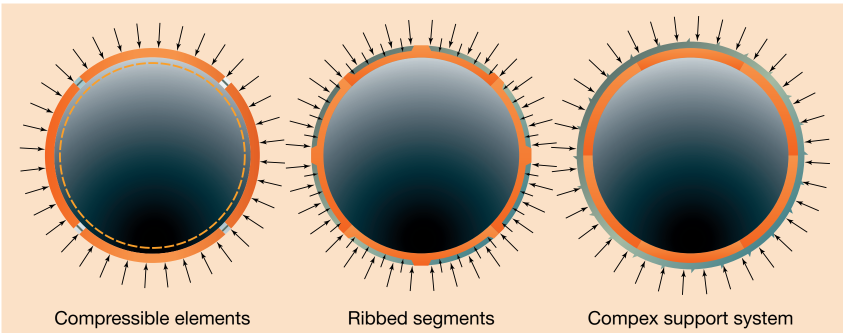
The idea for the ribbed-segments (Vigl[8]) originates from observations in the Walgau and Evinos Tunnels. On both projects, plastic deformation over long sections of the rock-mass was observed between the rigid steel ribs. For several days, before the support was completed by shotcrete, the ground was allowed to creep inward. The ribbed segments follow the same principle. The ribs can be considered as the rigid members of the system. The recesses give room for radial deformation of the surrounding rock mass.

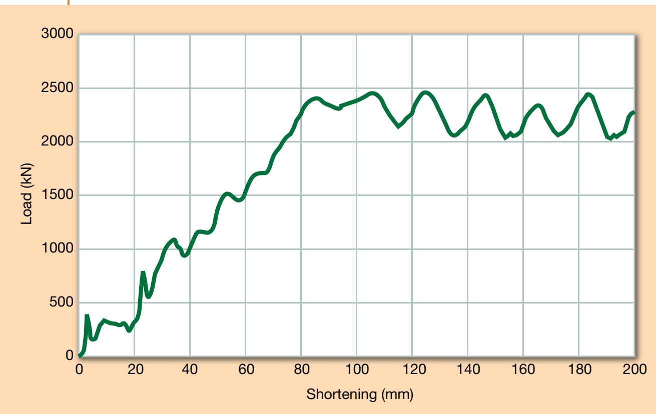
As mentioned the idea to fill the annular gap between the segments and the rock mass with compressible material was first published in the late 1970's. The patent applied for;

"...a deformable intermediate layer of a compressible material between the tunnel lining and the surrounding ground..."

Unfortunately for the inventor this proposal remained unheard of for more than 15 years before a group of engineers and supply companies headed by D2Consult from Austria launched a

Below: **Fig 3 – Overview of the systems**





Above, left: **Fig 4 – Load displacement diagram for a project designed group of 4 LSC (B. Moritz 2008);** Above, right: **Section through a yielding element[7]**

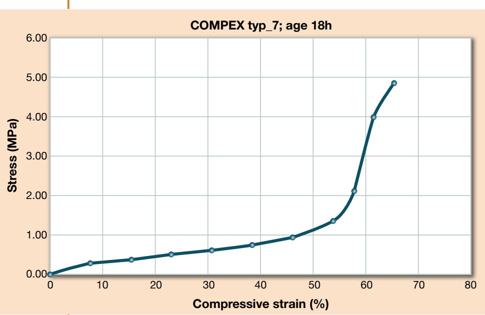
research project aimed at the; "development of a fully mechanised tunnelling system with a single shell lining made from prefabricated segments of reinforced concrete for application in tunnels with high overburden."

Compressible elements designed for installation in the longitudinal joints, sealing-systems, membranes, connecting bolts, pressure relieving valves, yielding anchors, amongst others were developed. A minor part of the project was the development of a compressible mortar for filling the annular gap.

Recent developments

Independently, and unaware of earlier developments, an Austrian engineer, K. Rotter from Innsbruck, began to develop a method by which long sections of squeezing rock could be excavated by shielded TBM and lined with precast concrete segments. Research was two tiered; the development of a new type of TBM capable of dealing with squeezing conditions; and the development of a compressible mortar. After intensive discussions with TBM manufacturers and the authors of this paper the first was abandoned and efforts were focused on further

Below: Fig 5 – Stress deformation diagram COMPEX (type 7) (Schretter & CIE)



developing a compressible mortar, on which Rotter had already spent considerable time and money. In the 1990's he was successful in finding two industrial partners to join him. One was a cement manufacturer, the other a polystyrene technology company. A series of lab tests and large scale mixing and pumping tests were performed and the result was a near perfect material named COMPEX-mortar, which suited all requirements[9].

It came as a surprise to the ROTTER-group, when it found a paper in the Tunnelbautaschenbuch 2008 by German company Hochtief presenting a very similar development[10]. Since then, intensive discussions have been ongoing between the parties. The aim is to forge an agreement whereby the two competitors join forces to perfect the method.

COMPEX Support System

The mortars developed by the two groups have similar characteristics. They are both formulated on a cement-based binding material and aggregates made from polystyrene. The properties of the mortar are such that under confined lateral expansion conditions a minimum compression of 50% is achieved without cracking or fracturing. The stress-deformation curve starts with an initial increase followed by a plateau and ends with a final increase to the maximum load.

The load bearing capacity of a tunnel support, or lining, is normally determined by its segments. Through modification of the mortar it is possible to adjust the compressive strength accordingly in a range between 1 and 5MPa by 50% compressive strain. The progress of stiffening and hardening of the mortar can be adjusted to the deformation characteristics of the rock-mass. It is possible to modify the binding-material in such a way that the mortar remains compressible over a substantial length of time, varying from one to around 21 - 28 days according to requirements (figure 4).

Filling the annular gap with compressible mortar has the following advantages:

- Fast and if required gives active support of the tunnel roof and walls
- Homogeneous bedding of the segments over the full radius
- Avoiding point loads on the segments
- In combination with a defined overcut of the TBM the thickness of the gap and the allowance for radial deformation can be adjusted to the expected amount of deformation
- The load on segments is much reduced

Applications

It was the first goal of the development to allow TBM excavations in squeezing rock. Such sections are expected in most of the Alpine Base Tunnels such as the Brenner, the Koralm and in the Lyon - Turin Base Tunnel. It is expected that with the application of the COMPEX support system major sections of this could be undertaken. The subsequent lining by concrete segments will allow higher advance rates than conventional excavation or by gripper type TBM.

Another application of the COMPEX support system could be in swelling rock. This type of rockmass behaviour is found in many tunnels in the Swiss Jura and in the Schwäbische Alb in Germany.

Processing problems

Major problems to be solved before the COMPEX System can be practiced are:

- Mixing of mortar
- Pumping of mortar
- Holding of pressure (sealing problems)

Mixing is a problem, because the polystyrene aggregates have a very low density of 28 to 60kg/m³ and the water-cement ratio should be kept below 0.4 to guarantee good long-term stability and maximum strength. To provide good handling the mortar should have a setting time of a minimum three hours. For the segmental lining stability of the segment lining the mortar should start to stiffen as soon as possible after being filled in.

To meet these demands the grain size of the aggregates was chosen carefully. The type of cement chosen was fine grinded with a Blaine-value of approximately 5.000cm²/g. Furthermore a combination of fast and slow reacting cement plus a number of additives was developed.

The problems related to mixing could be solved by the use of special mixers and a special cement. For compressible mortar a continuously working screw or hose-type pump is considered the most appropriate. Filling the annular gap with mortar requires a seal between the outside of the shield and the rock surface. This problem required extensive discussions with TBM manufacturer Herrenknecht until a viable solution was found.

Summary

Convergency compatible support systems are well established in conventional tunnelling. Solutions for convergency compatible systems in tunnels driven by shielded TBMs with subsequent segmental lining are still under development.

One solution - the installation of deformable elements in the longitudinal joints - is unlikely to make its way from use in conventional tunnelling into mechanised tunnelling.

Of the two other remaining solutions – ribbed segment with recess, or compressible filling of the annular gap – the latter is the more promising one. Its application will facilitate tunnel driving by TBM through sections of squeezing rock. Since this method provides higher advance rates than conventional methods of excavation and support its application will save cost and time. For huge projects like the Alpine base-tunnels in Austria, Italy and France and tunnels in Jurassic formations this could be of great importance. T&T

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