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Design of Ductile Tunnel Linings

Schubert, W.
Geotechnical Group Graz, Graz University of Technology, Austria

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ABSTRACT: In weak rock or under high overburden, considerable displacements occur during excavation of tunnels and galleries. The strains developing in many cases exceed the deformability of standard linings, frequently leading to severe damages and the necessity of costly repairs. To allow for a safe and economical tunnel construction, strategies have to be used, which guarantee support characteristics compatible with the strains, and at the same time utilize the supports as much as possible.

After a review of traditional methods, mainly used in mining in the past recent developments to deal with high displacements in combination with modern standard supports, such as shotcrete and rock bolts are shown. The different systems currently available are critically reviewed. For the design of such supports the development of the expected displacements must be predicted and the time dependent properties of shotcrete considered. Special tools have been developed to predict displacements.

A relatively simple analysis method to design shotcrete linings with integrated steel elements, based on predicted displacements and the transient lining properties is used to demonstrate the effectiveness and practical applicability of the various systems available.

1. INTRODUCTION

Large displacements during excavation of tunnels due to poor rock and high stresses are a challenge for designers and contractors. Displacements can reach several tens of centimeters, in some cases displacements of one meter and more have been reported [1,2]. Associated with those large displacements are difficulties in predicting their magnitude and development, as well as problems of the limited deformability of standard supports. Tunnel supports on the one hand should provide as much resistance against deformation as possible, on the other hand should be able to sustain the large imposed strains. Various methods have been developed over the decades to cope with the difficulties. This paper addresses some aspects of consequences of large displacements in relation to the lining design. This includes a review of support techniques used in the past and recent developments of yielding supports, and the experience made with their application on site.

2. DEVELOPMENT OF SUPPORTS FOR LARGE DISPLACEMENTS

A traditional method in mining when experiencing large displacements was to use U-shaped steel sets with sliding couplings in combination with wire mesh or lagging.

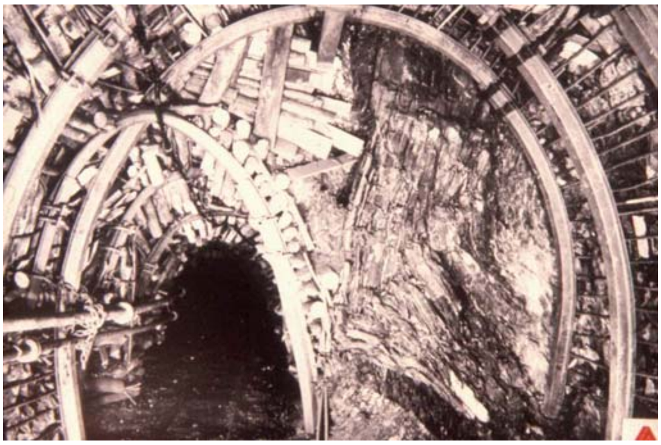

Figure 1. Destroyed steel set support with sliding couplings. Photo: DMT

Figure 1 illustrates the deficiencies of such supports. In particular in cases of anisotropic deformation the steel sets buckle, and costly and dangerous repairs are required. Timber supports had to be replaced many times until stabilization was reached.

2.1. *Timber elements*

With the introduction of concrete and shotcrete linings in the late nineteen fifties, the previous problem of excessive loosening diminished, but the comparatively low deformability of concrete lead to destruction of the lining in case of larger displacements. Rabcewicz proposed timber elements integrated into a concrete lining as early as 1950 to provide sufficient deformation capacity of the system [3]. Depending on the required ductility and resistance different types of timber can be used.

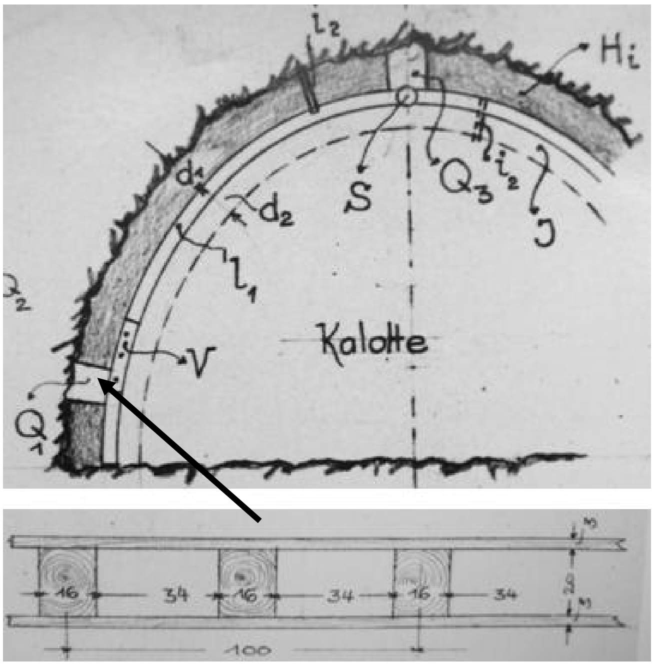

Figure 2. Concrete support with integrated timber element, as proposed by Rabcewicz [3]

2.2. *Open slots*

The improvement of the tunneling technique during the nineteen sixties, in particular the increased use of shotcrete and rock bolts, considerably reduced the problems in poor ground. Severe problems with considerable displacements and destruction of the shotcrete lining were experienced in a fault zone at the Tauern tunnel in the Austrian Alps in the early nineteen seventies [4]. To prevent the failure of the shotcrete, open deformation slots were left in the lining, which closed with deformation. In combination with a dense bolting, this concept worked quite well. The same concept was later used at the Arlbergtunnel [5], the Karawankentunnel [6] and Inntaltunnel [7,8] in western Austria with quite some success. The relatively homogeneous, although extremely poor rock mass conditions in those projects contributed to an execution without major technical problems.

A serious collapse occurred during the excavation of the Galgenbergtunnel in a very heterogeneous fault zone, where also open slots in the lining in combination with heavy rock bolting had been used. The investigation into the accident showed that among other factors contributing to the failure, a certain resistance of the lining would at least have slowed down the evolution of the failure [9].

3. YIELDING ELEMENTS INTEGRATED IN LINING

The need to better utilize the linings in combination with the required ductility has led to the development of a number of different yielding elements.

3.1. *Requirements*

Support for tunnels in fault zones nowadays commonly consists of reinforced shotcrete, steel sets and rock bolts. To cope with the large displacements, a certain strain tolerance of the support elements is required. Unfortunately the highest strain rates are imposed on the lining when the strength of the shotcrete is lowest. To avoid overloading of the shotcrete in its early age, the response of the yielding elements to strains immediately after installation has to be rather “soft”. Besides the final magnitude of the displacements, the displacement characteristics and the advance rate influence the evolution of the displacements over time.

Additional factors to be considered for a design of ductile linings are the strength and stiffness development, as well as creeping and shrinking of shotcrete.

3.2. *Yielding steel elements*

Following the accident on the Galgenberg tunnel ductile steel elements, which are integrated in the shotcrete lining were developed at the Institute for Rock Mechanics and Tunnelling at the Graz University of Technology [9]. The system consisted of a set of steel pipes with a foot and head plate. The onset of the buckling should start before the capacity of the lining was reached.

Figure 3. Buckling of steel tube in the laboratory test.
Foto: Schubert

The required capacity can be controlled by the number of tubes per element. Experiments showed that the load to initiate the initial buckling is relatively high, and after the first peak a strong drop in the resistance was found. To ease the initiation of buckling, the tubes were weakened by drill holes or reduction of the section by slots. The system was then successfully used at the Galgenbergtunnel, as well as at the Strenger tunnel in western Austria.

Development of Lining Stress Controllers (LSC)

The resistance of the yielding steel elements shown above varies in a wide range, depending on the state of buckling. Moritz conducted research with the aim to decrease the variation of the load with shortening of the tubes, and thus increase the energy absorbed by the elements [10].

Following requirements had to be met:

- Relatively low initial resistance to account for the strength development of shotcrete
- Small variation in resistance after reaching the peak load
- Use of standard, off the shelf elements

After a series of tests and a number of numerical simulations, a system of concentrically arranged tubes emerged as the most feasible solution (see Figure 4). The guiding tubes influence the buckling of the load tube, in this way smoothen the load line. Different dimensions of tubes were chosen, with a capacity of up to 700 kN per tube.

Figure 4. Left: section through improved yielding element with concentrically arranged steel tubes [10]; right: group of 4 elements assembled for the installation in the lining

The system shown above is produced by ALWAG and known in the market as LSC (Lining Stress Controller) and has been used on a number of projects in Austria, Switzerland, Slovenia, and Greece.

One of the critical issues, when applying such systems with shotcrete linings is the time dependent hardening of the shotcrete in combination with the highest displacement rates immediately after installation of the lining. To provide a soft response of the lining system, not all elements in a group have the same length. Figure 5 shows the development of the load over shortening for a 4-element LSC Type II. It can be seen, that the peak load is reached after about 80 mm of shortening. The peak load for this type is approximately 2.500 kN, and the load variation during further shortening due to the buckling is between 200 to 400 kN.

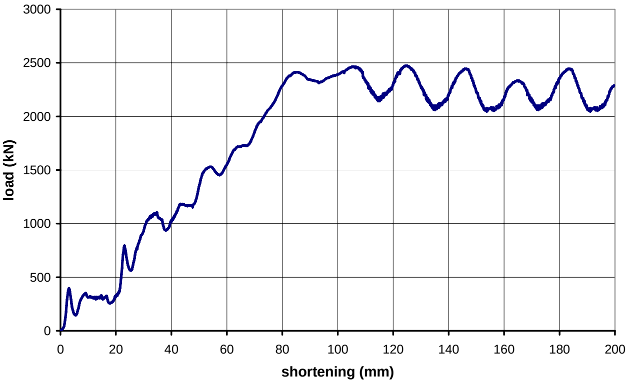

Figure 5. Load versus shortening of a 4-element LSC (length 90 cm)

BE yielding elements

With the construction of a number of tunnels in the Alps, the demand in ductile linings increased. This demand triggered the development of a number of yielding elements in different layouts.

One system, which also uses steel tubes, is produced by Bochumer Eisenhütte. The steel tubes are loaded perpendicular to their axis, which leads to an oval shape, when loaded. Several tubes are arranged parallel and in layers (see Figure 6).

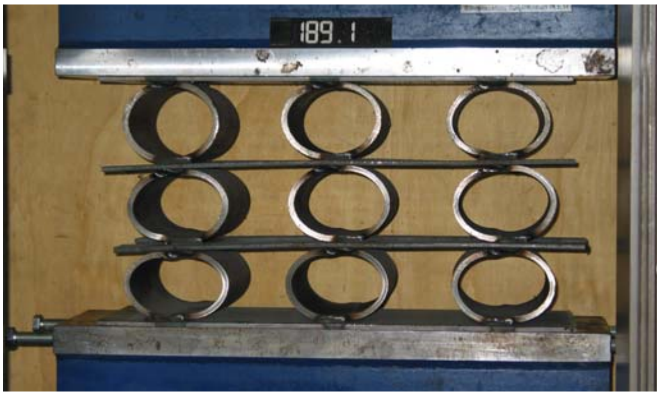

Figure 6. Yielding steel element, as produced by Bochumer Eisenhütte (BE)

Inserts of smaller diameter tubes can be used to increase the resistance. The response of the element to loading is rather smooth. However, due to the direction of loading the resistance developing on the first 200 mm of deformation is rather low (Figure 7), when compared to the LSC elements. At the same time, the steel consumption for one element is higher than for the LSCs.

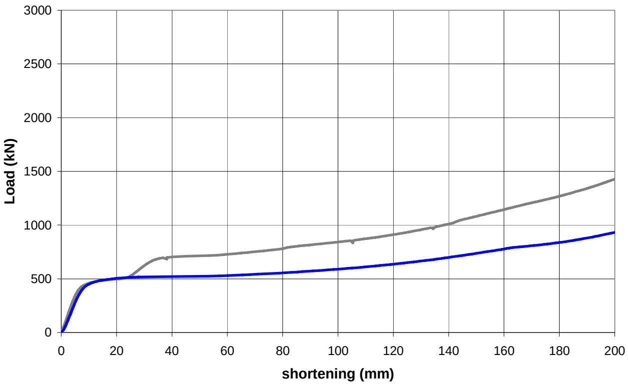

Figure 7. Shortening versus load for the BE elements; lower line without inserts, upper line with inserts (length 100 cm)

Cement based elements

At least two producers attempted to produce yielding elements based on deformable concrete. One of those is the so called HiDCon element, which is distributed by Solexperts, Switzerland.

Figure 8. HiDCon element installed in shotcrete lining (from (12)

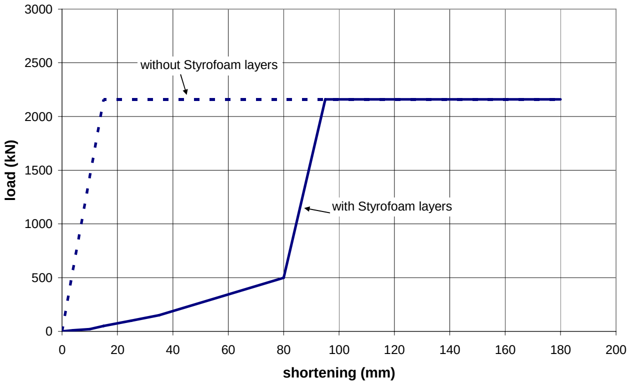

Figure 9. Load versus shortening for HiDCon element with a length of 90 cm, simplified from [11]

The elements are composed of a mixture of cement, steel fibers and hollow glass particles and a transverse reinforcement [11, 12]. The characteristic of those elements is a very stiff response, reaching a relatively high load already at approximately 2% of strain.

Considering the relatively low strength of young shotcrete, this stiff response easily leads to damages of the lining. Reportedly, Styrofoam sheets of a thickness of 40mm have been used on the top and bottom of the elements at the Lötschberg Basis tunnel to prevent failure of the lining at an early stage. This Styrofoam inserts prevent failure of the lining, but on the other hand lead to a practically zero resistance of the elements (and thus the lining) until the inserts are totally compressed.

Compex element

A similar approach was chosen by Schretter, Austria. Styrofoam bubbles are mixed with cement; in addition a light wire mesh is used to control the inevitable disintegration of the elements.

Figure 10. Compex element in laboratory test [13]

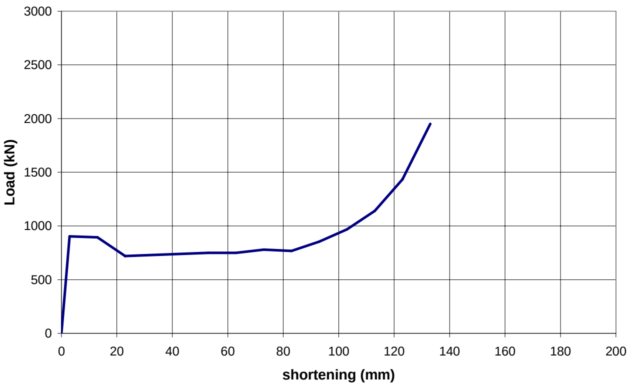

Figure 11. Load versus shortening for Compex element with a length of 90 cm, derived from [13]

Figure 11 shows a very stiff initial response, an then a constant load level over about 100 mm of shortening. Site tests with this system on the Tauerntunnel due to the complete disintegration of the elements were not successful.

3.3. *Comparison of yielding elements*

The comparison of the element types LSC, HiDCon, and BE is done first in terms of lining utilization for a given imposed displacement, and activated support resistance. Then the accumulated energy in the single yielding elements is shown over a shortening of 150mm.

A case was chosen with a tunnel of 10 m diameter, a final radial displacement of about 30 cm, an advance rate of 3 m/day, a shotcrete final strength of 25 MPa, and a lining thickness of 35 cm. Six elements with a length of 50 cm each are installed in all cases. The model used for the calculation of the lining utilization assumes radial symmetric displacements, time dependent development of shotcrete properties and deformation behavior of the yielding elements. The response of the shotcrete is modeled with the rate of flow method [14]. The approach of Guenot et al. is used for modeling the evolution of displacements [15].

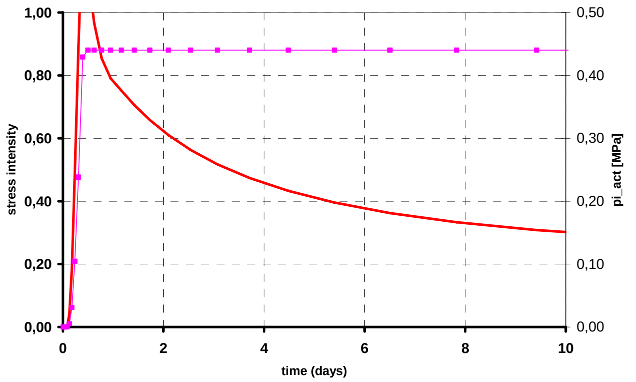

Figure 12. Development of stress/strength ratio (stress intensity) and radial support pressure (pi_act) for a HiDCon element without Styrofoam inserts

As can be seen from Figure 12, the capacity of the lining is exceeded within a few hours after installation. This has shown also on site. The situation with 2x4cm Styrofoam layers on each side is shown in Figure 13. Although the stress in the lining is slightly below the strength, a strong peak can still be observed due to the stiff reaction of the element after the Styrofoam layers are compressed.

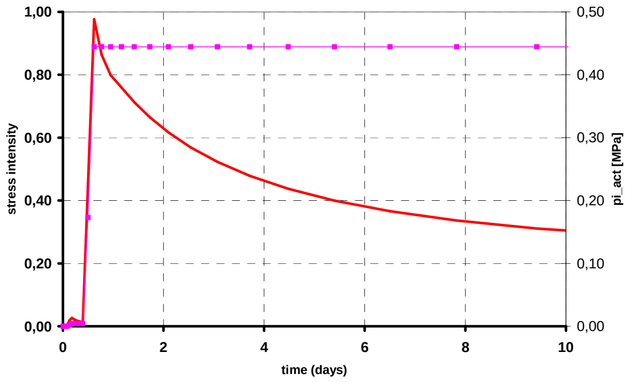

Figure 13. Development of stress/strength ratio (stress intensity) and radial support pressure (pi_act) for a HiDCon element with Styrofoam inserts

The support resistance developing with this system is approximately 0,45 MPa, when neglecting shear bond between lining and ground. Due to the increase in the shotcrete strength and creeping, the lining utilization rate drops with time to about 30%.

Figure 14 shows the poor utilization of the steel with the BE elements. The relatively stiff response in the beginning of loading yields stress a intensity peak of some 35% within the first day. The utilization rate then drops to around 10%. The activated lining resistance is around 0,15 MPa.

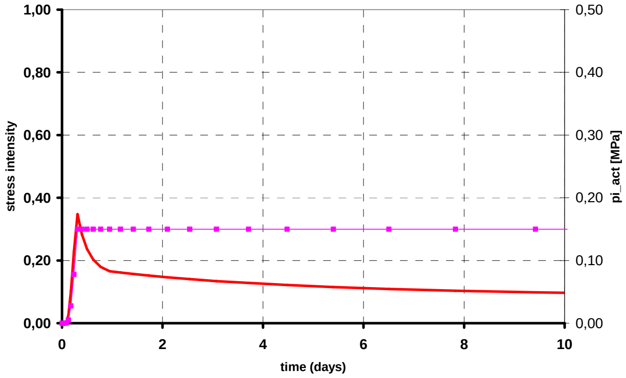

Figure 14. Development of stress/strength ratio (stress intensity) and radial support pressure (pi_act) for a BE element with additional steel inserts

As last example the development of a 4 tube LSC element is shown in Figure 15.

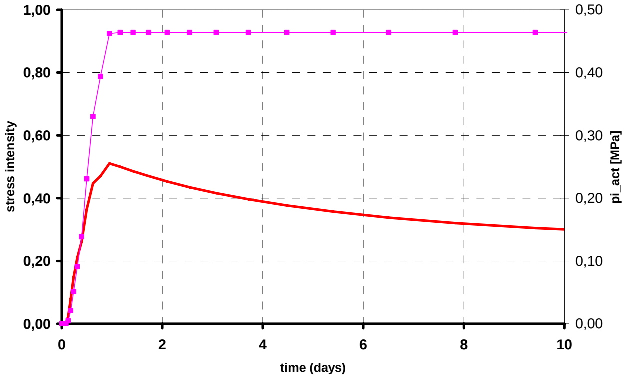

Figure 15. Development of stress/strength ratio (stress intensity) and lining resistance (pi_act) for a 4 tube LSC element

Due to the smooth initial response of the system, the lining utilization ratio never exceeds 50%, and decreases to about 30% with the development of shotcrete strength. The activated lining resistance is slightly below 0,5 MPa.

This simple comparison clearly shows that the layout of ductile lining systems has to be done with great care.

Although the accumulated energy does not indicate if the elements work properly under site conditions, it can serve as an indicator for material utilization. Table 1 shows the accumulated energy of above element types for a shortening of 150mm.

It shows that the HiDCon element without Styrofoam layers accumulates the same energy as the LSC, while with Styrofoam it yields only 63%. The BE elements, although a lot of steel is used – one element weighs about 100kg – accumulates less than half the energy of a LSC element.

Table 1. Accumulated energy after 150 mm of shortening

Element	Energy (kNm)	% (LSC = 100%)
HiDCon 1)	307	100%
HiDCon+Styro	195	63%
BE w/o inserts	109	35%
BE w inserts	147	48%
LSC 4-tube	307	100%

1) stiff reaction without Styrofoam inserts leads to damage of the shotcrete

4. CONCLUSION

A number of factors have to be considered, when designing supports for tunnels with large displacements. Key issues are the adjustment of the system to the evolution of the displacements with respect to the face advance, and the development of the shotcrete strength over time. Relatively sophisticated material models for shotcrete have to be used to obtain a realistic interaction between displacements and support reaction. Most critical for the lining system are the first one or two days, when the displacement rate is highest and the shotcrete strength lowest. Ductile elements integrated into the lining have a rather soft response to initial loading to prevent lining failure at those early stages. The comparison shows that cement based elements tend to build up load rather quickly, while with steel elements the reaction to loads can be more easily controlled. In order to prevent failure of the lining, additional soft layers, such as Styrofoam have to be used in combination with cement based elements.

One of the aims is to provide as much support resistance against displacements as possible, and at the same time protect the lining against damages. This is expressed as accumulated energy over shortening. In this respect, the LSC elements due to their controlled initial response show the best results. The BE elements appear to be rather uneconomical due to their poor ratio between steel used and performance.

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