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Investigations on telescope yielding elements with porous filling

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ABSTRACT: Tunnelling in weak ground and under high overburden always proves to be challenging during the design and construction phase. Currently, tunnels are constructed with great lengths, which increases the probability of crossing tectonic fault zones under high overburden. These geological conditions are commonly associated with high loads and massive deformation of the lining. The idea of using ductile elements in the lining has become a well-known practice in such conditions. During the last century, different solutions have been developed. In this paper, the focus is on Telescope-Yielding-Elements (TSR). The big advantage of these elements is that force-oscillation can be reduced to an insignificantly low level and the deformation behavior can be controlled by the use of porous fillings, different types of steel pipes and additional free space. We discuss the results and show the scope of application of such elements. In addition, we highlight how minor modifications of the element configuration can look like to suit Telescope-Yielding-Elements to specific project conditions.

1 INTRODUCTION

Conventional linings have a tendency to suffer considerable damage in zones of poor rock mass conditions (e.g., tectonic fault zones) with high overburden, which subsequently leads to significant repair costs. To protect the lining from damage, the idea of using highly ductile elements in the lining has become a well-known practice in above-mentioned conditions. During the last decades, different solutions (e.g. yielding elements like the Lining Stress Controller (Moritz 1999), the WABE system (Eisenhütte Bochum) or the hiDCon system (Solexperts)) have been developed to mitigate the adverse effect these high deformations are prone to have on the shotcrete lining (Radončić et al. 2009).

Maximum displacement rates usually occur close behind the tunnel face, where the young shotcrete still has a low strength. Therefore, a yielding element with a deformation controlled stiffness behavior is required to protect the young shotcrete. Energy subjected to the lining and caused by deformation of the ground is transformed to deformation of the yielding elements. With increasing stiffness of the shotcrete lining, the stiffness of the yielding elements should increase as well. The ideal result would be a characteristic yielding-element curve that follows the characteristic time-dependent curve of the shotcrete capacity with respect to the advance rate and the stress regime, prevailing on site.

In 2011, Sitzwohl conducted lab trials on Lining Stress Controllers (LSC) at the Institute for Rock Mechanics and Tunnelling, Graz University of Technology. While conducting these tests, the principles of the Telescope-Yielding-Elements (TSR) were specified representing a further development of the LSC (Sitzwohl 2011, Radončić 2011).

The big advantage of the TSR elements is that force-oscillation can be reduced to an insignificantly low level and the deformation behaviour can be controlled by the use and modification of porous fillings.

1.1 Basic setup of the TSR

The basic arrangement of a TSR features two steel pipes in a telescopic arrangement with a height of 400 mm, containing a porous filler. Figure 1 shows the different components of the telescope element.

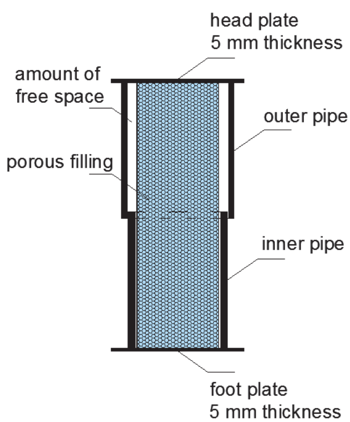

Figure 1. Telescope element (head and foot plate are made of S355 steel; other elements are described in Chapter 3).

At the beginning of the deformation, when the shotcrete has a low strength, the filler should carry the entire load. With increasing deformation of the ground and of the yielding elements, respectively, the filler compacts, increasing its resistance. Due to the lateral expansion of the filler, the steel pipes buckle, thus contributing to the load transfer. The filler is squeezed into the buckling folds preventing the otherwise inevitable drop in the system's resistance. Because now all free space within the element is depleted, a more or less constant increase of the load with displacement should follow.

2 REQUIREMENTS ON YIELDING ELEMENTS

The utilization of the shotcrete lining is amongst others directly linked to the time-dependent behaviour of the shotcrete and the displacement development of the rock mass. However, for the purposes of this study, full-face excavation was considered and influence of additional support measures (e.g. bolts) is neglected. To account for boundary conditions not considered with the approach described in this paper (sequential excavation, non-hydrostatic stress regime etc.) and to provide capacity reserves of the lining for deviating and unexpected boundary conditions, the maximum utilization of the shotcrete lining was limited with 80% of its capacity.
To arrive at an ideal load-displacement characteristic of the yielding elements, a MATLAB program (Mathworks 2014) was developed.

For the determination of this curve, amongst the usual parameters (e.g., tunnel radius, specific weight of the ground) the following one had to be considered:

- Time and force depending rheological behaviour of the shotcrete (Pacher 2010, Schubert 1988)
    - Shrinkage and creep of the shotcrete
    - Deformation caused by the loading
    - Age of the shotcrete
- Displacement development in relation to the face distance (Feder & Arwanitakis 1976, Panet & Guenot 1982, Radončić et al. 2008, Sulem et al. 1987)
- Advance rate
- Geometry of the shotcrete lining (number of gaps for the yielding elements, thickness of shotcrete)

Figure 2 shows two characteristic curves (black solid lines). For a specific tunnel project encountering different rock mass conditions, the upper curve relates to tunnel sections with higher rock mass quality, whereas the lower curve relates to sections with lower rock mass quality.

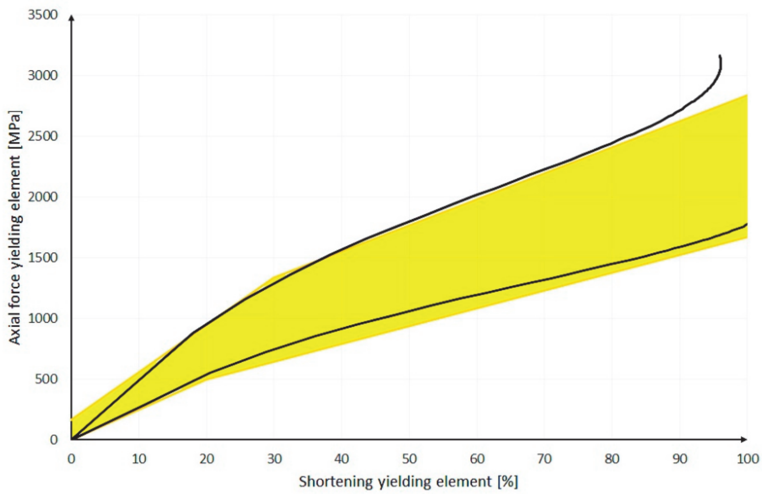

Figure 2. Ideal-characteristic curves of one single yielding element for two different rock mass conditions calculated with MATLAB.

The aim of the performed studies was to find an appropriate configuration of the TSR, which results in a force-shortening behaviour of the yielding element within the simplified range shown in Figure 2 (yellow region). In the following sections, the course of action of the studies is described.

3 MATERIALS

At the beginning of the deformation process of the TSR, the porous cement bonded filling should carry the load only in order not to overload the shotcrete. The steel pipes would be too stiff for the liner at this stage (yielding elements and shotcrete liner are installed; the shotcrete is still "green"). On the one hand, to get a large deformation (e.g. 5% for < 1,000 kN) of the TSR and of the filler, respectively, a high porosity of the filling material is required. On the other hand, it is necessary to ensure that the filling is not too porous, because the load capacity would decrease to an unacceptable low amount.

3.1 Filling

For the production of the porous cement bonded filling, following materials, singularly or in combination, and with various mixing ratios were tested:

- Portland cement (42.5 N/mm^2 compressive strength after 28 days of curing time)
- Expanded clay by Liapor (Liapor 2014)
- Sand, grain size < 2 mm
- Quartz sand, grain size 2 mm

3.2 Elastic / Plastic inlays

In some test series, different elastic or plastic inlays were tested. The purpose was to postpone the failure of the filling and obtain a smoother load development. Four different materials were tested. Two of them were made of rubber, one was a polyurethane plate and the last plate was made of cork. The plates featured a height of 2 cm.

3.3 Steel pipes

The steel pipes in the first test series were of the type S355 (construction steel with a yield strength of 355 N/mm^2). The inner pipe had an inner diameter of 126 mm and a wall thickness of 10 mm. The outer pipe had an inner diameter of 149.1 mm and a wall thickness of 8 mm. With these elements the desired level of deformation could not be reached.

Therefore, pipes with less wall thickness were used. The quality of these pipes was S235 steel (construction steel with a yield strength of 235 N/mm^2). The pipes had a wall thickness of 2 mm. The inner pipe had an inner diameter of 120 mm and the outer pipe had an inner diameter of 130 mm. With this set-up, a shortening of up to 73% was possible.

4 LAB TESTS

The tests were executed in the laboratory of the Institute for Rock Mechanics and Tunnelling, Graz University of Technology, with a servo-controlled compression test apparatus.

The procedure was the same for all tests. The load rate was set to 2 mm/min. The axial force as well as the axial displacement were recorded continuously. The maximal stroke of the machine is 10 cm. After 10 cm of compression, the installation of additional steel rings between the yielding element and the pressure cylinders was necessary to continue the test. Because of the hydraulic loading system, the load is limited to approximately 2,700 kN.

A few tests were aborted manually. Either because the maximal deformation was reached before the force limit, or because the set-up of the yielding element led to undesirable results.

4.1 Test results

The performed test series covered different types and combinations of elements and fillings. Exemplarily Figure 3 shows the force-shortening diagram of the very first test (test (1.1)). The element features massive steel pipes and a hexagonal shaped, porous cement bonded filling. After reaching the uniaxial compressive strength (UCS) of the filling material, a load drop occurs at approximately 1% of shortening. Due to the porosity of the filling and the free space between the steel pipes and the filler, for the next 20% shortening of the element the load increased very slowly. As the majority of the pores of the filling material has been closed and the free space has been filled with crushed filling particles, the force increased rapidly.

Because of the load drop and the long lasting, flat load development, the tested element set-up is not suitable. On the one hand, to avoid the load drop, the sudden shear failure of the filling had to be prevented. On the other hand, the element had to be adjusted in a way a higher resistance can be yielded at an earlier stage of deformation in order to follow the desired force-shortening development (yellow area).

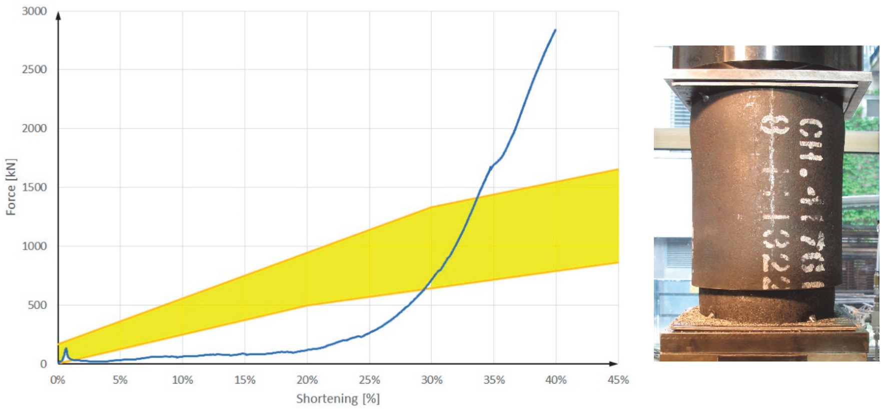

Figure 3. Left: Force-shortening diagram of test (1.1); Right: Yielding element (test (1.1)) before test execution.

Several ideas to modify the element were developed and tested (e.g., additional steel pipe with a wall thickness of 0.6 mm as lost formwork around the filler, different combinations of the inner and outer pipes to control the moment one of the pipes gets in contact either with the head plate or with the top plate). In another test series of lab tests (test (4.1) and (4.2)), different combinations of steel pipe lengths were tested. The idea was to mobilize more resistance after a certain amount of deformation, leading to a higher increase of the force. This worked quite well, but the first peak of the loading was above the characteristic area. Therefore, with minor modifications it was possible to delay this peak to a certain amount of shortening.

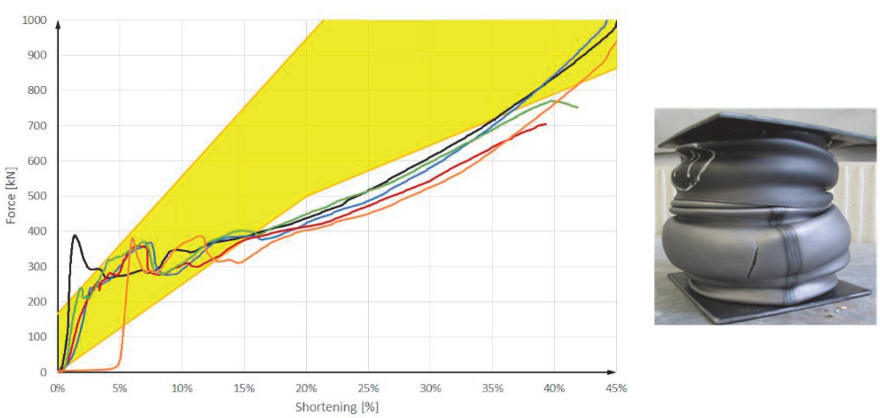

Figure 4. Left: Force-shortening diagram of following tests (all tests with same combination of steel pipes and filling mixture): (4.2), black line, without inlay – (5.1), blue line, cork inlay – (5.2), red line, soft rubber inlay – (5.3), green line, medium hard rubber inlay – (5.4), orange line, polyurethane inlay; Right: Yielding element (test (5.1)) after test execution.

In the fifth test series, four different inlays with a height of 2 cm and with different properties were tested. These inlays should postpone the point of the first peak, which means a slightly flatter trend at the beginning of the force-shortening curve. This also results in more time for the hardening of the shotcrete at site. The mixture of the filling was the same for all four samples.

With the last modification (installation of various inlays), we were able to eliminate the peak crossing the target range (cf. test (4.2), black line in Figure 4). However, the attained resistance of the yielding element between ~15% and ~40% of shortening is still below the target range. Increasing the wall thickness of the pipes, or slightly modifying the filler should solve this problem.

For a detailed report of all performed tests including steel pipe dimensions, filling mixtures, test procedure, test results and interpretation, we want to refer to Verient (2014).

5 CONCLUSION

After some try and error at the beginning, an appropriate combination of steel pipes and filler could be found, featuring a deformational behavior to be at least for the most part within the desired range. Contrary requirements – relatively high stiffness at the beginning, but with limited loading capacity at high deformation, and that following a gradually decreasing stiffness with a shortening of the yielding element of up to 40% – make it difficult to find a perfect solution upon the demands not to give up the favorable concept of yielding elements, to use materials available at site, and not to get too expensive with regard to industrial production. However, relatively thin walled steel pipes were found to be suitable as confinement for the filler. The filler itself contains a mix of cement, expanded clay bubbles, and sand. The unfavorable response of the elements to the initial loading could be eliminated by using inlays of various, high deformable materials. Additional fine-tuning is required to adjust the TSR suitable for specific project requirements. Such adjustments can be e.g. the use of different inlays, the modification of the properties of the filler, or a slight change of the pipe wall thicknesses.

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