ADECO-RS as an Alternative to SEM in the U.S.?

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1 INTRODUCTION

Recent tunnel projects using SEM (Sequential Excavation Method) in the U.S. include the Devils Slide Tunnel, the Caldecott 4th bore and the Stanford Linear Accelerator (LINAC) Tunnels in California, the Dulles Corridor Metrorail Project, a reach of the San Vicente Tunnel, the Michigan Street Pedestrian Tunnel, the Dulles International Airport People Mover and the San Diego Mission Valley East Extension as e.g. reported in the RETC (2005, 2007, 2009) proceedings. To the author’s knowledge the ADECO-RS method has not been applied to any major U.S. project so far.

Based on comparable boundary conditions the two excavation methods - SEM versus A.DE.CO-RS – are compared to each other. The paper describes three-dimensional FE calculations which show the varying ground and load-bearing behavior when simulating the two excavation methods.

The use of horizontal rock bolts ahead of face (fibre-reinforced anchors, micropiles, and the like) to stabilize the “advance core” has been pursued in Italy since the early 1990s. With the introduction of this support ahead of face, tunnels were driven by means of full-face excavation. It was discovered that the measures at the core constituted a means of stabilizing the tunnel. To make the design safe, the attention of the tunnel designer was directed to the interactive system "tunnel face - advance core". This concept was systematically implemented, starting from soil investigation, design, construction, to monitoring. The tunnel advance concept was designed as an “industrial” one, which in part resulted in exceptionally high advance rates. The system was named A.DE.CO-RS (acronym of the Italian term for Analysis of Controlled Deformations in Rock and Soils).

In comparison, in the typical SEM attention is basically paid to the deformations of the opening. The three essential characteristics are:

- ground considered as a load-bearing element mobilized by rock bolting
- enhancing ground reaction using shotcrete
- control of deformations by adaptation of support measures using systematic measurements

Advance conservation techniques, such as inclined face, face buttress, pre-cutting support techniques, horizontal face anchors, horizontal micropiles, flexible support systems and advance improvement techniques, such as ground freezing, jet grouting and drainage systems can easily be adopted using SEM.

This paper systematically compares the two methods SEM and ADECO-RS under the same boundary conditions, with regard to mechanical properties taking account of the varying behavior in the course of the ongoing excavation process on the one hand, and on the other with regard to construction sequences.
2 EXCAVATION METHODS
In the New Austrian Tunneling Method (NATM) often described as Sequential Excavation Method (SEM) the initial support to the rock is provided by a shotcrete primary lining including steel ribs and mesh reinforcement, rock bolts and spiles. This yielding support reduces the rock pressure through movements. The pressure is redistributed to the surrounding rock. A “load-bearing ring” of the rock is thus mobilized. It is only after the rock deformations have subsided that the final lining will be installed. This makes the final lining subject to less stresses, allowing the installation of a lining of significantly less thickness.

In the A.DE.CO-RS method new terms of reference were introduced in order to describe the deformation response globally:
- The advance core is the volume of ground that lies ahead of face with a height and diameter approx. the same size as the diameter of the tunnel,
- the extrusion is the deformation response inside the advance core depending on the strength and deformation properties of the core,
- the preconvergence is the convergence of the theoretical profile of the tunnel ahead of face. It was determined that there is a close connection between extrusion of the core at the face and the phenomenon of preconvergence of the tunnel. Further, a consequent manifestation of instability was postulated (category A: fall of ground, category B: failure of the face and category C: collapse of the cavity).

According to the method all deformation behaviors (extrusion, preconvergence and convergence) and all manifestations of instability depend, directly or indirectly, on the rigidity of the advance core. Therefore the advance core was determined as a point of reference for the tunnel specifications. It is proposed to divide the underground works into the following phases: survey phase, diagnosis phase, therapy phase, construction phase and monitoring phase. Conservation techniques which are commonly used for the A.DE.CO-RS approach are summarized in Lunardi (2008), including an overview of additional literature.

3 NUMERICAL ANALYSIS
This chapter describes the main results of 3-D numerical studies to investigate the special features of a full-face excavation according the A.DE.CO-RS method using fibre-glass elements in front of the face of a full excavation scheme in comparison to the classic SEM with a heading, bench and invert excavation.

3.1 Tunnel Geometry
The example chosen represents a typical cross-section which is used in three-lane road tunnels in Austria. The tunnel has a cross-section with a height of approx. 7 m and a width of approx. 14 m. A flat invert arch has been assumed (approx. 3.9 m below street level). An equivalent tunnel area of 140 m² is considered, resulting in a theoretical tunnel diameter D of 6.7 m. The groundwater level was assumed to be below the tunnel.

3.2 FE Model
The 3D Finite-Element program “Plaxis 3D Tunnel” is used for the calculations, Brinkgreve et al. (2001). Because the geometry is symmetric only half the boundary problem needs to be considered. The circumferential boundaries are restrained in both the x and y directions. The ground surface is free to move, the bottom of the model is fully fixed.

The dimensions of the Finite-Element mesh are chosen in such a way that the impact of the cavity on the edges of the FE mesh has subsided. The length of the model depends strongly on the excavation method and has to be evaluated depending on the relevant excavation phases in longitudinal direction.

The ground is modeled with 15-node wedge elements using Mohr-Coulomb's constitutive model. In order to model time-dependent behavior of the shotcrete (creep and hardening), two stiffnesses of the shotcrete lining (initial support measure) are taken into account, i.e. John et al. (2003). For a short time after tunnel lining installation “young” shotcrete with \( E = 7500 \text{ MN/m}^2 \) is used. For a long-term period “mature” shotcrete with \( E = 15000 \text{ MN/m}^2 \) is applied. This change of
lining properties was activated three round lengths behind the face, which corresponds to a shotcrete age of approx. 2 - 3 days.

The characteristics of additional support measures as well as the specific excavation phases are described separately for the two excavation methods:

**SEM model:**
- the thickness of the shotcrete lining was assumed to be 35 cm.
- rock bolts - radial SN anchors installed from the tunnel - were modeled by equivalent FE-plate elements with a length of 6 m. The activation of the anchors was simulated parallel to the relevant activation of the shotcrete lining.
- the steel ribs (e.g. lattice girders) are not included in the FE calculations as they only increase the stiffness of the lining insignificantly due to the large distance between the steel ribs and due to the fact that the ribs are embedded in the shotcrete (not active in the elastic state of the shotcrete).
- spiles are not included in the calculations as they are of little static relevance and mainly serve to provide safety at the face.
- no support ahead of face was considered.
- the final lining was not taken into account as it will be installed after the rock deformations have subsided.
- excavation phases: the "step-by-step tunneling sequence" was applied using the phased analysis option available in the FE program used. Separate excavation phases for heading, bench and invert each with separate application of the young/mature shotcrete were considered. A round length of top heading excavation of 1.3 m was used. The subsequent excavations of bench and invert were minimized by following the heading excavation at a distance of approx. 30 m and 45 m respectively in order to reduce the model length to save computation time.

**A.DE.CO-RS model:**
- the thickness of the shotcrete lining in the tunnel heading was assumed to be 30 cm.
- no rock bolts were used.
- the steel ribs were taken into account as they are placed on the outer side of the initial sup-port shotcrete and therefore act immediately as a support measure (active in the elastic state of the shotcrete). Two HEB180 ribs were installed after each round length of 1.3 m.
- no spiles were used.
- for the support ahead of face fibre-glass structural elements were considered. One anchor consists of three fibre-glass plane elements 40 x 6 mm and grouting pipes. Four face anchors in reality are replaced by one equivalent numerical anchor placed in the centre of gravity of the replaced anchors (to save computation time). The active length of the anchors in front of the face is constantly approx. 17 m. The anchors are modeled with

![Figure 1: FE model for SEM.](image)
a diameter of 0.4 m. In order to describe a realistic material behavior the anchors are modeled with the Mohr Coulomb failure criterion.

- the final lining is modeled by means of volume elements (15-node wedge elements) with an elastic behavior. The modulus of the concrete of the final lining is determined according to the predetermined concrete class. The thickness of the final lining heading has been assumed to be 45 cm and that of the invert arch to be 90 cm.
- excavation phases: a "step-by-step tunneling sequence" was applied using the phased analysis option available in the FE program used. The excavation is carried out as nearly full-face excavation. Only the area of the tunnel invert has to be excavated just before casting the final invert lining approx. 10 m behind the face. A round length of 1.3 m is used. The final lining of the heading follows the face at a distance of approx. 25 m.

Figure 2: FE model for A.DE.CO-RS method.

3.3 Ground properties
Excavation through homogeneous ground was considered. Two different ground types were selected in the analysis describing relatively weak rock, such as limestone of varying degrees of weathering and disintegration, consisting of bedding of dense claystone, siltstone, marl and marlstone.

<table>
<thead>
<tr>
<th>Parameter Set</th>
<th>E modulus $E$ [MN/m²]</th>
<th>Friction angle $\varphi'$ [°]</th>
<th>Cohesion $c'$ [kN/m²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>300</td>
<td>27.5</td>
<td>150</td>
</tr>
<tr>
<td>II</td>
<td>140</td>
<td>25</td>
<td>65</td>
</tr>
</tbody>
</table>

Table 1: Ground Properties.

A unit weight of $\gamma = 24$ kN/m³ was assumed with Poisson's ratio of $\nu = 0.25$. The overburden of the tunnel is chosen to be 40 m. The initial stress conditions in the ground are defined by the specific weight $\gamma$ and the coefficient of lateral earth pressure $K_0 = 0.5$.

3.4 Comparison of numerical results

**Stress arching:** Every excavation state implies a change to the stresses and strains around the tunnel. Especially in the intermediate construction stages the structure is subject to the greatest amount of stress as the disturbance is not yet fully supported by the lining. Generally the pre-existing stresses in the rock mass will be deviated by the tunnel excavation and will be channeled around the tunnel. This redistribution of stresses takes place as:

a) arching effect around the tunnel,
b) arching effect along the tunnel axis,
c) dome effect in front of the tunnel.

The combination of these effects determines the resulting stress and strain state.
Figure 3: Resulting mean effective stresses due to SEM excavation (left) and A.DE.CO-RS excavation (right).

Figure 3 compares the stress states at the face, depicting the principal stress trajectories (mean effective stress crosses) of the two tunnel excavation methods. While the SEM excavation only mobilizes small stresses arching ahead of face, the A.DE.CO-RS advance shows marked stress effects:

- as a result of support ahead of face (face reinforcement) the dome effect in front of the face is much more pronounced.
- the short distance of the invert to the face leads to stress arching which extends from ahead of the face to below the rigid support of the invert.
- the relatively short distance of the permanent lining to the face results in marked stress arching between face and permanent lining longitudinally above the crown.

A comparison shows that the shape of the cross-section and the face as well as the stiffness of the area ahead of the face decisively influences the stress and deformation state. The cross-section should be as circular in shape as possible and the face should have a concave shape.

**Axial Deformation at the Tunnel Face:** The effect of face reinforcement is illustrated in Fig. 4 in a plot of the excavation rate (Plaxis: MStage 0 ÷ 1) of slice A versus the horizontal face displacement $\Delta z$ approximately 2 m below the crown. In this context the excavation rate of slice A should be considered as various stages of face pressure release. A comparison of the SEM sequential excavation with the full face excavation of A.DE.CO-RS with respect to this deformation behavior indicates that the face axial displacement is significantly reduced for face reinforcement with the A.DE.CO-RS method. In SEM excavation the face area is much smaller, the stability of the face is fulfilled without additional measures taking present ground properties into account, but still there is an pronounced increase in horizontal face displacement. This indicates a high degree of full mobilization of strength (plastic zones) around and in front of the tunnel face.

Figure 4: Face axial displacements due to excavation of slice A: SEM versus A.DE.CO-RS.
This accumulative increase of the horizontal face displacements as a function of the tunnel advance has been determined by Lunardi (2008) as the extrusion rate of the tunnel face. Fig. 5 illustrates that this extrusion rate for the case of top heading excavation (SEM) is more than three times higher than in case of face excavation according to the A.DE.CO-RS method.

**Figure 5: Accumulative development of axial displacements due to excavation: SEM versus A.DE.CO-RS.**

**Vertical Displacements at the Tunnel Face:** Several authors, such as Kovari (2000), Lunardi (2008), Brandl (2000), Poma (2001) and Yoo & Shin (2003) have proven that the effect of face reinforcement affects the vertical deformations on the tunnel crown as well as on the surface positively. The plot in Fig. 6 (left) illustrates a point located on the crown of the tunnel still to be excavated (slice 21). When plotting the vertical displacement on a graph as a function of the tunnel advance it can be visualized that the pre-convergence (as determined by Lunardi (2008)) starts at a certain distance of the considered point from the tunnel face. The amount of settlement depends on the strength and deformation properties of the ground in front of the tunnel face (see Fig. 6, right).

**Fig. 6: Vertical displacements at the tunnel face: SEM versus A.DE.CO-RS.**

Pre-convergence rate of both methods is almost the same, the convergence rate after installation of the initial support is slightly higher with SEM excavation. However, for both methods poor soil conditions considerably increase the settlement for both pre-convergence and convergence.

**Settlement behavior:** Fig. 7 indicates that both methods, A.DE.CO-RS with full-face excavation and SEM with top heading excavation, show a similar settlement behavior. The reason is the fact that the A.DE.CO-RS method uses face reinforcement, whereas the SEM excavation face area is much smaller.
3.5 Sensitivity Analysis
The above calculations for A.DE.CO-RS were carried out assuming that the final invert lining is approx. 10 m behind the face. The final lining of the heading follows the face at a distance of approx. 25 m. Additional calculations were done with a greater distance of the final lining from the face. The distances of the final lining to the face depicted in Fig. 8 (left) significantly limit the possibility of a backup system suitable for construction. That is why numerical studies were undertaken to determine the influence on the system behavior when changing the backup of the final lining. The sensitivity analyses show that the system reacts very sensitively when changing the distance of the invert arch of the final lining (marked increase of deformations), while much smaller displacements occur when the distance of the upper part of the final lining is changed. The reasons are, in addition to the assumed ground properties, especially the already rather stiff primary support on account of the massive steel ribs. The distance depicted in Fig. 8 (right) of the final lining to the face result in negligible larger deformations as compared to the initial situation (Fig. 8 – left) which significantly facilitate the practical work sequence. However, it has to be noted that this sensitivity analysis is only valid under the assumption of the considered range of ground properties. With markedly poorer soil parameters these effects cannot be expected.

3.6 Summary
The objective of this study was to compare the classic SEM which uses sequential excavation (heading, bench, invert) to the A.DE.CO-RS method. To this end almost equal tunnel cross-sections were used. For the analyzed soil parameters no additional face support is required for SEM, the face of the top heading remains stable. A comparison under these boundary conditions shows that:

- the shape of the cross-section and the face as well as the stiffness of the area ahead of the face decisively influences the stress and deformation state. The cross-section should be as circular in shape as possible and the face should have a concave shape.
the face axial displacement is significantly reduced for the case of face reinforcement. In SEM excavation the face area is much smaller but still there is a rapid increase in horizontal face displacement indicating full mobilization of strength in front of the face.

- face reinforcement affects the vertical deformations on the tunnel crown as well as on the surface (settlement behavior) positively.

Under the given boundary conditions it becomes apparent that the two excavation methods yield equal results. The larger deformation of the advance core in SEM advance is compensated by a significantly smaller face area when using sequential excavation. However, it has to be noted that in case of complex boundary conditions (such as intersections, widening sections, cavern excavations) the advantages of the SEM method as compared to A.DE.CO-RS increase markedly (see Marcher et al. 2008).

4 CONCLUSIONS

A.DE.CO-RS or SEM? In general it is always difficult to figure out the most economic method for a specific project. The numerical studies show that the two advance methods - for the example chosen - provide comparable results with respect to the deformation behavior. The FE results illustrate that especially the face reinforcement positively influences the deformation mechanisms allowing excavating larger cross sections.

The SEM method is able to optimize both the construction process and the support measures with a positive effect on the investment costs. But it requires more detailed observation of the ground behavior during construction and a high degree of technical interest of all involved parties. It also requires transparent rules and regulations and precise contractual relationships. The A.DE.CO-RS method does not allow quick respond to changing geotechnical conditions. The full face excavation requires special attention to the face stability and a quick ring closure of both primary support as well as the final lining. The cast in place final lining operation which takes place concurrently with the excavation has to take into account special technical issues such as concrete quality control and mass concrete effects.

The potential of a greater degree of mechanization by using A.DE.CO-RS has to be compared with the higher flexibility provided by SEM. A great part of the cost advantages that result from increased efficiency by using an “industrial” full face excavation are lost due to expensive arrangements for the support ahead of face, for heavier primary lining and for a thicker mostly reinforced inner lining.

LITERATURE