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Interaction between
portal wall and tunnel advance

Master's Thesis

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Supervisor

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AFFIDAVIT

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Acknowledgements

Ich möchte an dieser Stelle meiner Familie danken – Adelheid, Axel und Lisa, die mich während meiner gesamten Ausbildungszeit unterstützt und meinen Abschluss erst möglich gemacht haben.

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Graz, Jänner 2018 Felix Laubreiter

Abstract

In this thesis, three-dimensional numerical calculations of a tunnel in weathered rock with shallow overburden are examined.

The simulation of a sample tunnel was used as a basis to create various models and determine the influence of the tunnel advance on the portal wall. It is intended to prevent damage to the portal wall support caused by tunnel displacements. The geological conditions and execution documents of the Granitztal tunnel chain were used as a basis to imitate the conditions surrounding the tunnel and to create a realistic simulation of the excavation process.

The evaluation of the data focuses on the displacements of the shotcrete liner of the portal wall, the utilization of the anchors and the shear stress occurring in the shotcrete liner.

Kurzfassung

In dieser Diplomarbeit werden die dreidimensionalen numerischen Finite Elemente Berechnungen von Tunneln in verwittertem Gestein mit kleiner Überlagerung betrachtet.

Die Ausführung eines Beispieltunnels wurden als Grundlage verwendet, um verschiedene Modelle zu erstellen und den Einfluss des Tunnelvortriebs auf die Portalwand zu bestimmen. Es sollen Schäden an der Portalwandsicherung verhindert werden, die durch Verschiebungen auf Grund des Tunnelvortriebes auftreten. Die geologischen Gegebenheiten und Ausführungsunterlagen der Tunnelkette Granitztal wurden als Basis verwendet, um die Gegebenheiten nachzuahmen und eine realitätsnahe Simulation zu gewährleisten.

Die Auswertung der Daten fokussiert auf die Verschiebungen der Spritzbetonsicherung, die Ausnutzung der Portalwandanker und die Scherbeanspruchung des Spritzbetons.

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Abbreviations

GT ....Granitztal

DG.................Deutsch Grutschen

LB..................Langer Berg

MC.................Mohr-Coulomb

HB ....Hoek-Brown

NATM ....New Austrian Tunnelling Method

TBM...............Tunnel Boring Machine

RS 3 ....Rock And Soil 3

BM.................Basic Model

RM.................Reinforced Model

USM ....Uncoupled Shotcrete Model

1 Introduction

Excavating a tunnel in rock demands an installation of support in form of sprayed concrete, anchors, bolts and similar measures to guarantee a safe work environment and a stable tunnel. Subsequent advances of the tunnel construction are causing deformations of the surrounding rock mass. Excavations in shallow overburden with weak, weathered rock mass or slope debris have to be passed through before entering sound rock mass. Therefore, displacements in the portal area tend to be comparatively larger due to the poor rock quality of the ground. The influence from the excavation advance on the portal wall is examined and useful hints for the designer should be established to optimize the support.
During the construction of the Koralm railway tunnel Langer Berg between Carinthia and Styria in Austria, the portal wall suffered larger displacements than expected. In order to prevent such problems the portal wall construction and the tunnel excavation were modelled with finite element software and the results analysed.

1.1 Aim of Research

The advance in the tunnel excavation influences the stress distribution and the displacements at the tunnel portal. This master's thesis deals with the study of the interaction between the excavation progress and the displacements at the portal wall, to avoid support problems at the tunnel portal area.

The evaluation of the deformation behavior of the portal wall in dependence on the excavation progress is the focus of this thesis. The influence of the displacements created by the tunnel excavation on the support of the tunnel portal is investigated.

A numerical simulation of the tunnel construction, inspired by the example project tunnel Langer Berg, is created in 3D finite element program RS3. In the end a parameter study and a principle is developed to provide guidance for the designing the portal wall support.

2 Example Project

In the course of the construction of the Koralm railway, completing the baltic-adriatic corridor, the tunnel chain Granitztal was built.

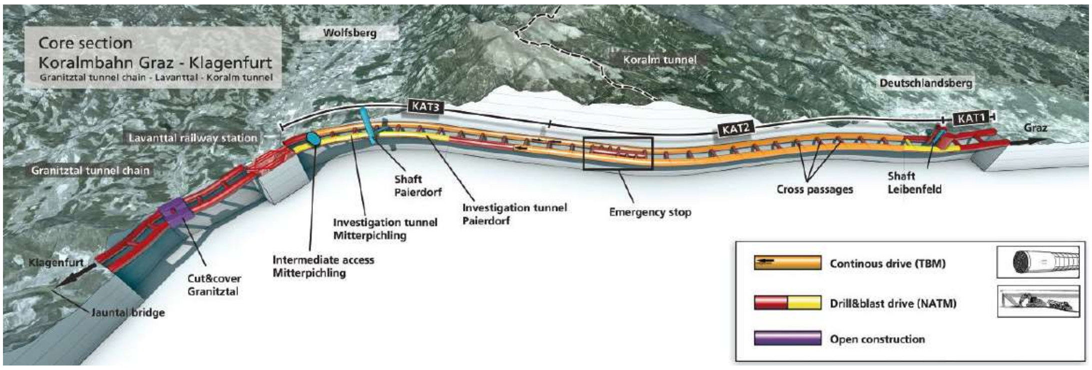


Figure 2.1 Project overview of Koralm Tunnel (Zwittnig 2017: 722)

2.1 Tunnel Langer Berg

The tunnel Langer Berg is located in the south west of Graz, Austria. It is built in the course of the Granitztal tunnel chain by the Austrian state railway company and is part of the Austrian high-performance railroad network and the Koralm Railway. It consists of the tunnel Deutsch Grutschen, the tunnel Granitztal and the tunnel Langer Berg. Both tunnels DG and LB were excavated with the sequential method, tunnel GT was built using the cut-and-cover method. Figure 2.1 illustrates the overview of the excavation methods used. The portal wall important for this thesis is located at the transition of tunnel GT to tunnel LB. The railway tunnel LB extends over the length of 2.95 km using two tubes, the difficult geotechnical and geological ground conditions in this area need a flexible method of excavation. Therefor the use of a tunnel boring machine is not suitable for the tunnel LB, instead the New Austrian Tunneling Method was used. This excavation method is based on the idea that the ground around the tunnel acts not only as a load, but also as a load-bearing element.

After constructing the portal wall and excavating several tunnel meters, damage at the portal wall occurred. Unexpected, large, horizontal deformations at the portal area around the excavation contour led to cracks in the shotcrete and required additional measures at the portal wall support. The displacements at the portal wall and in the tunnel were documented and the problem was noticed quickly. The crossing of a nearby gas pipeline demanded a cautious approach. The solution was the placement of additional portal wall anchors and partially backfilling at the portal wall to reduce and stop the further development of displacements.

2.2 Geotechnical Considerations

This section deals with the geotechnical estimation done to assess the rock parameters used to calculate the project in the numerical model. A glance on the geology of the Koralm and the dominating rock masses gives information to predict the necessary parameters correctly. Together with the final geotechnical report on the construction of the Granitztal tunnel chain an accurate assessment is developed.

2.2.1 Geology

The tunnel Langer Berg is located between Klagenfurt and Graz, in detail between St. Andrä and Aich, in the Lavanttaler fault zone.

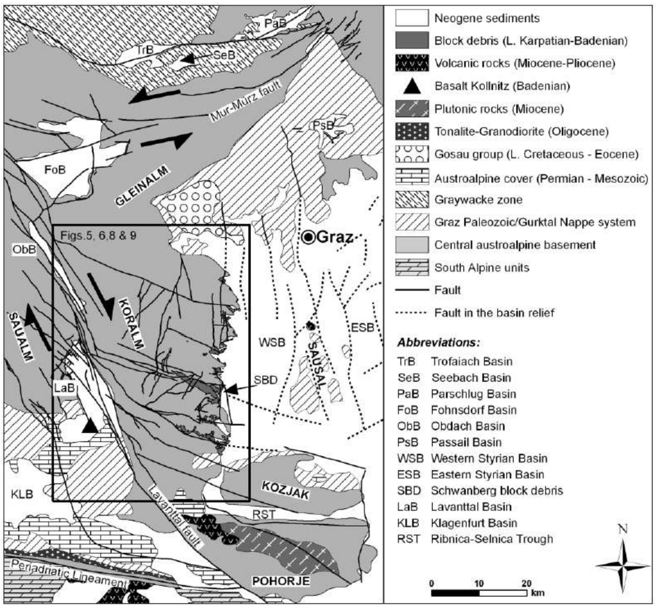


Figure 2.2 Geological map of Koralm massif (Pischinger 2008: 237)

The northern area of the tunnel Langer Berg is dominated by Miocene sediments of the Granitztaler beds. The Miocene is a series and part of the Neogene system. These Miocene sediments consist of offshore deposited silt, sand and gravel, which occure as slightly cemented silt- and sandstones as well as conglomerates.

In the Neogenic section (chainage 0 to 1200 m) the groundwater conditions are indicated dry to damp, with exceptionally dripping to weakly running ground water ingress.

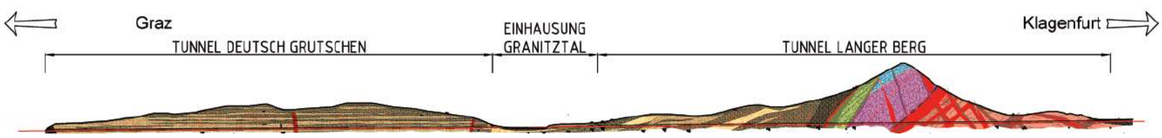


Figure 2.3 Granitztal tunnel chain (Bauer 2016: 421)

2.2.1.1 Neogene

“The emergence and folding of the Koralm mountain, paired with erosion, weathering and a tectonically formed basin led to a deposit of the material 17 to 7 million years ago. […] This basin fill, geologically described as Neogenic, consists of various sedimentary soils and rocks:

- Slightly overprinted soils like clay, silt, sand and gravel.
- Soils overprinted by geological and tectonic processes to rock with very low compression strengths, mostly less than 5 MPa, for example conglomerate, sand-, siltstone and shale.” (Kiesling 2015: 482f)

2.2.1.2 Permo-Mesozoic nappes

The permo-mesozoic zone contains sediments, dolomites, and fossils of the Werfener formation. Also anhydrites are found in several areas, causing special challenges crossing those layers.

The Neogene is the dominant geological formation and the one with the most relevance for this thesis. The paper covers the influences of the tunnel excavation advance on the portal wall in the first few meters of tunnel construction, therefore the rock mass stretching over the first tunnel meters are of importance.

2.2.2 Geotechnical Rock Parameters

The geotechnical attributes of the permo-mesozoic rocks are characterized mainly by the tectonical fault system. In the slope end region of the Werfener nappe a major fault zone extends over several dozen of meters dipping to the north. The fault zone, caused by tectonic processes is oriented parallel to the foliation. At tunnel level, heavily disturbed, sheared sand and clay alternation are present, also sedimentary intercalations of brecciated dolomite in sulfatic matrix are encountered. The overburden increases from north to south to a maximum of 340 m, decreasing to 40 m overburden at the Jauntal. (Gschwandtner 2018: 20)

Concluding the information gathered from the paper *Fault slip analysis in the Koralm Massif […]* from Pischinger et al. (2008: 237) and the final geotechnical report of the example tunnel project, the parameters for the rock mass used in the numerical model were set to reasonable values.

The unit weight is set to 20 kN/m³ friction angle set to 30° and cohesion to 10 kPa. An overview of the parameters is found in Table 3.2 Material properties - weathered rock.

3 Numerical Modelling

The portal and tunnel structures are modelled in the engineering software RS3.

RS3 is designed for 3D analysis of geotechnical structures for civil and mining applications. Applicable for both rock and soil, hence the name, RS3 is a general-purpose finite element analysis program for underground excavations, tunnel and support design and more. It has options for staging of excavations and support installations. After the analysis is completed, RS3 offers numerous options for viewing and displaying the results in 2D and 3D. (Rocscience 2018)

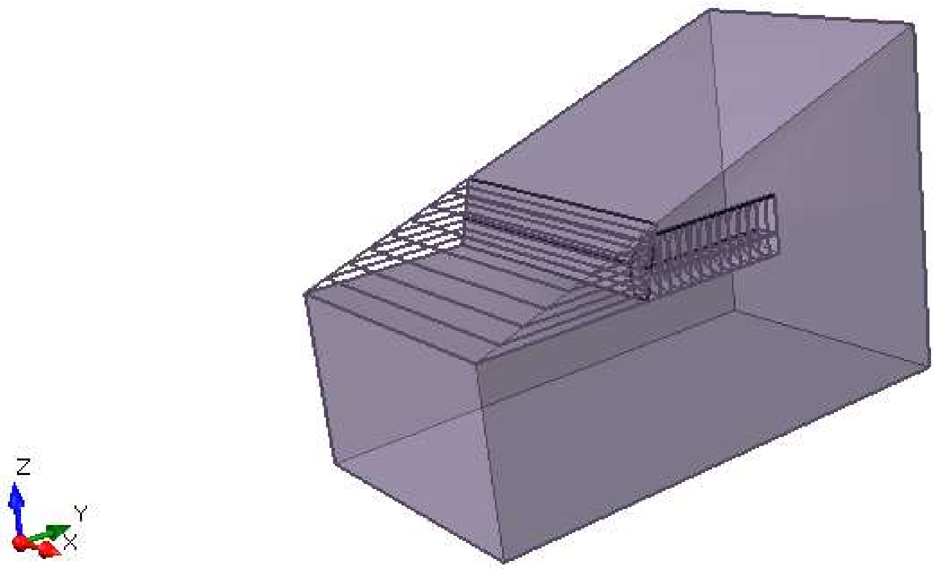


Figure 3.1 Overview of model

3.1 Portal Slope

The natural slope at the tunnel portal was adapted to an inclination of 23 degrees, a ratio of 1:2.5. This free slope provides a stable condition of the ground without the need of additional support measures. It represents the initial state of the excavation model, before performing subsequent construction work. The area of the tunnel portal needs a steeper slope of approximately 80 degrees to proceed excavating the tunnel profile.

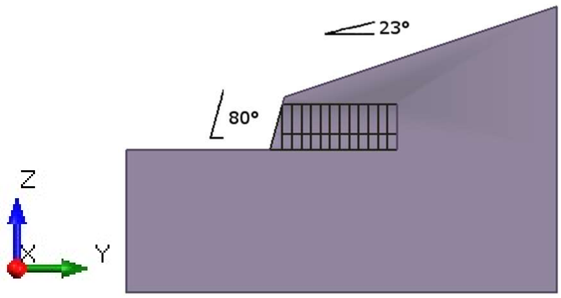


Figure 3.2 Side view of model

3.2 Boundary Conditions

Before executing the finite element calculation, the tunnel, the surrounding rock mass and the support measures have to be discretized.
Only a limited section of the rock mass surrounding the tunnel is included in the model. The area of influence with occurring displacements is set to dimensions shown in Figure 3.3. The dimensions of the area is selected assuming the influence of the excavation does not extend to the border of the model. The influenced area is roughly described as a symmetrical box with horizontal lateral edge distances of about five times, horizontal depth distance of nine times and vertical edge distance of three to six times the tunnel diameter.

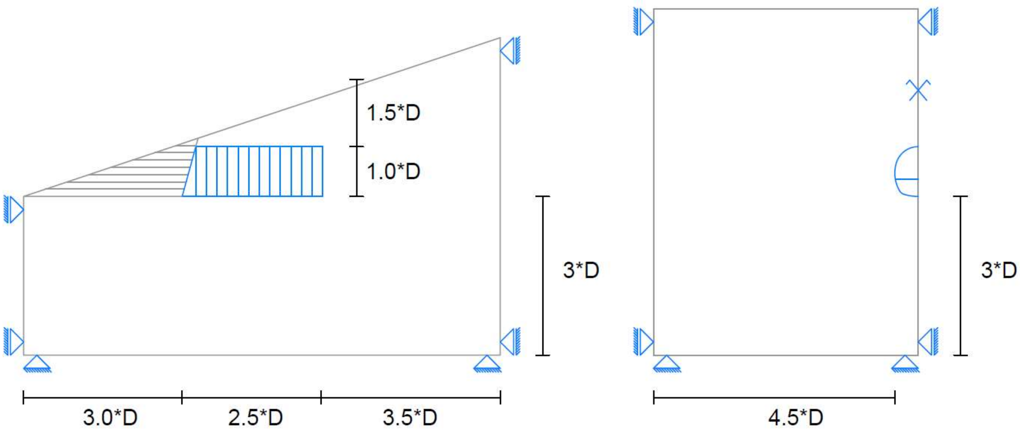


Figure 3.3 Side and front view of discretized model

3.3 Tunnel Cross Section

The tunnel cross section is chosen according to the execution drawings used on the construction site from the example tunnel Langer Berg. The profile is constructed in AutoCAD and implemented in RS3.

The cross section is displayed in Figure 3.4. Additional information regarding the geometry is shown in Table 3.1.

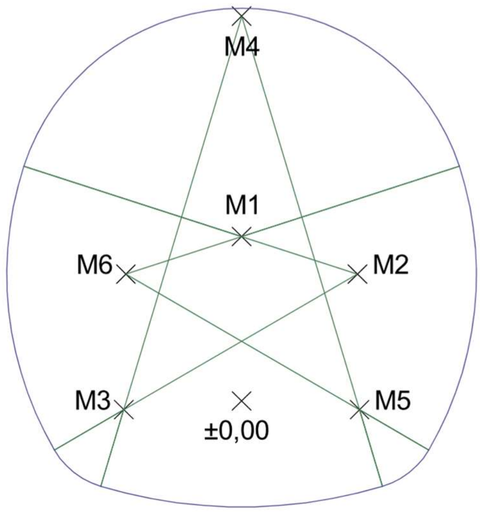


Figure 3.4 Significant midpoints of tunnel cross section

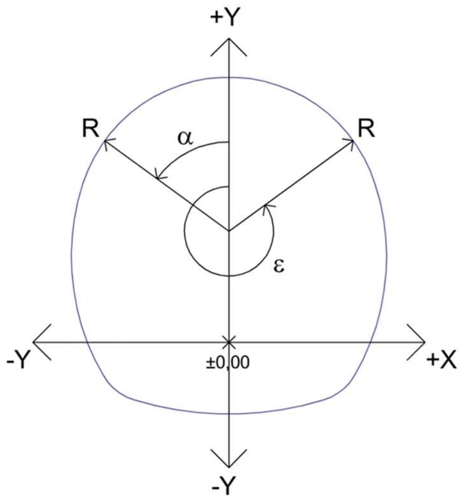


Figure 3.5 Information on the utilized coordinate system

Table 3.1 Parameters of tunnel geometry

Point Nr.	Radius Nr.	Radius [m]	X-Coordinate	Y-Coordinate	Angle Start α [°]	Angle End ε [°]
M1	R1	4.109+d_s	0.000	3.100	287.9328	72.0672
M2	R2	6.400+d_s	2.180	2.394	72.0672	120.1939
M3	R3	1.310+d_s	-2.219	-0.165	120.1939	163.3595
M4	R4	9.060+d_s	0.000	7.260	163.3595	196.6405
M5	R5	1.310+d_s	2.219	-0.165	196.6405	239.8061
M6	R6	6.400+d_s	-2.180	2.394	239.8061	287.9328
Excavation area: 68.64 m², d_s = 0.25 m						

The tunnel height is 9.41 m, the partial conventional excavation splits the excavation area in a top heading and invert. The height of the invert is set according to the execution plan to 3.3 m.

3.4 Material Properties

In this chapter, the properties of the materials used in this thesis are described. The numerical model is created of the excavated material, the rock mass, and the support installed, the anchors, bolts and shotcrete.
The simple failure criterion used for calculation of the materials is Mohr-Coulomb, a plastic material type model is used.

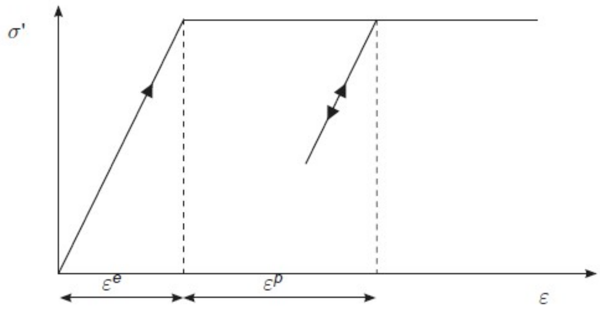


Figure 3.6 Basic idea of elastic, perfectly plastic material model (Plaxis 2018)

The following parameters are used to describe the behaviour of the materials:

- Young's modulus E [kPa]
- Poisson's ratio ν [-]
- Friction angle φ [°]
- Dilatancy angle ψ [°]
- Cohesion c [kPa]

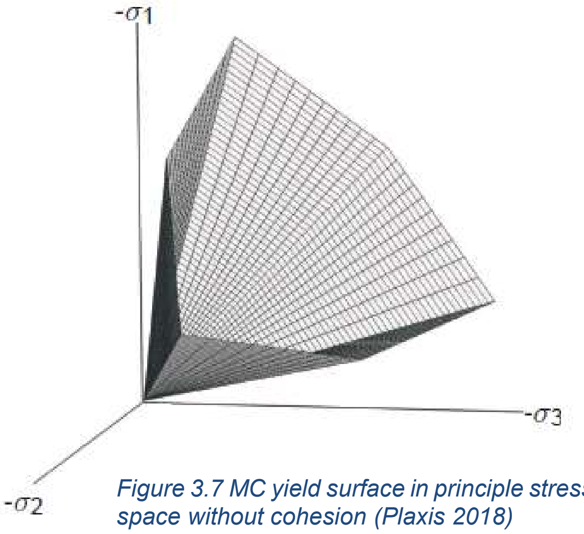


Figure 3.7 MC yield surface in principle stress space without cohesion (Plaxis 2018)

3.4.1 Rock Mass

The principal material where the tunnel is excavated in is stated as weathered rock. Important parameters used to describe the weathered rock are displayed in Table 3.2. The field stress and body forces are set as initial element loading. Effective stresses are presumed.

Table 3.2 Material properties - weathered rock

Weathered rock	Material Type plastic
Unit weight [kN/m³]	20
Friction angle [°]	30
Cohesion [kPa]	10
Young's Modulus [kPa]	$1.20*10^7$
Poisson's Ratio [-]	0.30

The numerical model starts as unaffected simplified terrain composed of homogeneous weathered rock. The first sketches created by the responsible geologists, show a layer structure of mostly Miocene sediments, silt- and sandstone, as well as conglomerate. They resemble similar parameters and are simplified to the class weathered rock.

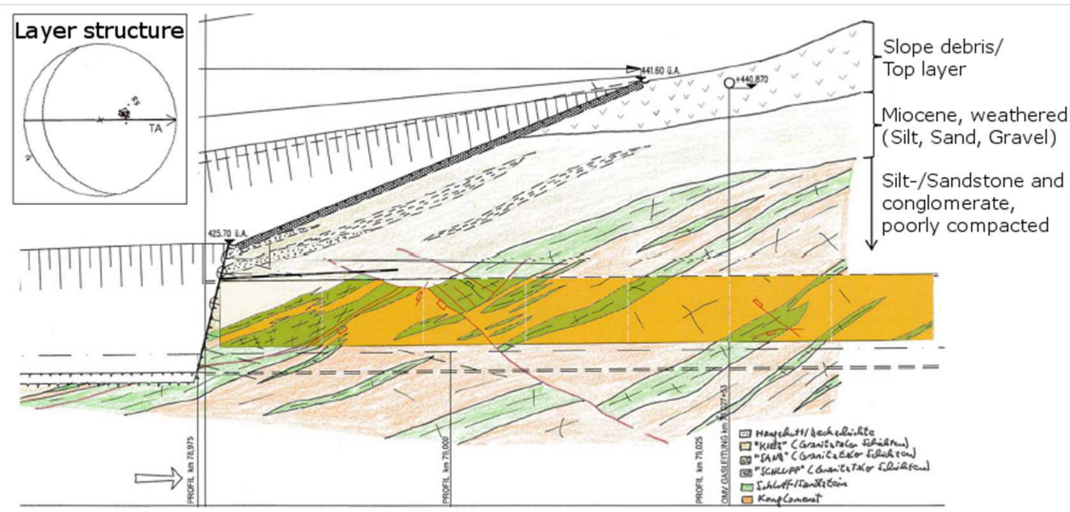


Figure 3.8 Layer structure at the portal wall (Gschwandtner 2018: 77)

3.4.2 Shotcrete

Shotcrete is used as immediate support after excavating a round and to support the portal wall. The material type of shotcrete is assumed as plastic. The thickness of the shotcrete liner is set to 0.25 m, the slope support thickness is set to 0.15 m; furthermore the thickness of the temporary shotcrete support at the excavation face is also selected to 0.15 m. The numerical model of the shotcrete created in RS3 is done by generating a layer on the slope and excavation surface with the properties of the sprayed concrete listed in Table 3.3.

Table 3.3 Material properties - shotcrete

Shotcrete	Material Type plastic
Unit weight [kN/m³]	24.00
Young's Modulus [kPa]	$4.00*10^{6}$
Thickness [m]	0.15 / 0.25

Figure 3.9 shows the installed shotcrete liners in RS3, the purple colored elements are the slope shotcrete layers with a thickness of 0.15 m, the pink elements represent the tunnel linings with a thickness of 0.25 m.

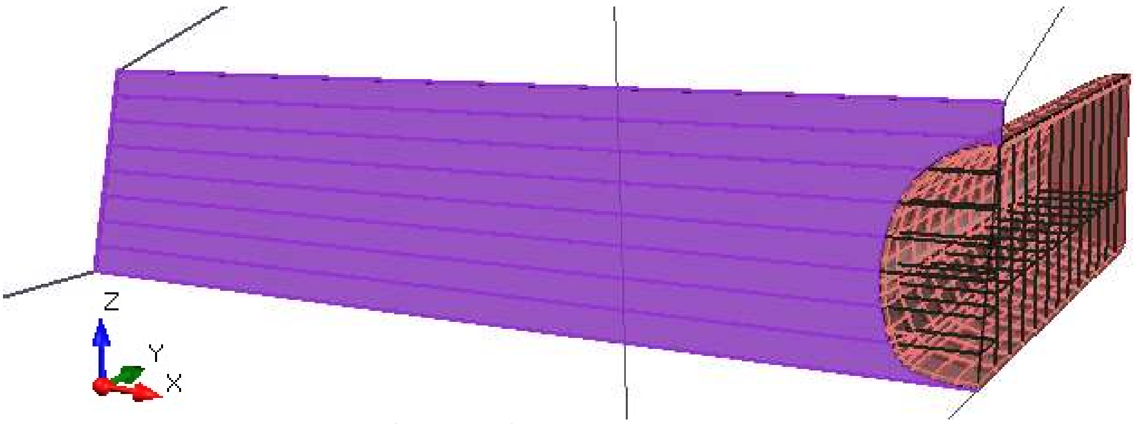


Figure 3.9 Overview of shotcrete liner on slope and in tunnel

3.4.3 Tunnel Anchors

In RS3, anchors are one-dimensional support elements used to model a variety of types commonly used as support elements to support geotechnical structures. (Rocscience 2018)

The anchors used at the tunnel excavation are installed perpendicular to the excavation surface according to the execution plan when a round is excavated.
The Tunnel anchors are added individually, calculating the coordinates of each anchor installed after each excavation round and added one by one. There are three anchors mounted each round with the upper two changing in elevation and the lower one staying on the same height each round. Every odd round the height of the anchors is set to 2.05 m, 4.75 m and 6.05 m, every even round the height is set to 2.05 m, 5.40 m and 6.70 m. Figure 3.10 shows the installation of the tunnel support after 12 rounds of crown and invert excavation.

Table 3.4 Material properties - radial anchors

Self-drilling Anchor, fully bonded	IBO-Anker R32-250
Bolt Diameter [m]	0.0217
Length [m]	6
Young's Modulus [kPa]	$2.05*10^{8}$
Tensile Capacity [kN]	250

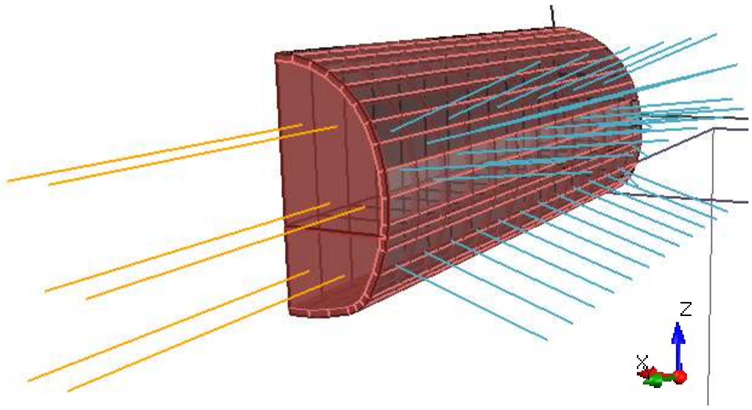


Figure 3.10 Overview of all tunnel anchors installed

3.4.4 Slope Anchors and Bolts

The anchors and bolts used at the portal wall are described below and parameters are shown in Table 3.5 and respectively in Table 3.6.

Table 3.5 Material properties - slope anchors

Prestressed anchor, end anchored	Freispielanker Y1770
Bolt Diameter [m]	0.02985
Length [m]	30 / 34
Young's Modulus [kPa]	$2.05 \cdot 10^8$
Tensile Capacity [kN]	1200
Preload [kN]	600

Table 3.6 Material properties - slope bolts

Soil nail, fully bonded	
Bolt Diameter [m]	0.0217
Length [m]	6 / 8
Young's Modulus [kPa]	$2.05 \cdot 10^8$
Tensile Capacity [kN]	250 / 330

The different anchors and nails installed at the portal wall are displayed in Figure 3.11, each type differently coloured:
Prestressed anchors are shown in green, the upper row is 34 m long, the lower one 30 m. Soil nails are coloured orange with a tensile capacity of 330 kN and yellow with a tensile capacity of 250 kN.

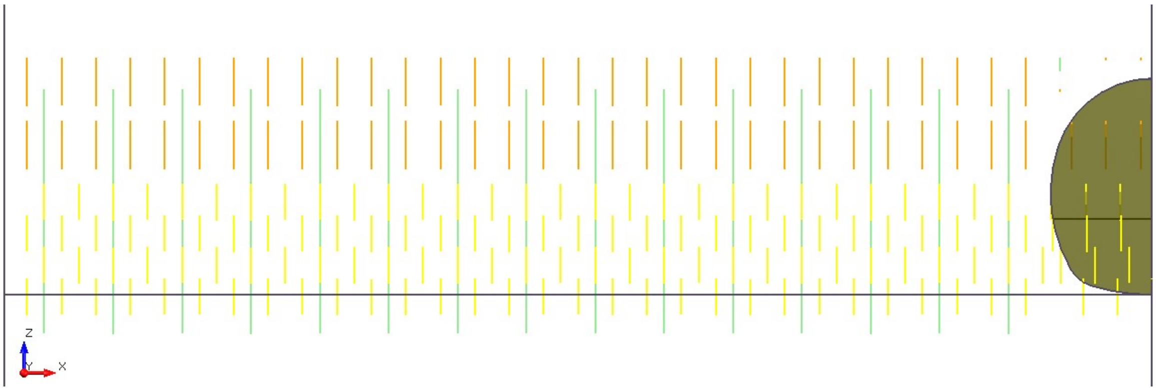


Figure 3.11 Overview of installed slope anchors and bolts

3.5 Excavation Sequence

The simulation is divided into several excavation steps to demonstrate the different processes necessary for constructing a tunnel.

A new step is created when a new construction measure is installed or the next round is excavated, for this project the total number of steps is set to 34.

Figure 3.12 Project stages

OriginalSlope
SlopeWork1 – 8
Excavation R0
Excavation R1K – R12K
Excavation R1S – R12S

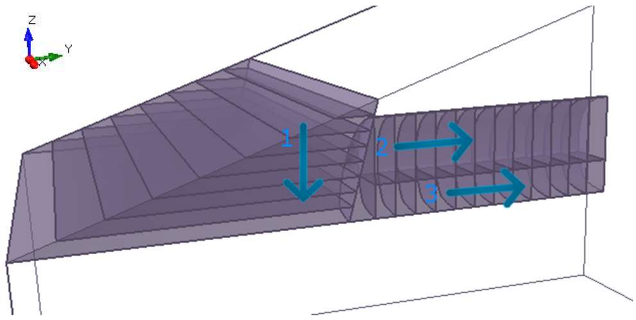


Figure 3.13 Schematic excavation sequence

Looking at Figure 3.13 Schematic excavation sequence a quick overview of the excavation sequence is given. Arrow number 1 shows the progress of the slope excavation, arrow number 2 displays the excavation advance of the heading, and arrow number 3 portrays the subsequent bench excavation.

The Step OriginalSlope represents the natural surface before the construction work begins. There are no support measures installed and the portal area has not been excavated or modified. In the next step SlopeWork1, the first layer of rock mass with a thickness of 1.38 m at the tunnel portal is removed. Then the support measures, the shotcrete layer and the upper row of anchors are installed in the same stage. In the next steps from SlopeWork2 to SlopeWork8, the subsequent rock mass layers are excavated and supported like in the stage before.

The next step contains the partial excavation of the tunnel profile to provide for a vertical tunnel face at the portal wall, preparing for excavation advance, which is done in the step Excavation R0. The support measures are installed to secure the first round of excavation. Excavation Step 0 starts with the excavation of the tunnel. The round length of Excavation R0 is determined by geometry of the embankment and measures 0.79 m excavation length at the crown and 2.35 m at the bottom, every other round following after R0 has a length of 2 m.

Simulation continues with the excavation of the top heading of the tunnel, starting with the first round named Excavation R1K, until twelve rounds are excavated consecutively, ending with Excavation R12K. Then the excavation of the tunnel invert starts. It is modelled like the excavation of the tunnel top heading, sequentially from Excavation R1S to Excavation R12S. There are also 12 rounds excavated, with a round length of 2 m.

3.6 Displacement Restraints

The principal stress of the primary stress state of the model is assumed to run along the Z-axis, representing the gravitational force. Boundary conditions to surfaces, edges and points have to be added to define the numerical model, enabling the computing. Therefore the normal displacements at the outer faces below ground level and the directions of movement of the corresponding edges are set to be zero.

Figure 3.14 shows the restraints applied to the numerical model. Every side, which is not a free surface, has to be confined in its normal direction, edges and corner points have to be restricted as well.

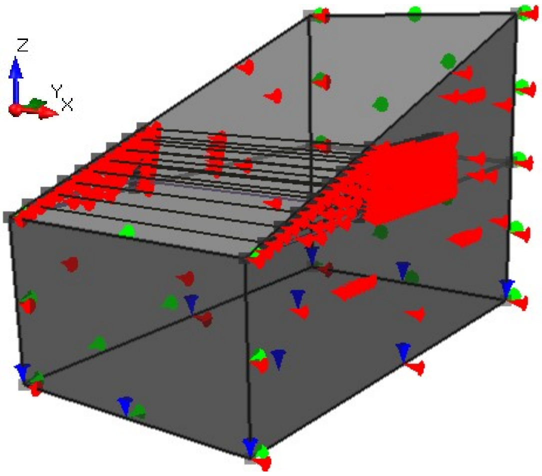


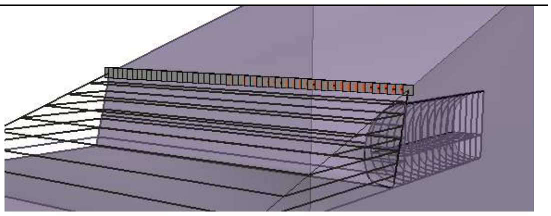
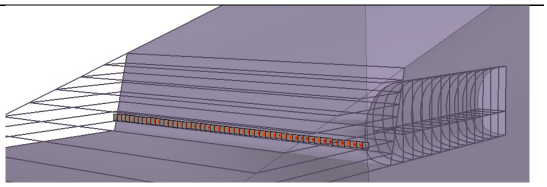
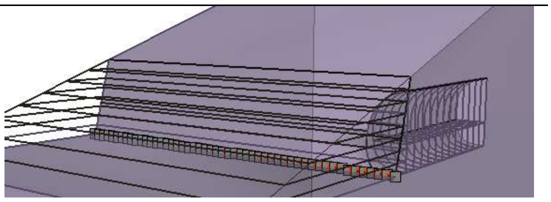
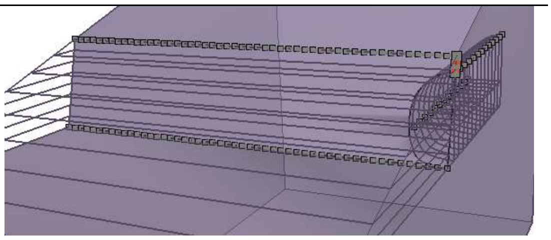
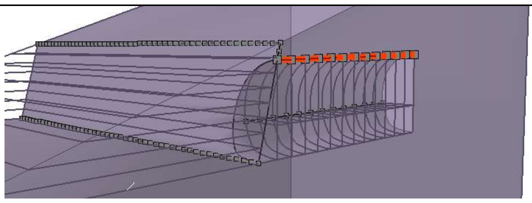
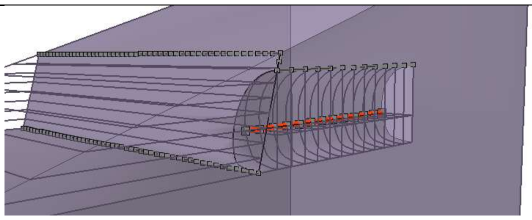
Figure 3.14 Restraints of displacements (red: x-axis, green: y-axis, blue: z-axis)

It is important to assign the restrictions carefully, because flaws in the restraints lead to calculation errors causing convergence issues when computing the model.

3.7 Line Query

The displacements occurring during the different stages of excavation are measured along several lines on the numerical model. Line Queries are polylines at significant areas, where acquisition of displacement information is useful and desired. The nodes along the line have to be created each meter to visualise the overall stress behaviour and displacements of the model. In this project, several Line Queries were added, displayed in Table 3.7, to evaluate the results:

Table 3.7 Overview of the Line Queries

Line Query label and description	Line Query location
Line Query Slope Upper Edge (LQ-SUE): Located at the upper edge of the slope, the line is running along the portal wall for 50 m, with a measurement node at each meter.	
Line Query Mid Slope 7 (LQ-MS7): Located at a significant layer of the portal wall at 1.90 m height, 51 nodes gathering data along the portal wall every 0.92 m.	
Line Query Slope Lower Edge (LQ-SLE): Similar to the Query Slope Upper Edge, measuring information at the lower edge of the portal wall.	
Line Query Vertical (LQ-V): A short query line centred above the tunnel crown along the inclination of the portal wall, containing 3 query nodes over a length of 1.6 m.	
Line Query Tunnel Top (LQ-TT): This line measures the data along the crown of the tunnel every 2 m to gather info of every excavation step.	
Line Query Tunnel Mid (LQ-TM): Similar to the line query before, this polygon is placed at the edge of the different excavation areas running along the tunnel axis.	

3.8 Model Variation

Three different numerical models are established and computed: The basic shall represent the original design without additional reinforcements, while other models contain additional supports or variations of the support.

3.8.1 Basic Model

The basic model parameters and geometry of the tunnel Langer Berg are described in chapter 2 Example Project, the detailed construction is described in chapter 3 Numerical Modelling. No additional support measures are installed, the model construction was done following the original design.

3.8.2 Reinforced Model

The first alternative is an augmented model with additional support, installed at certain heights at the portal wall to decrease deformations.
Two anchor rows are added, the parameters used are shown in Table 3.8 Material properties - additional anchors:

Table 3.8 Material properties - additional anchors

Prestressed anchor, end anchored	Freispielanker Y1770
Bolt Diameter [m]	0.02985
Length [m]	25
Young's Modulus [kPa]	$2.05 \cdot 10^{8}$
Tensile Capacity [kN]	1200
Preload [kN]	500
Young's Modulus [kPa]	$2.05 \cdot 10^{7}$

The installation of additional anchors was done at two different elevations, see Figure 3.15. One additional anchor row was mounted at a height of 4.20 m the second one at a height of 2.06 m, both rows have a spacing of 3 m.

Figure 3.15 Additional anchor row placements

3.8.3 Uncoupled Shotcrete Model

This alternative tries to reduce the displacements and stresses in the shotcrete layer at the portal wall without the use of additional support. The method used was to uncouple the shotcrete liner of the slope support and the liner used in the tunnel. This was carried out by leaving a gap of shotcrete open around the excavation profile at the portal wall.

A ribbon with a gauge of 0.4 m around the tunnel excavation was intentionally left out, when installing the shotcrete liner. The idea was to prevent the transfer of shear forces created when excavating the tunnel and thus reduce stresses in the slope support.
The rest of the model is identical to the Basic Model, mentioned in chapter 173.8.1.

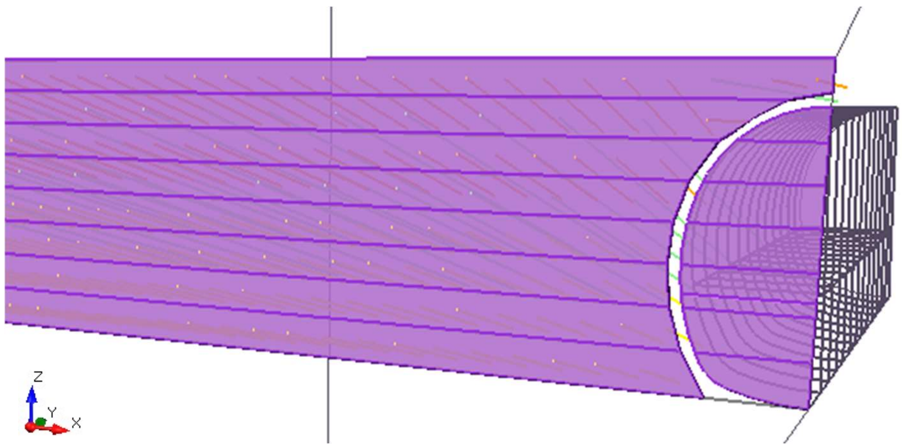


Figure 3.16 Display of shotcrete gap at portal wall

4 Results

Different models were created to compare the structural differences and their influences on the numerical model. In this chapter the results of the various models are evaluated and compared. The focus is on the horizontal Y-displacements, the anchor forces and the YZ-shear stress along the portal wall.
All results named relative measurement data are referring to the Stage OriginalSlope.

4.1 Displacements

Displacements are divided into total relative and relative displacements facing X-/Y- and Z-direction. The area around the excavation contour is the centre of attention, therefore the area 5 m around the tunnel excavation contour is shown in the following figures.

4.1.1 Basic Model

The basic model shows comprehensible results, giving a general overview of the dimension of the displacements occurring with the chosen parameters.
Figure 4.1 displays the total displacements of the Basic Model after the last excavation stage, followed by figures and descriptions of the X-/Y- and Z-direction. The small dot of minimal movement at the top left of the tunnel contour origins from the prestressed anchor holding back the movement in that region. The maximum displacements occur at height 1.9 m most frequently, where LQ-MS7 is located.
Subsequent to the overview of the total displacements, the relative displacements in total and in Y-direction are displayed afterwards.

The total displacements in Figure 4.1 range from 0.05 m (blue colouring) to 0.08 m (red), the displacements at the area of interest with the elevation of 1.9 m, have a maximum of 0.075 m.

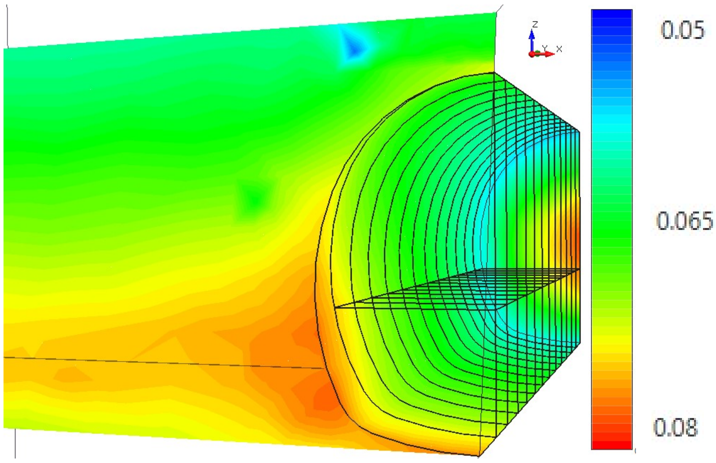


Figure 4.1 Total displacements after Excavation R12S - BM

X-displacements are shown in Figure 4.2, the displacements located on the portal wall are very small compared to the results of the other directed displacements, reaching a maximum relative displacement of 0.002 m.

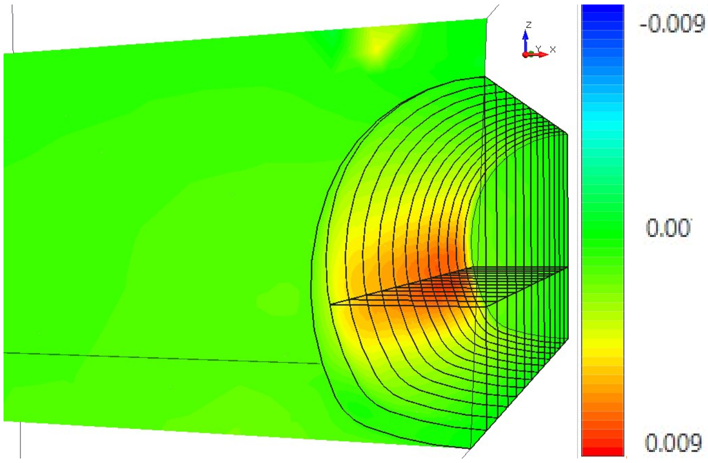


Figure 4.2 Total X-displacements after Excavation R12S - BM

Figure 4.3 displays the total Y-displacements ranging from -0.08 m - 0.045 m, which measure a maximum relative displacement of -0.020 m at the significant measurement line LQ-MS7.

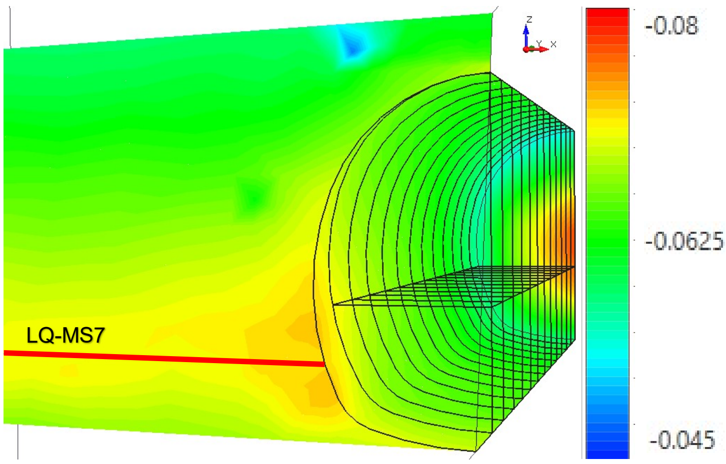


Figure 4.3 Total Y-displacements after Excavation R12S - BM

Figure 4.4 shows the total displacements in Z-direction with a domain of -0.018 m to -0.032 m. Calculating the relative displacements, the relative Z-displacements peak at 0.013 m.

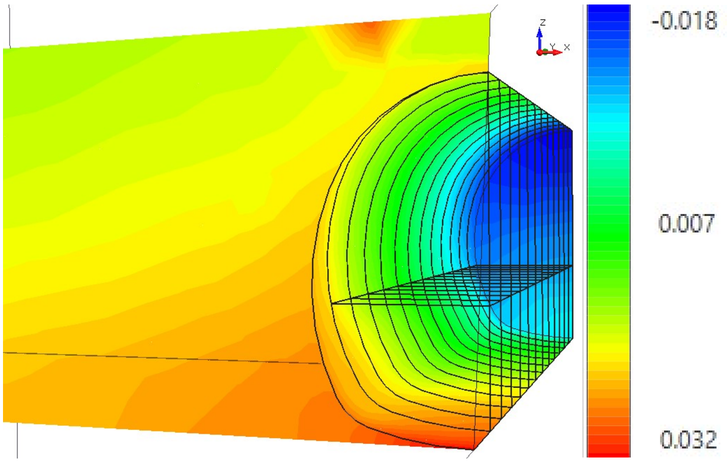


Figure 4.4 Total Z-displacements after Stage Excavation R12S - BM

The graph shown in Figure 4.5 shows the total relative displacements of the Basic Model at a height of 1.9 m, where the biggest displacements occur. The sequencing of the stages lead to different displacements, which vary slightly from 0.021 m at Stage SlopeWork8 to 0.022 m at Stage Excavation R12K, located at the tunnel excavation contour.

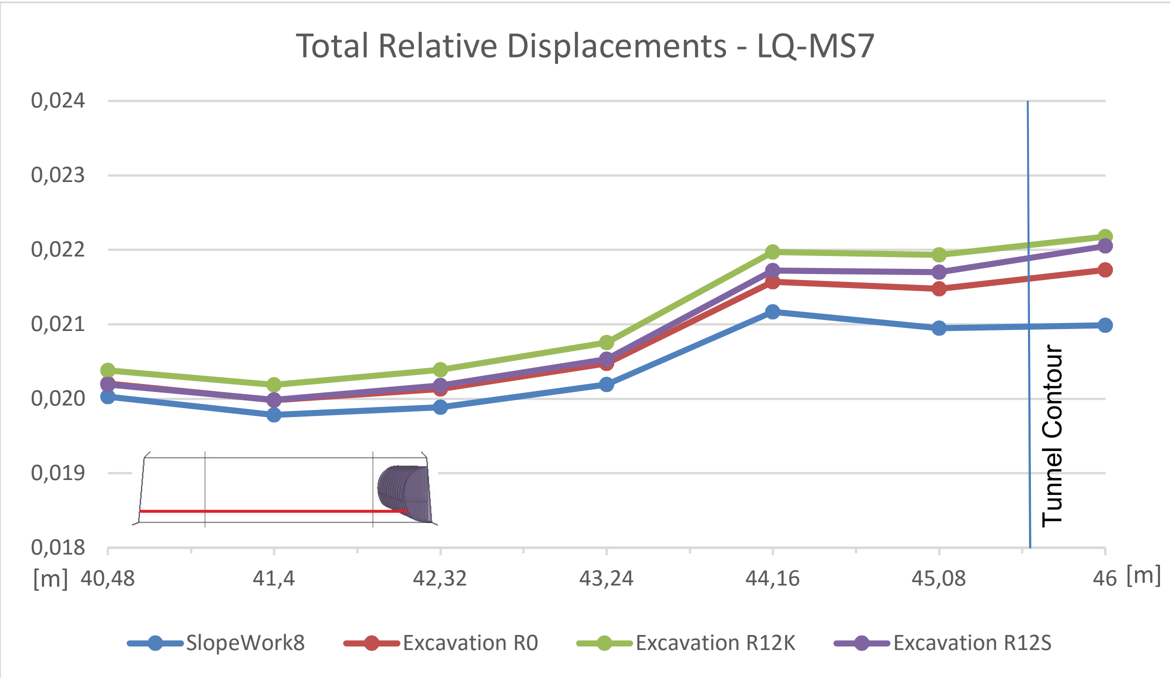


Figure 4.5 Total relative displacements - LQ-MS7, BM

The relative Y-displacements pictured in Figure 4.6 show the significant horizontal movement at LQ-MS7, the biggest values are documented at the Stage Excavation R0 with a displacement of 0.020 m at the tunnel excavation contour. The prestressed anchor located around meter 43 hinders relative movement, with increased displacements after that area.

The values are negative because of the orientation of the coordinate system, moving in negative direction against the tunnel excavation advance.

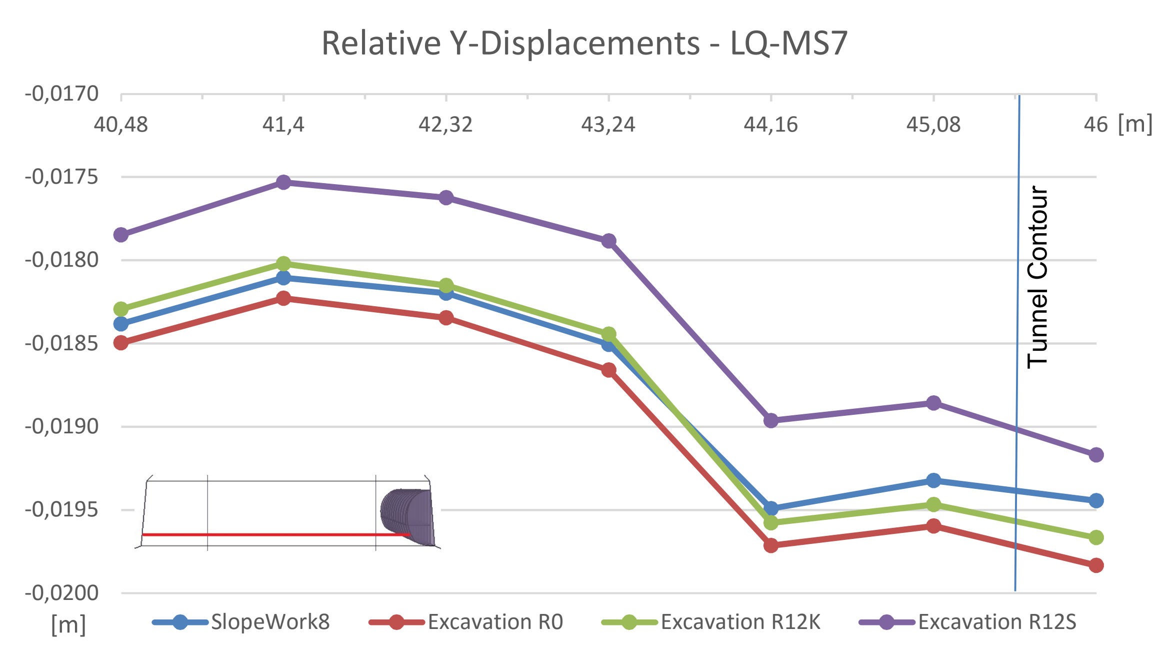


Figure 4.6 Relative Y-displacements - LQ-MS7, BM

The total relative displacements of the tunnel crown shown in Figure 4.7 are as expected and displayed below.

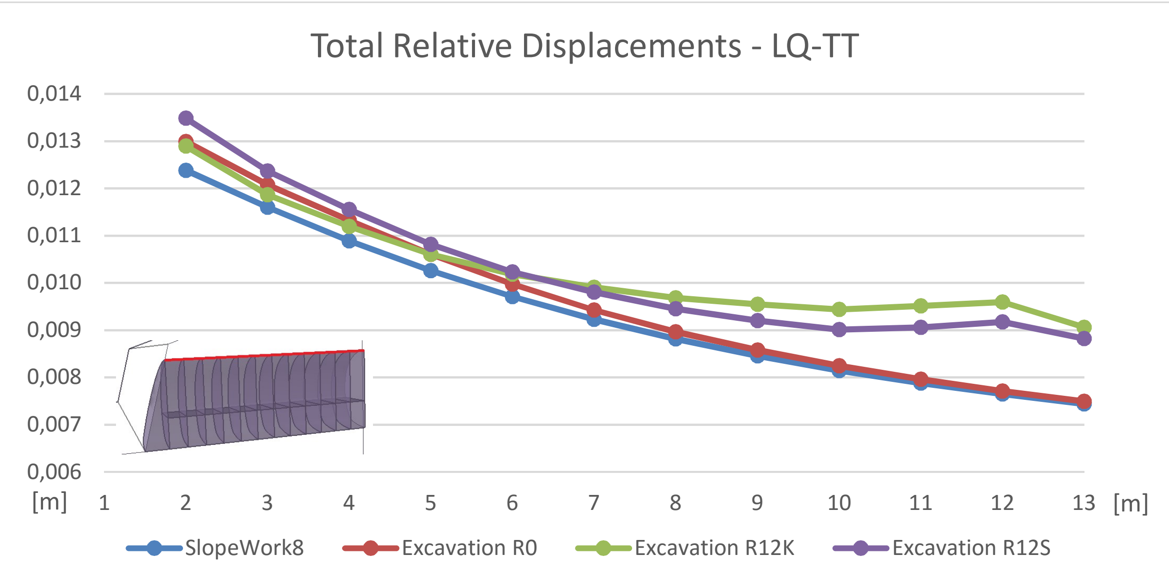


Figure 4.7 Total Relative Displacements - LQ-TT, BM

The relative vertical displacements pictured below in Figure 4.8 illustrated the crown movement of the tunnel over the excavation stages. The positive values show an uplift, which is caused by the simple MC material model, lifting up the material under lower pressure.

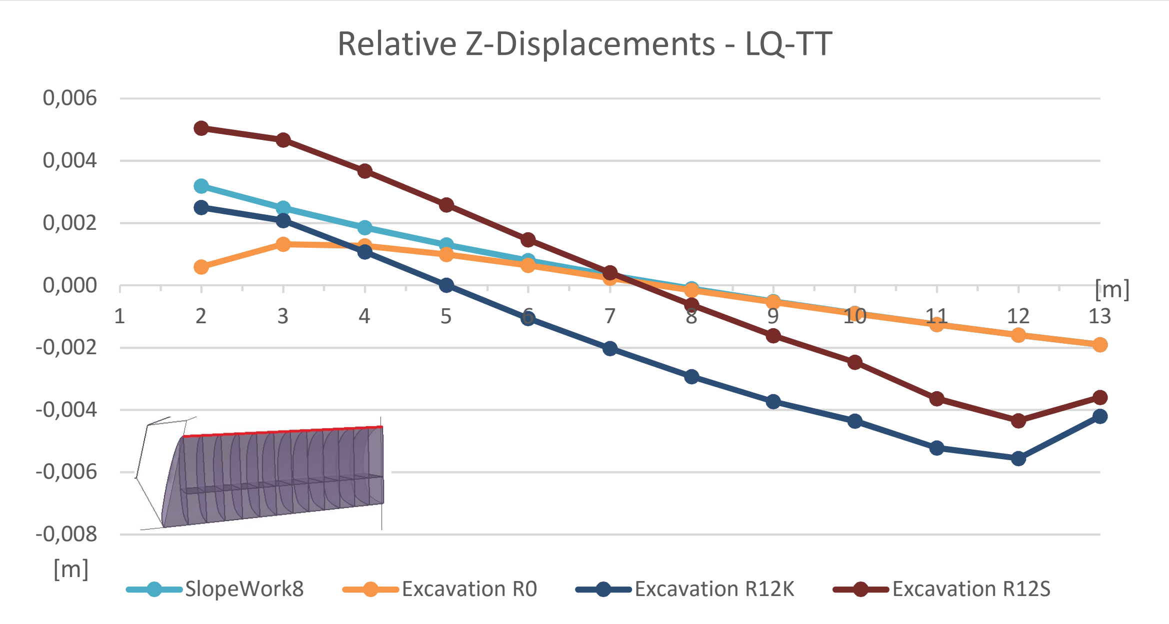


Figure 4.8 Relative Z-Displacements - LQ-TT, BM

The displacements at the tunnel wall are displayed in Figure 4.9. The bend in the first few meter is caused by the geometry of the portal wall, having a change in inclination. Minimal differences in displacements occur over the various stages with a difference of only 0.0025 m at the beginning of the tunnel, right at the portal wall.

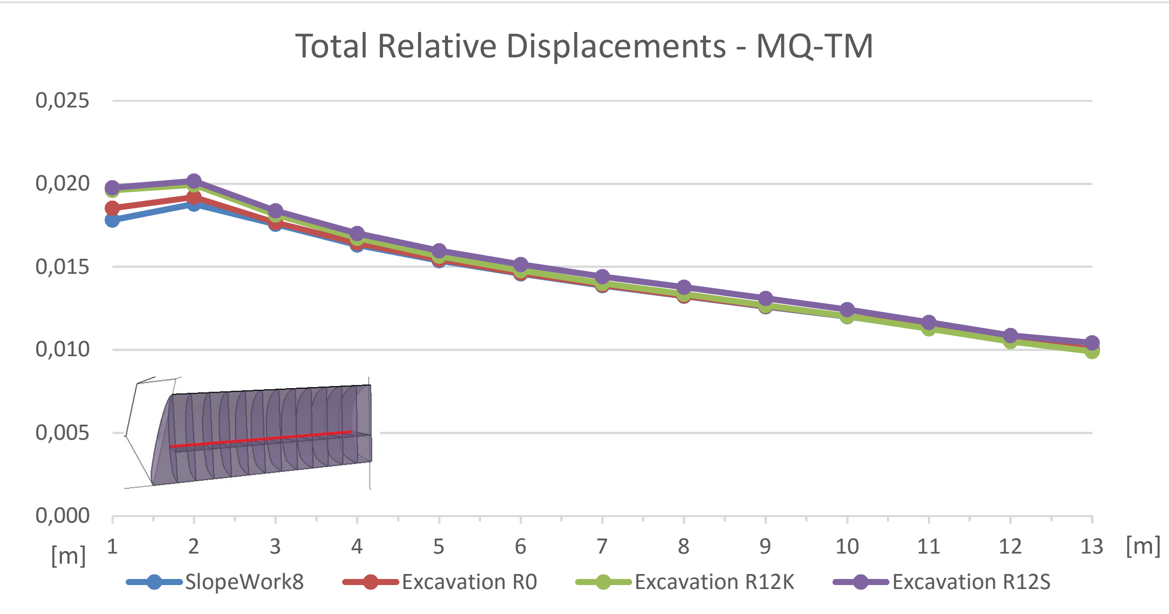


Figure 4.9 Total Relative Displacements - MQ-TM, BM

The relative X-displacements at the tunnel side displayed in next Figure 4.10, show the results expected, the main change in movement happening after top and invert excavation, with displacements at invert excavation two to three times higher that after top excavation.

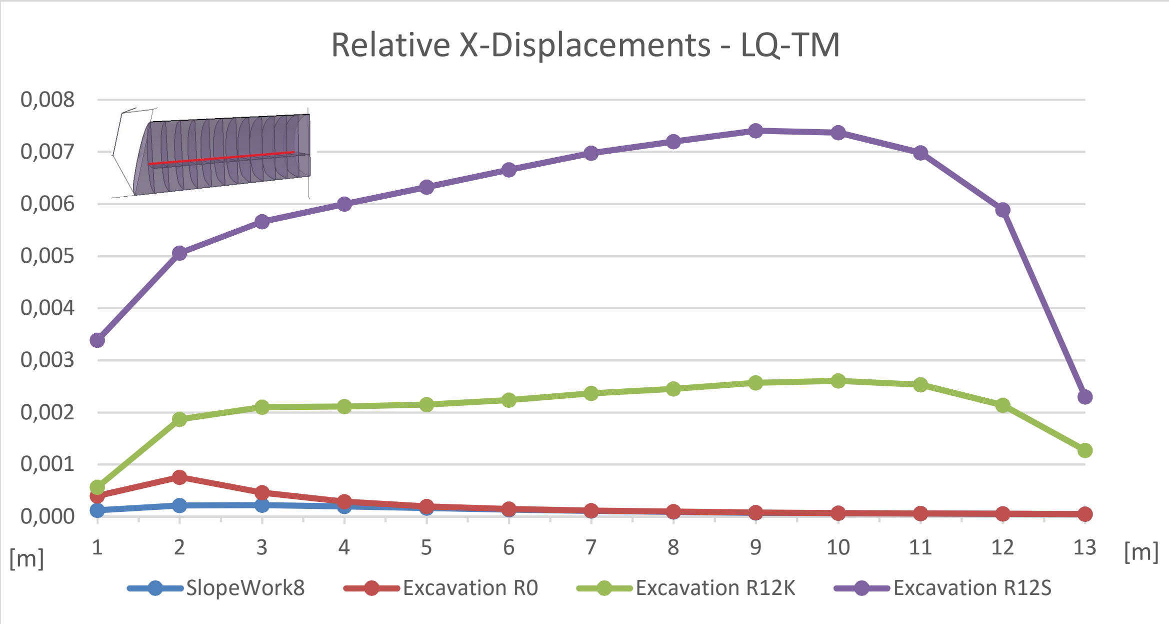


Figure 4.10 Relative X-Displacements - LQ-TM

4.1.2 Reinforced Model

The reinforced model reveals displacements slightly smaller than the calculated values from the basic model.

Only significant graphs are created and shown, varying in number of figures displayed.

Figure 4.11 indicates the total displacements in range from 0.05 m (blue colouring) to 0.08 m (red), the movement at the area of interest with the elevation of 1.9 m, amount 0.07 m (yellow).
In comparison to the Basic Model, a plausible decrease in movement is notable.

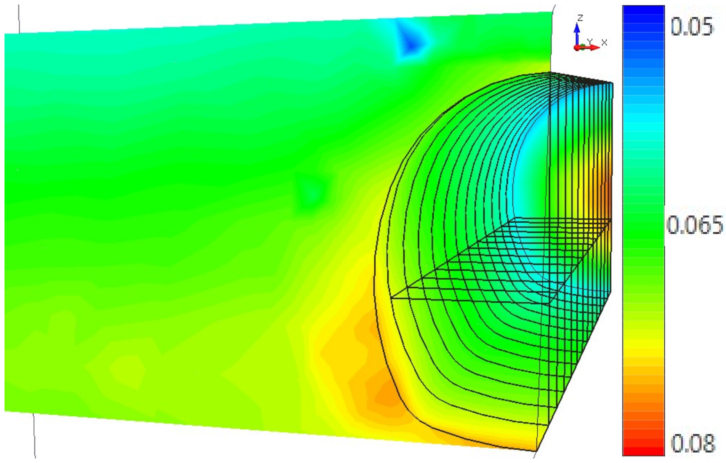


Figure 4.11 Total displacements after Stage Excavation R12S - RM

The X-displacements indicated in Figure 4.12 are again very small compared to the results of the other directed displacements, ranging to a maximum relative displacement of 0.0015 m.

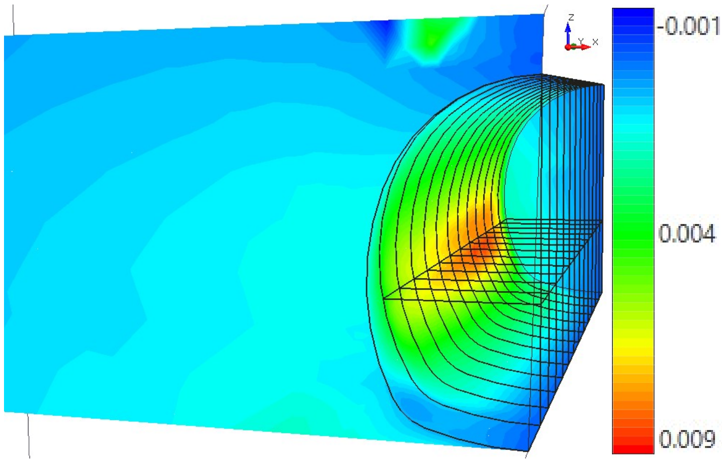


Figure 4.12 Total X-displacements after Stage Excavation R12S - RM

Figure 4.13 displays the total Y-displacements ranging from 0.045 m to 0.080 m, which measure a maximum relative displacement of 0.017 m at the tunnel excavation contour.

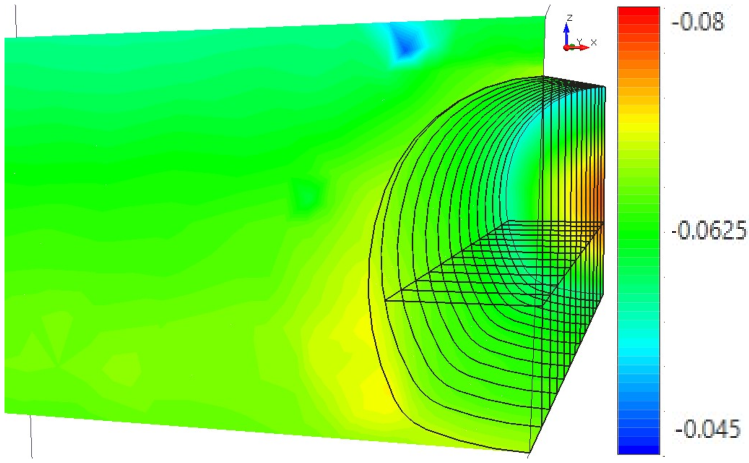


Figure 4.13 Total Y-displacements after Stage Excavation R12S - RM

The total displacements in Z-direction are marginally different to the values computed with the BM, only altering in the tenth part of a millimetre, displayed in Figure 4.14.

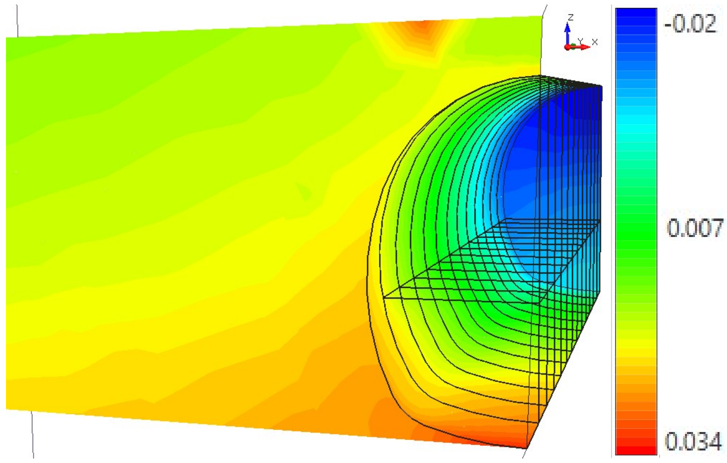


Figure 4.14 Total Z-displacements after Stage Excavation R12S - RM

Figure 4.15 shows the total relative displacements of the RM at the location of the biggest displacements. The different results vary slightly from 0.019 m to 0.020 m, located near the tunnel excavation contour.

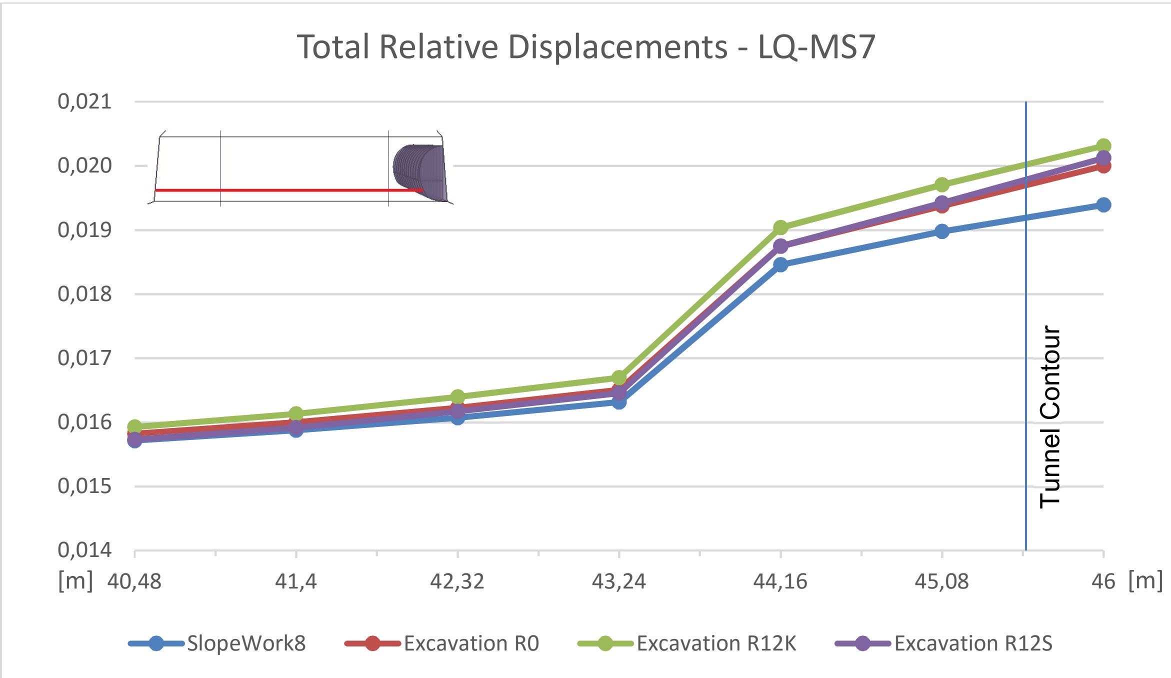


Figure 4.15 Total relative displacements - LQ-MS7, RM

The relative Y-displacements shown in Figure 4.16 range from 0.0175 m at Stage Excavation R12S up to 0.0181 m at Stage Excavation R0. That is an 8 % reduction of the Stage Excavation R12S and a 10 % reduction of the displacements in Stage Excavation R0, compared to the movement of the Basic Model.

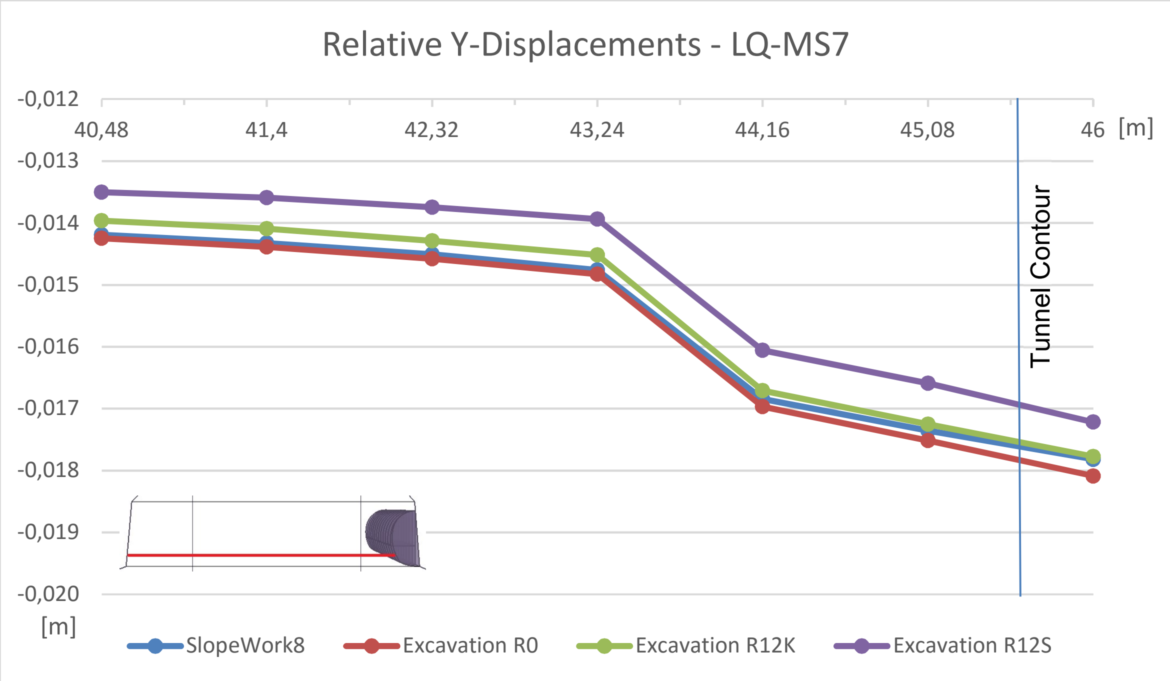


Figure 4.16 Relative Y-displacements - LQ-MS7, RM

4.1.3 Uncoupled Shotcrete Model

The displacements calculated using the uncoupled shotcrete model only show marginal differences from the reinforced model.

The total displacements shown in Figure 4.17 differ slightly from the BM, ranging from 0.052 m (blue colouring) to 0.079 m (red colouring). The LQ-MS7 measures maximum relative displacement of 0.022 m after Excavation R12S.

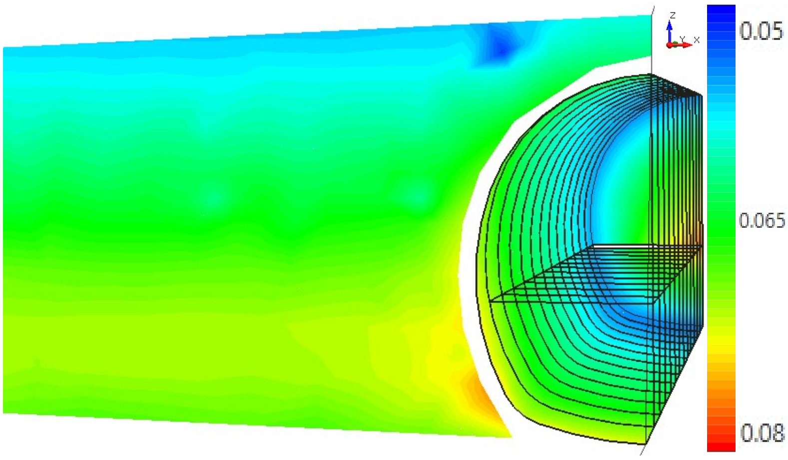


Figure 4.17 Total displacements after Stage Excavation R12S - USM

The X-displacements of the USM in Figure 4.18 are again very small compared to the other results, reaching maximum relative displacement of 0.002 m at the portal wall.

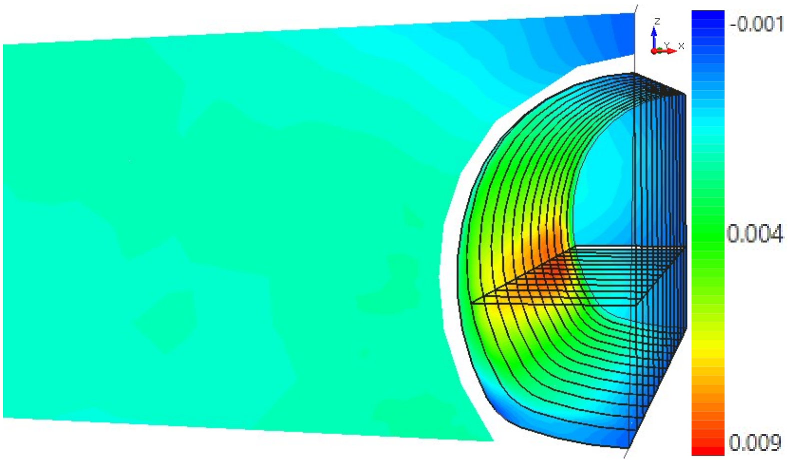


Figure 4.18 Total X-displacements after Stage Excavation R12S - USM

The total Y-displacements range from 0.045 m to 0.078 m pictured on the right hand Figure 4.19, the maximum relative displacement of 0.020 m occurs at LQ-MS7 at the tunnel excavation contour.

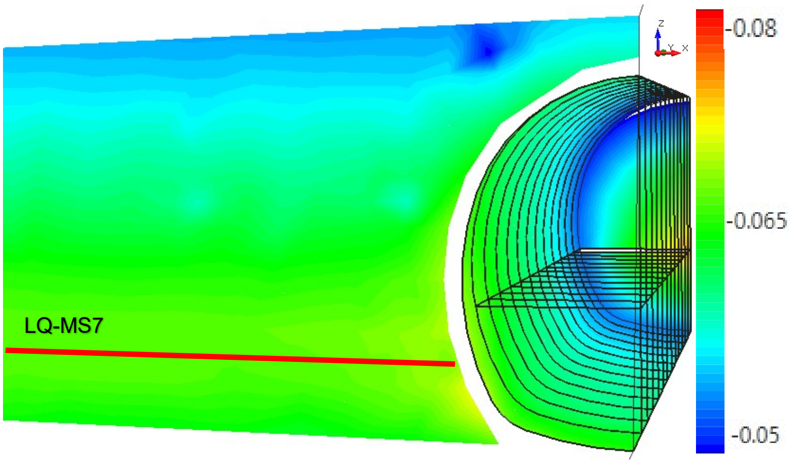


Figure 4.19 Total Y-displacements after Stage Excavation R12S - USM

Figure 4.20 shows the total displacements in Z-direction with a domain of 0.024 m to 0.051 m. Calculating the relative displacements, the relative Z-displacements have a maximum of 0.012 m.

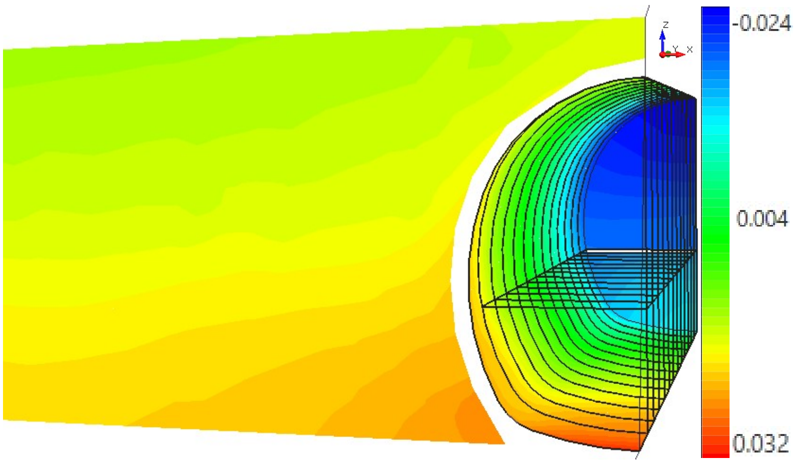


Figure 4.20 Total Z-displacements after Stage Excavation R12S - USM

The total relative displacements displayed in Figure 4.21 of the USM are similar to the results of the calculation of the BM. The different results of the stages differ slightly from 0.0204 m at Stage SlopeWork8 to 0.0221 m at Stage Excavation R12S, located near the tunnel excavation contour.

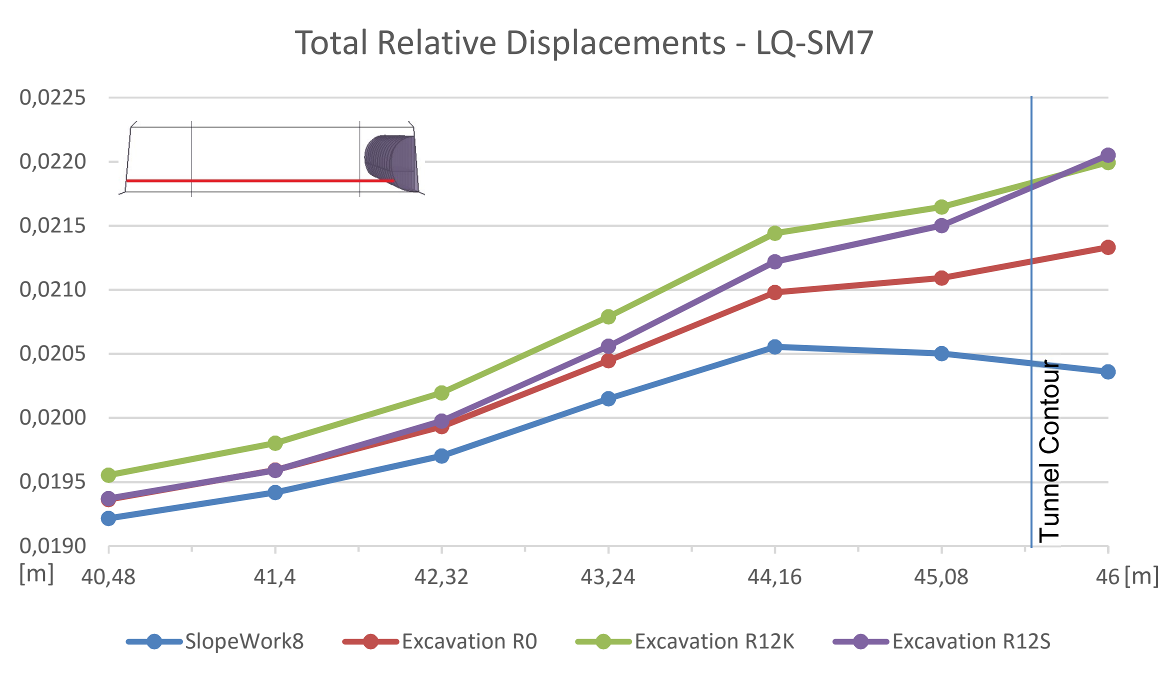


Figure 4.21 Total relative displacements - LQ-MS7, USM

The relative Y-displacements presented in Figure 4.22 range from 0.0190 m at Stage SlopeWork8 up to 0.0197 m at Stage Excavation R12K. That is a stagnation of the displacements of Stage SlopeWork8 and only a 5 % reduction of the displacements in Stage Excavation R12S compared to the movement of the Basic Model.

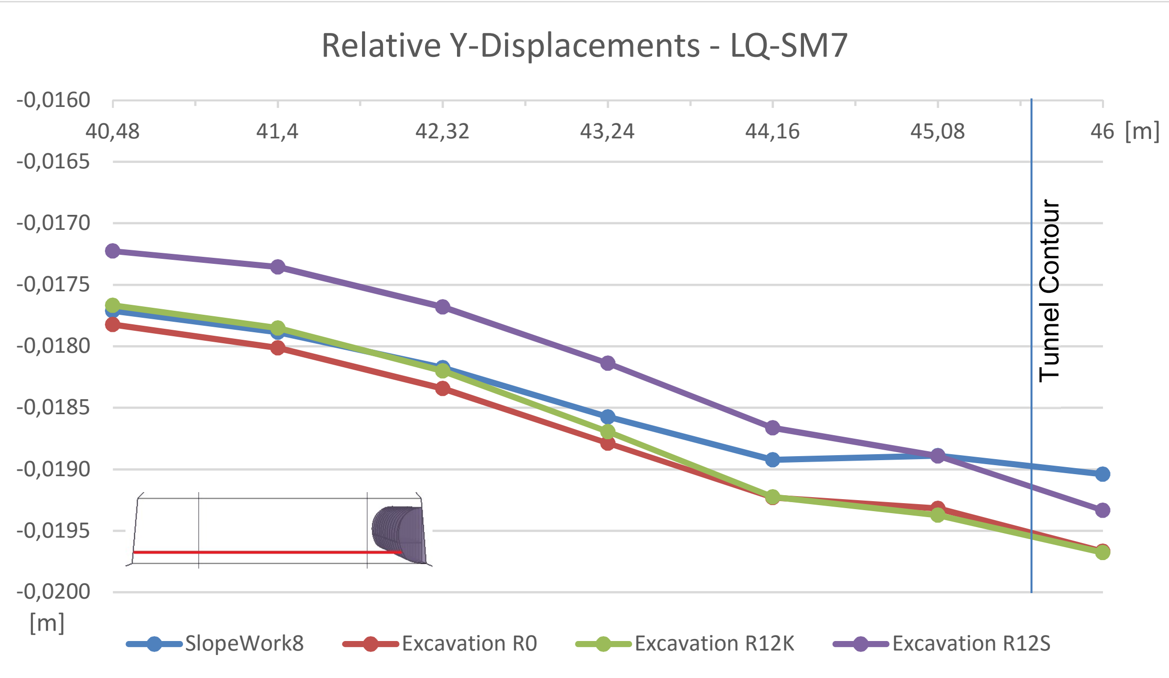


Figure 4.22 Relative Y-displacements - LQ-MS7, USM

4.2 Anchor Utilization

Anchor forces were evaluated to investigate if the tunnel excavation has a significant influence on the anchor utilization.

The observation of anchors focused on the two anchors surrounding the excavation of each anchor row, the anchor labels and coordinates are shown in Table 4.1. Anchor forces differ slightly from each other, peak forces are documented at the second anchor near the tunnel contour, decreasing with increasing distance from the tunnel contour.

The labelling runs from top to bottom and from the excavation contour away in direction of the negative X-axis.

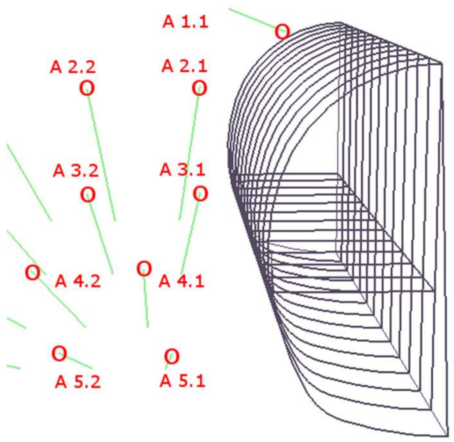
Anchors 4.1, 4.2, 5.1 and 5.2 are additional anchors only installed in the Reinforced Model.

The utilization of the anchors is classified as four groups, depending on the used capacity:

- Low 0 – 25 %
- Medium 25 – 50 %
- High 50 – 75 %
- Very high 75 – 100 %

Table 4.1 Anchor labels and coordinates

Anchor Nr.	X-coordinates	Y-coordinates	Z-coordinates
A 1.1	-4.00	2.81	10.31
A 2.1	-6.25	2.44	8.94
A 2.2	-9.25	2.44	8.94
A 3.1	-6.25	1.69	6.19
A 3.2	-9.25	1.69	6.19
A 4.1	-7.75	1.15	4.20
A 4.2	-10.75	1.15	4.20
A 5.1	-7.00	0.56	2.06
A 5.2	-10.00	0.56	2.06



4.2.1.1 Basic Model

The maximum anchor force occurs at the start of the tunnel excavation, showing a tensile force of 542.16 kN at A 3.2. In subsequent stages, the anchor force drops slightly by about 1 % of the maximum value. The anchor forces are at maximum in a radius of about 4 m around the excavation contour.

Table 4.2 Overview anchor forces - BM

Anchor label	Tensile Force [kN]		
	Excavation Stage		
	R0	R12K	R12S
A 1.1	510.978	508.987	508.468
A 2.1	533.585	532.906	532.588
A 2.2	532.478	531.640	530.711
A 3.1	539.075	538.023	537.879
A 3.2	542.162	541.155	539.012

The utilization of the anchors is situated at 42.3 to 45.2 % of the maximum tensile force of 1200 kN.
Therefore, the anchor utilization of the anchors is classified as medium for all observed anchors. The influence of the tunnel excavation appears to be minimal.

4.2.1.2 Reinforced Model

The maximum anchor force occurs at the start of the tunnel excavation accounting a tensile force of 533.88 kN. In subsequent stages, the anchor force drops slightly by about 1 % of the maximum value. Again, the anchor forces are at maximum in a radius of about 4 m around the excavation contour, listed in Table 4.3 Overview anchor forces - RM.

Table 4.3 Overview anchor forces - RM

Anchor label	Tensile Force [kN]		
	Excavation Stage		
	R0	R12K	R12S
A 1.1	508.008	505.607	504.997
A 2.1	528.411	527.220	526.763
A 2.2	526.143	524.930	523.903
A 3.1	530.849	528.996	526.639
A 3.2	530.334	528.848	526.574
A 4.1	533.877	533.546	531.763
A 4.2	531.908	531.329	529.820
A 5.1	521.234	518.826	514.964
A 5.2	522.159	518.768	515.537

The utilization of the anchors is situated at 42.1 to 44.5 % of the maximum tensile force of 1200 kN, the utilization of the anchors is classified medium.
In comparison with the BM, the utilization decreases slightly by 1 %.

4.2.1.3 Uncoupled Shotcrete Model

The anchor with the maximum tensile force measured is labelled A 3.2 at stage Excavation R0, the beginning of the tunnel excavation, and a force of 539.759 kN, displayed in Table 4.4.

Table 4.4 Overview anchor forces - USM

Anchor label	Tensile Force [kN]		
	Excavation Stage		
	R0	R12K	R12S
A 1.1	519.301	517.787	517.906
A 2.1	532.166	532.303	532.292
A 2.2	531.208	530.839	530.063
A 3.1	538.121	537.432	535.613
A 3.2	539.759	539.274	537.124

The utilization of the anchors amounts 43.2 to 45.0 % of the maximum tensile force of 1200 kN.

The values of utilization is similar to the BM, varying slightly in the range of few thousandth parts.

4.3 Shear Stress

The shear stress measured is located at the surface of the rock mass behind the shotcrete liner at the portal wall. It needs to be transformed to bring it in line with the portal wall inclination. The transformation of the stress has to be done for each model, converting the YZ-direction with the different models is running along the portal wall the in the YZ-direction, transformed to fit the portal wall inclination, which is rotated by 15.26 degrees around the X-axis.
The ordinates in the following figures show the shear stress in kPa, the abscissa show the meters on the X-axis of the model, whereby the tunnel axis is located at meter 50.

4.3.1.1 Basic Model

The figures above are the results of different query lines of the BM, sorted from highest to lowest elevation. First is the query located at the upper edge of the portal wall, followed by the query line at height 1.9 m and finally the query at the lower edge of the portal wall.

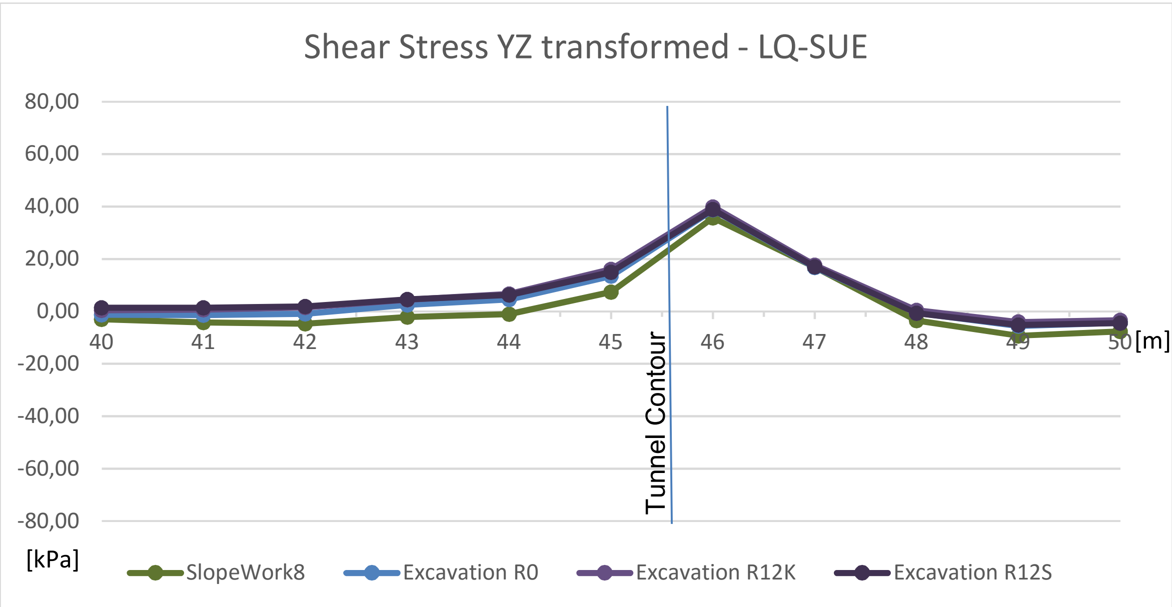


Figure 4.23 Shear stress YZ transformed LQ-SUE - BM

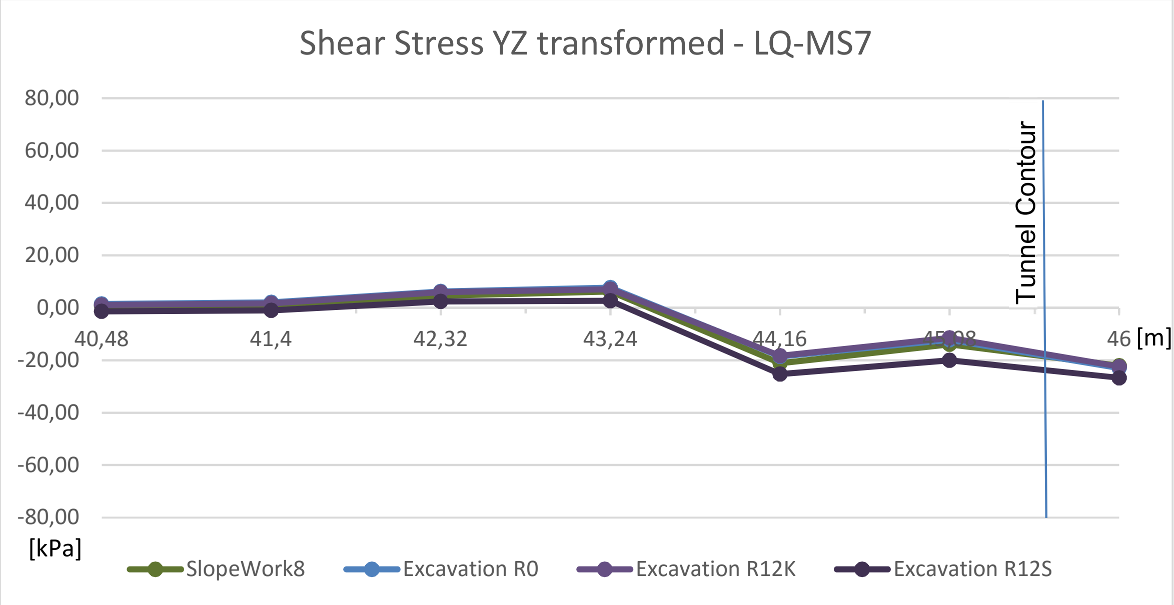


Figure 4.24 Shear stress YZ transformed LQ-MS7 - BM

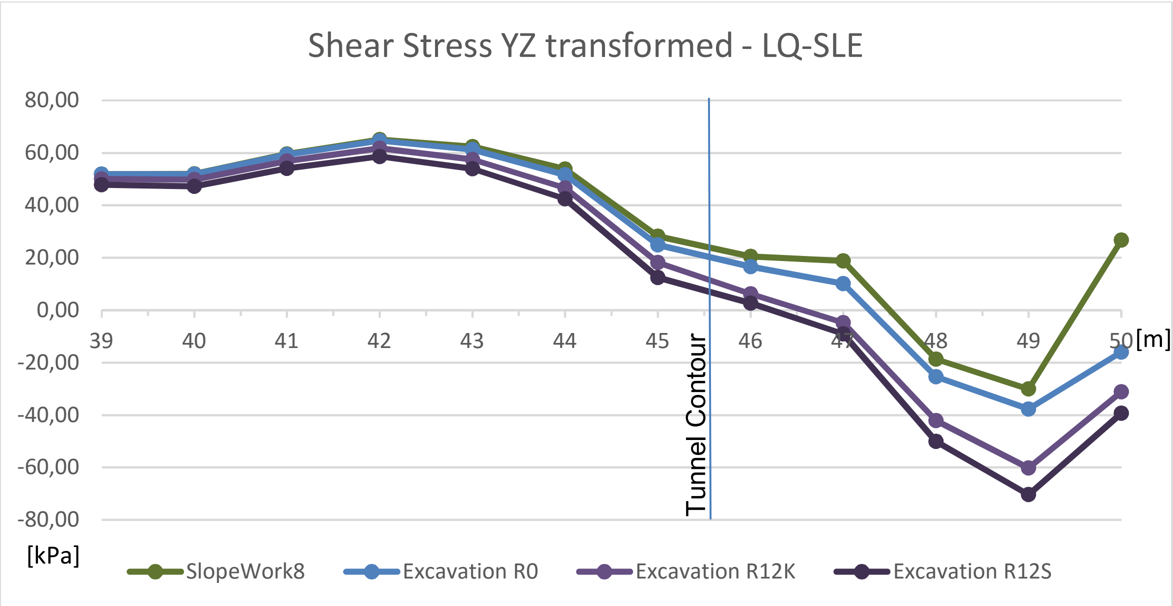


Figure 4.25 Shear stress YZ transformed LQ-SLE - BM

In Figure 4.23 the bend at meter 46 is caused by the prestressed anchor installed there, causing increased, but tolerable shear stress in that area with a maximum of 38.86 kPa through all stages.

Figure 4.24 shows slight shear stress of around 5 kPa, along different stages varying slightly over the progress of excavation, with a swing of the curve at the prestressed anchor location reaching a maximum of -26.67 kPa.

Shear stresses displayed in Figure 4.25 have its peak of 64.63 kPa, 3.5 m away from the tunnel excavation contour. With decreased distance to the tunnel contour and progress in excavation, the shear stress lowers to a minimum of -70.38 kPa at excavation R12S.

4.3.1.2 Reinforced Model

The figures above are the results of different query lines of the RM, sorted from highest to lowest elevation. First is the query located at the upper edge of the portal wall, followed by the query line at height 1.9 m and finally the query at the lower edge of the portal wall.

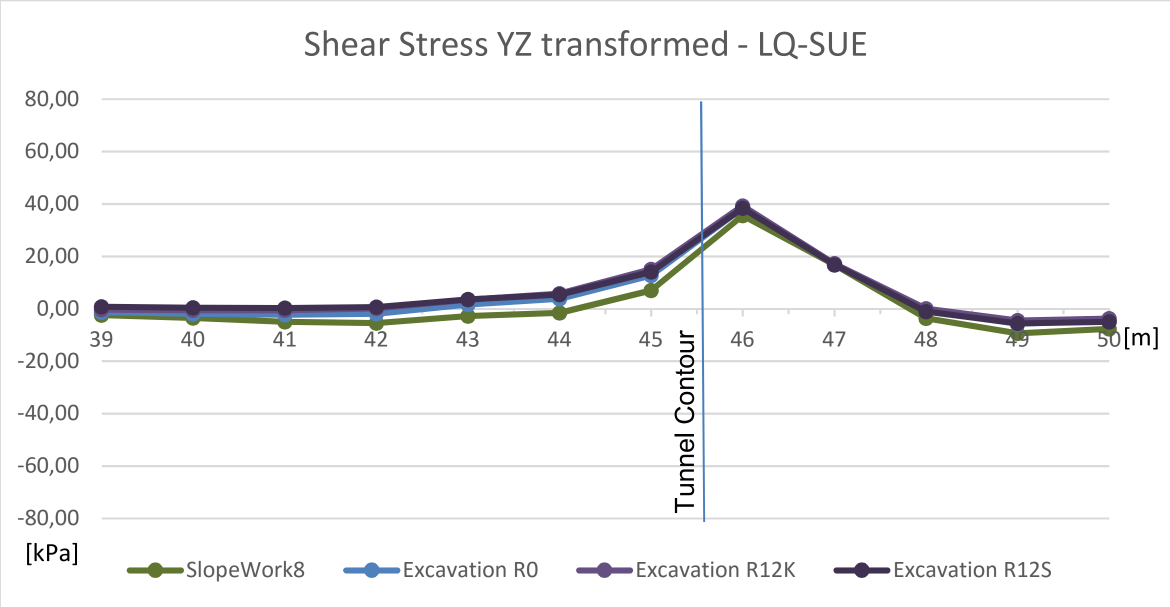


Figure 4.26 Shear stress YZ transformed LQ-SUE - RM

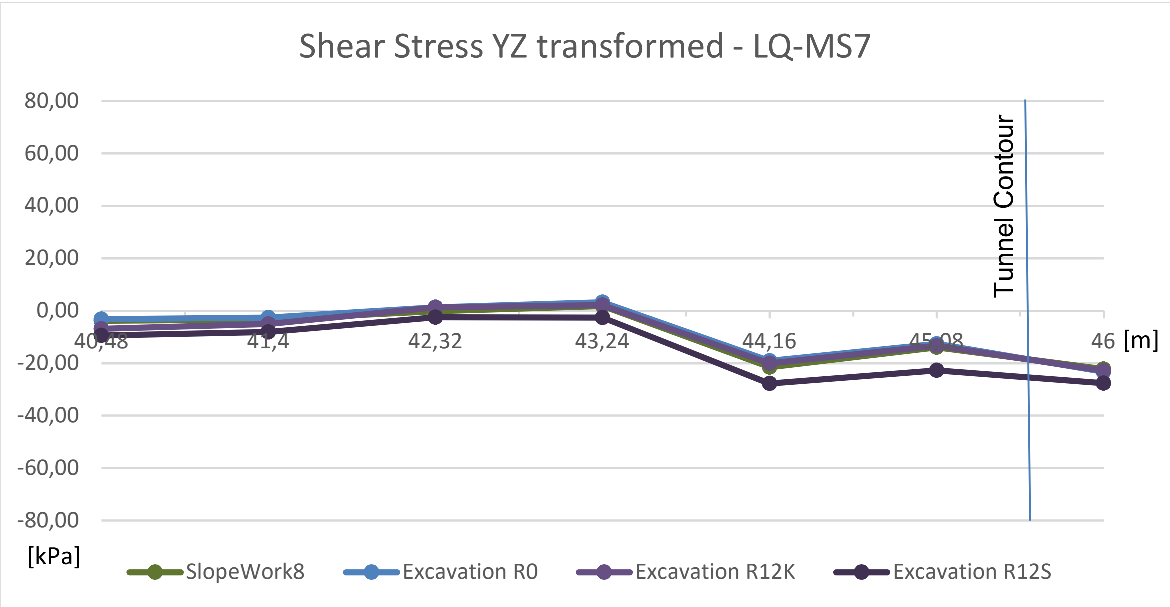


Figure 4.27 Shear stress YZ transformed LQ-MS7 - RM

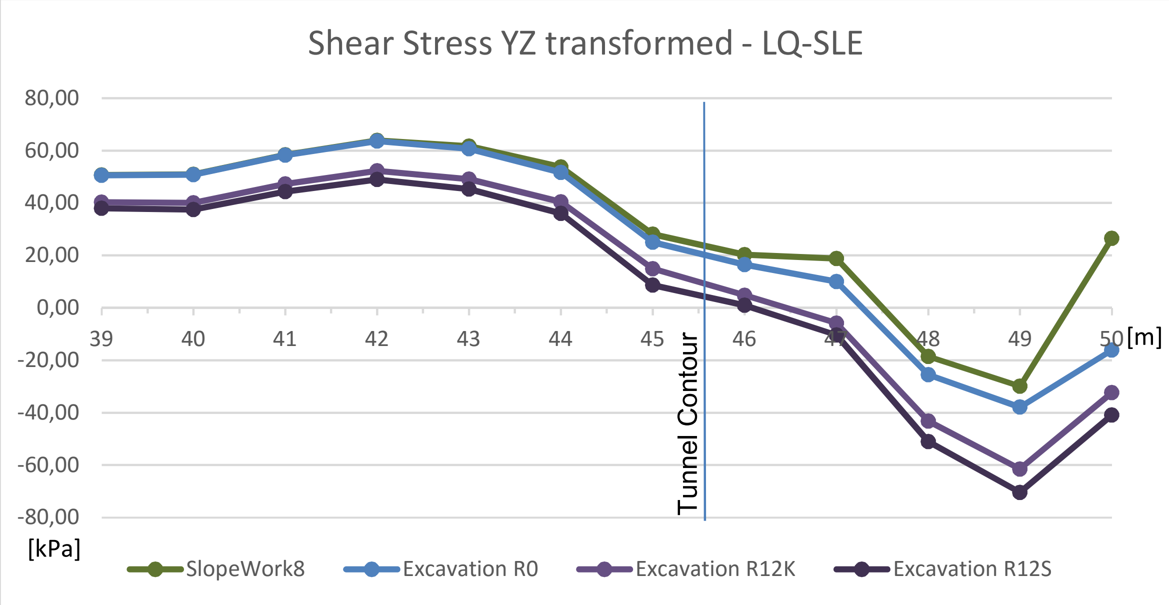


Figure 4.28 Shear stress YZ transformed LQ-SLE - RM

When looking at Figure 4.26 the peak at meter 46 with a value of 38.40 kPa is notable, caused by the prestressed anchor installed there, like explained in chapter 4.3.1.1.

Figure 4.27 shows minor shear stress around 3 kPa, peaking at around -27.78 kPa for excavation stage R12S at the distance of 1.5 m around the tunnel contour.

The line query shown in Figure 4.28 has similar behaviour as query line of the BM displayed in Figure 4.25 Shear stress YZ transformed LQ-SLE - BM, with a peak of 63.62 kPa at 3.5 m distance of the tunnel contour after slope excavation and a minimum of -70.43 kPa at excavation R12S located near the tunnel axis.

4.3.1.3 Uncoupled Shotcrete Model

The figures above are the results of different query lines of the USM, sorted from highest to lowest elevation. First is the query located at the upper edge of the portal wall, followed by the query line at height 1.9 m and finally the query at the lower edge of the portal wall.

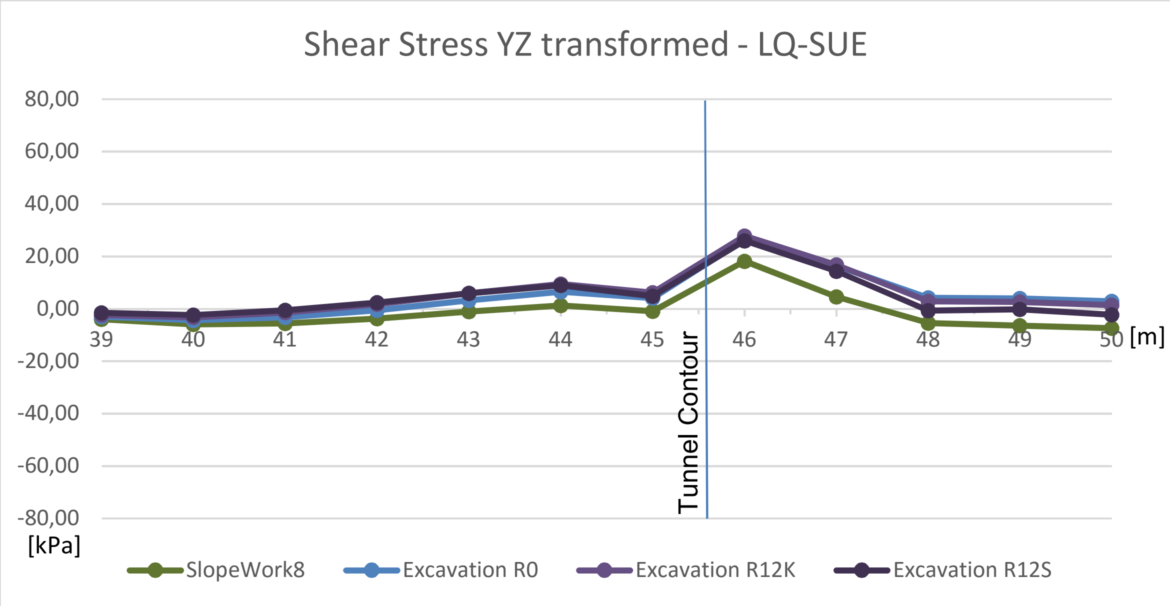


Figure 4.29 Shear stress YZ transformed LQ-SUE - USM

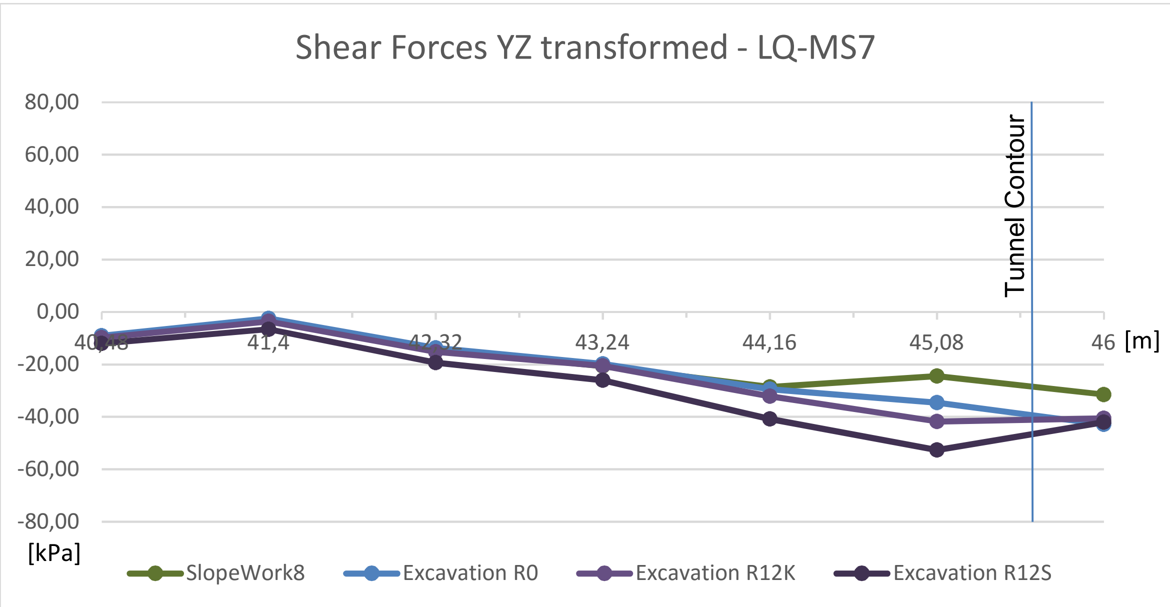


Figure 4.30 Shear stress YZ transformed LQ-MS7 - USM

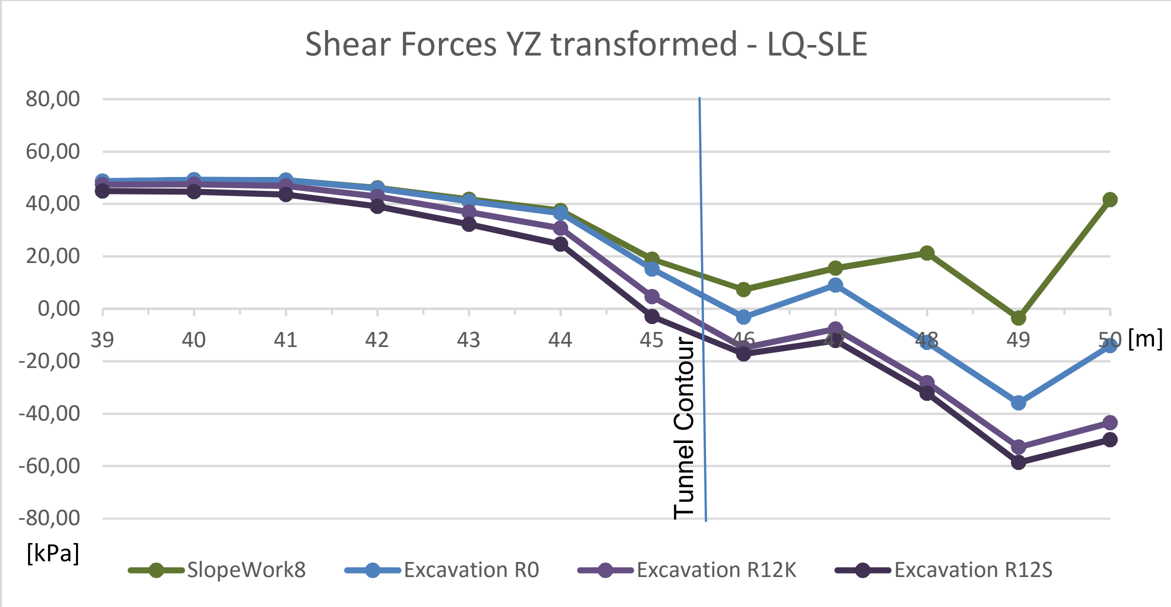


Figure 4.31 Shear stress YZ transformed LQ-SLE - USM

Figure 4.29 shows lower shear stresses compared to the BM and RM, with a peak of 25.98 kPa located at the prestressed anchor.

In Figure 4.30, a change of shear stress along the whole line can be noticed with a minimum of -52.67 kPa at excavation R12K at a distance of 1 m of the tunnel contour.

LQ-SLE displayed in Figure 4.31 pictures a peak shear stress of 46.86 kPa located 3.5 m away from the tunnel contour and a minimum of -58.61 kPa at excavation R12S at a distance of 1 m of the tunnel axis.

4.4 Model Comparison

4.4.1 Displacements

The displacements presented in chapter 4.1 are opposed here, focusing on the measurement line LQ-MS7. The total relative displacements of the BM are maximum 0.022 m, the RM results in decreased displacements by roughly 10 % in the same location. The USM doesn't show significant changes in movement on the observed lines.
The relative Y-displacements are also decreasing by approximately 10 % from BM to RM with the maximum near the excavation contour. The variation of the movements of the different stages get denser and the data show less scatter, providing a more uniform behaviour of the displacements when comparing BM to RM. The monitored data of USM shows slight increase in contrast to BM, but no substantial behaviour change is noticed.

4.4.2 Anchor Utilization

The anchors appear to be only marginally influenced by tunnel excavation. The general utilization ranges from 42.1 to 45.2 %, classified as medium. The maximum anchor forces appear at stage Excavation R0 throughout in every model, the anchors placed in a radius of 4 m to the tunnel contour hold the maximum forces. The BM issues the biggest force of 542.16 kN, RM with addition anchors measures 533.88 kN at the same location. The USM lies between the other two with an anchor force of 539.76 kN.
The outcomes vary marginally and are not big enough to point out meaningful features of the different models.

4.4.3 Shear Stress

Regarding the shear stresses occurring in the slope shotcrete lining in different models, the overall trend is decreasing from BM to RM, being at a minimum at USM when looking at the portal wall area around the tunnel excavation.
Results at LQ-SUE differ slightly between BM and RM with a negligible decrease of shear stress. The results of USM decrease to roughly 70 % at peak of the BM, with more impact on the results the nearer it is located to the tunnel contour.
At location LQ-MS7, the results of BM and RM are quite similar, USM shows an increase in shear stress almost doubling the minimum value.
Results at the bottom of the portal wall, measured in LS-SLE are almost equal when comparing BM to RM, USM on the other hand flattens the extreme values and decreases the values by approximately 20 %.

5 Summary

In this thesis a three dimensional model of the excavation of a tunnel in weathered rock mass with low overburden is simulated and the results evaluated.

The numerical modelling of specific tunnel projects is a challenging process, requiring intensive parameter study to receive values close to reality. The model is related to an example project built in Carinthia, providing execution plans and building site exploration documentation. The focus of the study lies in the displacements occurring at the portal wall, especially the horizontal displacements, as well as the anchor forces around the tunnel excavation contour and the shear stresses in the shotcrete liner. Three numerical models are created with different support measures to evaluate the displacements, utilizations and shear stresses.

In summary it is observed, that the biggest horizontal displacements are created when starting the tunnel excavation, in detail the first round of the tunnel excavation.
The same is true for the anchor utilization and shear stresses in the shotcrete lining at the portal wall.
The horizontal displacements of the basic model were lowered by roughly 10 %, due to reinforcing the model with two additional anchor rows during the slope excavation.
The anchor forces observed show a medium utilization of the prestressed anchors of up to 45 % of the tensile capacity, giving non-significant differences for the various models and stages.
Shear stresses were evaluated in all three models, showing biggest values for the basic model. The reinforced model showed lower displacements, also decreased shear stresses along the portal wall by roughly 5 % in contrast to the basic model are calculated. The third model is based on the basic model, but has a shotcrete free gap around the tunnel excavation contour over a width of 0.40 m. The idea is to decouple the tunnel lining and the portal wall lining, thus reducing the shear stress in the portal wall support. The results of the USM are around 30 % lower than those of the BM, only shear stresses located at 1.9 m height are increased, but for the case investigated the difference is not significant.

The study conducted did not reveal significant influences on the tunnel excavation on the stresses and displacements of the portal wall support for the case investigated. Different geological conditions and the use of a more advanced material model might lead to different results.

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