# Solution for Problem Set 5

## 1. Scope of work

The scope of the present report, is the presentation of the analytical design of a deep railway tunnel primary support. Based on the geological and geotechnical tunnel area investigation program, tunnel alignment will passes through the flysch formation of the Pindos geological zone, which is separated on the following two (2) engineering geological units:

A) Sandstone Flysch
B) Thrust Zone

The tunnel equivalent diameter is D= 9m and will be excavated by the conventional excavation method (NATM). On the engineering geological unit (A), due to the good rockmass conditions, drill and blast excavation method will be used and on the engineering geological unit (B), due to the poor rockmass conditions, excavation by hydraulic excavator will be used. On the engineering geological unit (A) the maximal tunnel overburden height, is estimated H= 250m and on the engineering geological unit (B) the maximal tunnel overburden height, is estimated H= 55m.

As it is presented on the following Figures 1 and 2, two (2) tunnel excavation sections will be taken into account on the tunnel design, where the Section A will used for the tunnel excavation on the engineering geological unit (A) and the Section B will used for the tunnel excavation on the engineering geological unit (B). On tunnel Section A, the excavation phases are the following: a) Top Heading and b) Bench and on tunnel Section B, the excavation phases are the following: a) Top Heading b) Temporary Invert, c) Bench and d) Final Invert.

For the engineering geological unit (A), due to the proposed excavation method by drill and blast, the excavation advance length is 3m (equal to blasting excavation length) and for the engineering geological unit (B), due to the usage of hydraulic excavator for the tunnel excavation, the excavation advance length is 1m.

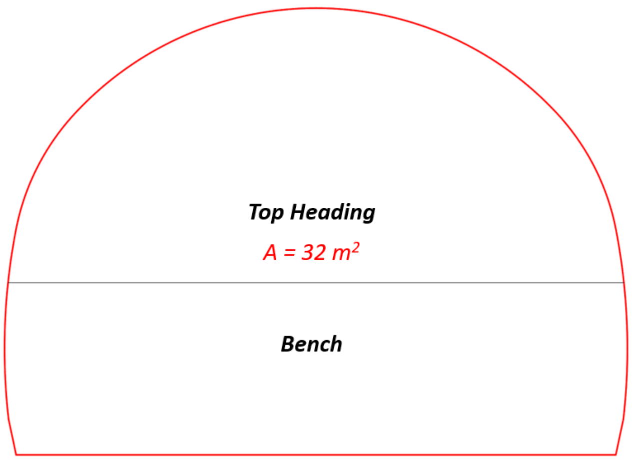


***Figure 1. Tunnel Section A.***

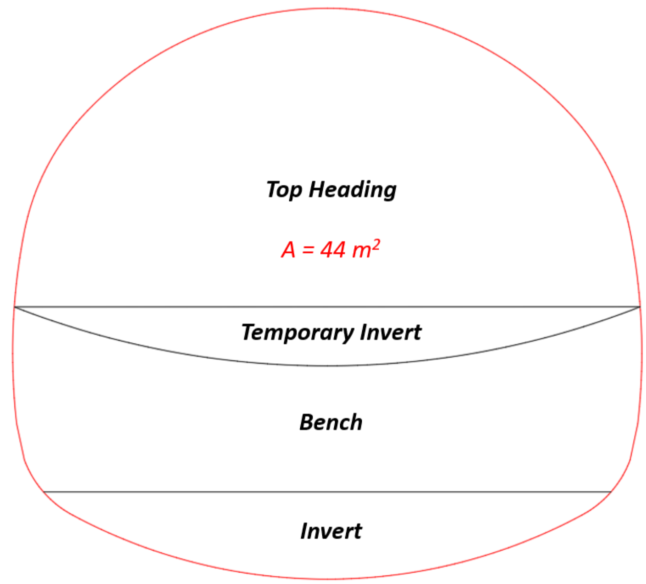


***Figure 2. Tunnel Section B.***

Tunnel design based on a two – dimensional (2D) numerical analyses, using the RS2 – Rocscience software and the excavation relaxation method, based on the equivalent ground relaxation modulus (E), in order to simulate the relaxation effect of the third dimension (along the tunnel axis).

For the tunnel lining design, the design standards of EC2 EN 1992-1 taken into account.

## 2. Numerical analyses

### 2.1. Software

For the tunnel design, the two – dimensional (2D) numerical software RS2 – Rocscience used.

### 2.2. Numerical models

The numerical models limits, are based on the tunnel equivalent diameter (D). Two numerical models designed, each one for each tunnel section and engineering geological unit. On both numerical models, the side external limits of the numerical model, placed five (5) tunnel diameters (5 x D) from the tunnel axis, the upper limit placed five (5) tunnel diameters (5 x D) from the tunnel axis and the bottom limit, placed three (3) tunnel diameters (3 x D) from the tunnel axis. On the following ***Figures 3*** *and* ***4***, the numerical models for both tunnel sections, are presented. For both models, one rockmass layer used on the whole model area.

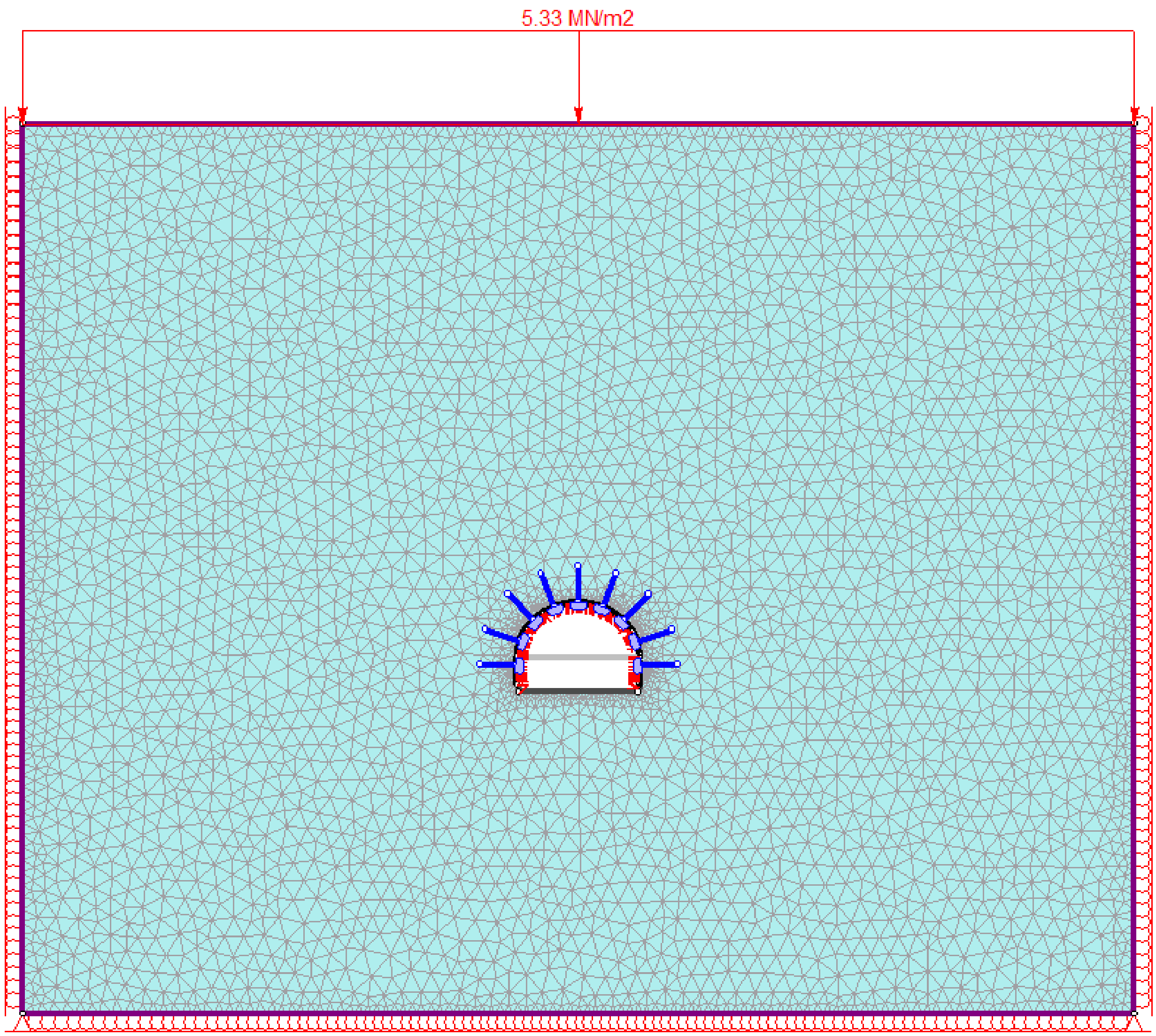


***Figure 3. Numerical model for tunnel Section A.***

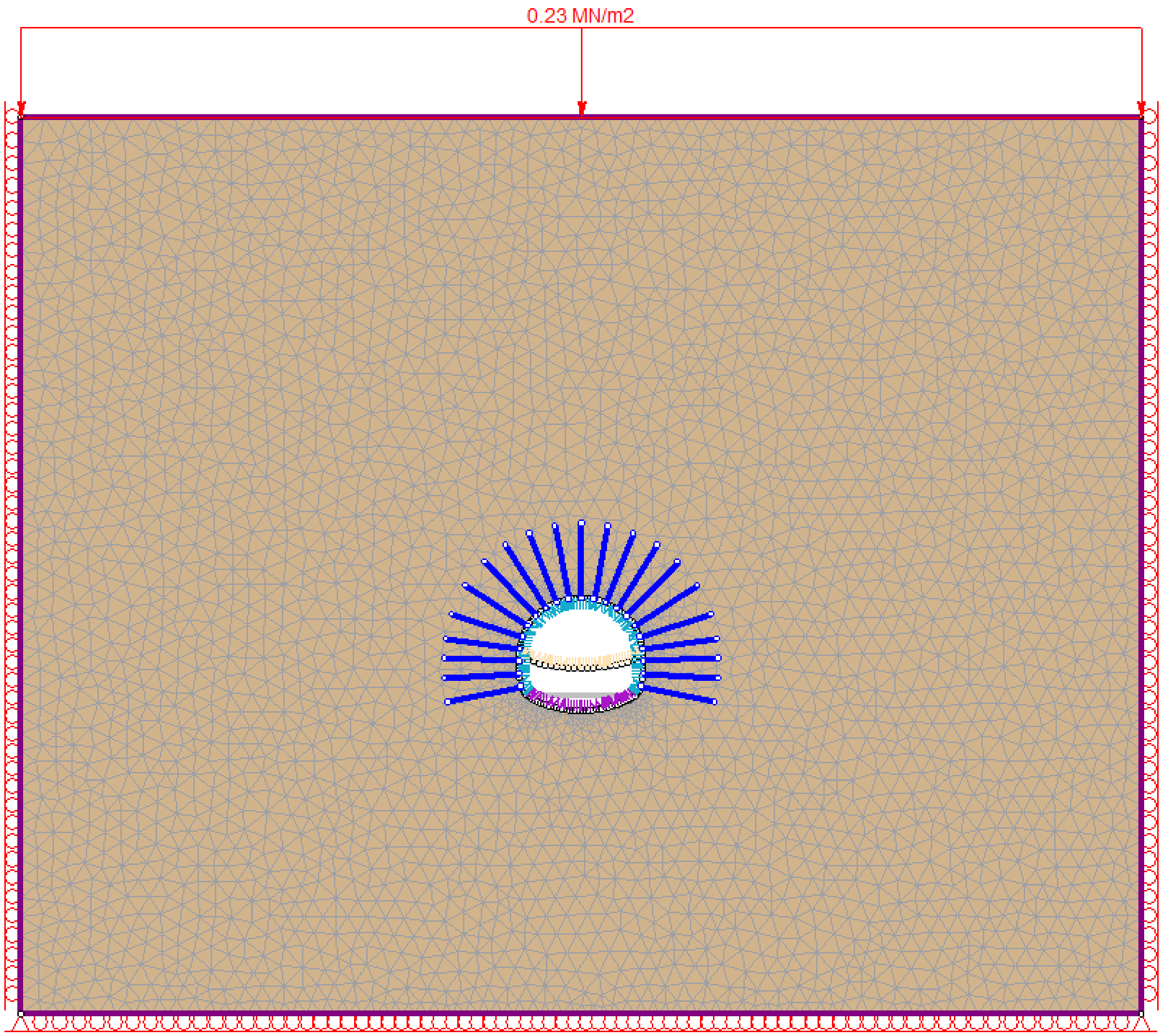


***Figure 4. Numerical model for tunnel Section B.***

### 2.3. Mesh

The numerical models mesh, consist of three nodded triangular continuum elements. On the following ***Table 1***, total elements and nodes number for the two numerical models, are presented.

***Table 1. Numerical models, mesh parameters.***

| Numerical Model | Elements | Nodes |
|---|---|---|
| *Section A* | 9435 | 5068 |
| *Section B* | 7214 | 3780 |

### 2.4. Geotechnical parameters

The two rockmass engineering geological units (A and B), simulated with elastoplastic behavior, using the Generalized Hoek & Brown 2002 failure criterion, based on the GSI value. On the following table the geotechnical input parameters for the engineering geological units, are presented.

*Table 2. Geotechnical parameters of engineering geological units.*

| Parameter | A | B |
|---|---|---|
| *Rockmass unit weight ($\gamma$)* | 26 $kN/m^3$ | 23 $kN/m^3$ |
| *Compressive strength of intact rock ($\sigma_{ci}$)* | 358 MPa | 18 MPa |
| *Intact rock modulus ($E_i$)* | 35 GPa | 20 GPa |
| *Friction angle ($\varphi$)* | 35° | 30° |
| *Poisson ratio ($v$)* | 0.4 | 0.3 |
| *mi* | 19 | 9 |
| *GSI* | 50 | 25 |
| *Disturbance factor (D)* | 0 | 0 |
| *Dilation angle ($\delta$)* | 0° | 0° |
| *Rockmass strength ($\sigma_{cm}$)* | 5.4 MPa | 0.96 MPa |
| *Rockmass modulus ($E_m$)* | 10.75 GPa | 1197 MPa |

A plain strain analysis used, taken into account a geostatic field stress loading, with horizontal stress ($K_o$), 0.4.

In all examined cases, the ground simulated in dry conditions, due to the installation of drainage holes on the tunnel perimeter.

### 2.5. Support parameters

On both examined cases (Sections A and B), the tunnel primary lining, consist of shotcrete lining, steel sets (only for Section A), Swellex bolts for Section A and rockbolts for Section B. Shotcrete lining and steels sets, simulated as composite beam elements on the excavation perimeter and the rockbolts simulated as truss elements, with radial placement on the tunnel perimeter. All of the supported elements, simulated with elastic behavior. On the following ***Tables 3*** and ***4***, the tunnel support parameters are presented, for the two examined tunnel sections.

*Table 3. Tunnel support parameters for Section A.*

| **Shotcrete** | |
|---|---|
| *Concrete class* | C30/37 |
| *Reinforcement* | T188 wire mesh |
| *Compression strength ($f_{ck}$)* | 30 MPa |
| *Tensile strength ($f_{tk}$)* | 6 MPa |
| *Elastic modulus ($E_{shot}$)* | 17 GPa |
| *Poisson ratio ($v$)* | 0.2 |
| *Unit weight ($\gamma_{shot}$)* | 25 $kN/m^3$ |
| **Swellex bolts** | |
| *Type* | Dextra DM160 |
| *Tensile capacity ($F_{tk}$)* | 141 kN |
| *Length (L)* | 3 m |
| *Pattern* | 3 x 3 m (longitudinal x radial) |

*Table 4. Tunnel support parameters for Section B.*

| **Shotcrete** | |
|---|---|
| *Concrete class* | C30/37 |
| *Reinforcement* | T188 wire mesh |

| | |
|---|---|
| *Compression strength ($f_{ck}$)* | 30 MPa |
| *Tensile strength ($f_{tk}$)* | 6 MPa |
| *Elastic modulus ($E_{shot}$)* | 17 GPa |
| *Poisson ratio (v)* | 0.2 |
| *Unit weight ($\gamma_{shot}$)* | 25 kN/$m^3$ |
| **Rockbolts** | |
| *Type* | Fully bonded |
| *Diameter (d)* | 25 mm, 40mm |
| *Tensile capacity ($F_{tk}$)* | 270 kN, 691 kN |
| *Elastic modulus ($E_{steel}$)* | 200 GPa |
| *Length (L)* | 6 m, 8 m |
| *Pattern* | 1 x 1 m (longitudinal x radial) |
| **Steel sets** | |
| *Type* | HEB 140 |
| *Elastic modulus ($E_{steel}$)* | 200 GPa |
| *Longitudinal spacing* | 1 set every excavation advance length |

In order to take into account the effect of the shotcrete time dependent hardening, the installation of shotcrete lining on each excavation step, is separated in three (3) stages, where on each stage the shotcrete thickness and strength is simulated as percentage of the total value, as follow:

- ✓ 1st installation stage: 50% of total thickness, 25% of total strength
- ✓ 2nd installation stage: 100% of total thickness, 50% of total strength
- ✓ 3d installation stage: full values of thickness and strength

### 2.6. Simulation stages

Tunnel numerical analyses, were based on a two-dimensional (2D) analyses, using the ground relaxation method, in order to simulate the effect of the third dimension, as the tunnel pre-convergence starts a lot of meters in front of the tunnel face.

Every tunnel excavation step, was separated in four (4) steps, where on the first one the tunnel excavation and relaxation was simulated and on the other excavation steps, the ground relaxation and the shotcrete hardening as presented on *Chapter 2.5*, were simulated. The sequence of the ground relaxation and shotcrete hardening simulation, is the following, based on the tunnel face advance length (Y):

- ✓ 1st stage: Ground relaxation in the tunnel face (Y=0), No support
- ✓ 2nd stage: Ground relaxation in a distance 1 x Y from the tunnel, Shotcrete installation: 50% of total thickness and 25% of total strength, Steel sets installation with full capacity values
- ✓ 3d stage: Ground relaxation in a distance 2 x Y from the tunnel face, Shotcrete: 100% of total thickness and 50% of total strength, Bolts installation with full capacity values
- ✓ 4th stage: No relaxation, Shotcrete with full thickness and strength values

In all the numerical analyses, first simulation stage was the geostatic stage, where was the initial condition of the ground without the tunnel construction.

On the following ***Tables 5*** and ***6***, the numerical analyses stages for both numerical models, are presented.

***Table 5. Simulation stages for tunnel Section A numerical analysis.***

| Stage | Description |
|---|---|
| 1. *Geostatic* | Simulation of the initial ground conditions, without tunnel construction |
| 2. *Relaxation Top Heading (x= 0m)* | Relaxation of the Top Heading area, with relaxation material at the tunnel face (x = 0m). |
| 3. *Relaxation Top Heading (x= -3m)* | Relaxation of the Top Heading area, with relaxation material in a distance x= 3m from the tunnel face. Installation of shotcrete: 50% of total thickness and 25% of total strength. |
| 4. *Relaxation Top Heading (x= -6m)* | Relaxation of the Top Heading area, with relaxation material in a distance x= 6m from the tunnel face. Installation of Swellex bolts. Hardening of shotcrete: 100% of total thickness and 50% of total strength. |
| 5. *Support Top Heading* | Ground material remove from the Top Heading area. Full parameters of shotcrete lining. |
| 6. *Relaxation Bench (x= 0m)* | Relaxation of the Bench area, with relaxation material at the tunnel face (x = 0m). |
| 7. *Relaxation Bench (x= -3m)* | Relaxation of the Bench area, with relaxation material in a distance x= 3m from the tunnel face. Installation of shotcrete: 50% of total thickness and 25% of total strength. |
| 8. *Relaxation Bench (x= -6m)* | Relaxation of the Bench area, with relaxation material in a distance x= 6m from the tunnel face. Installation of Swellex bolts. Hardening of shotcrete: 100% of total thickness and 50% of total strength. |
| 9. *Support Bench* | Ground material remove from the Bench area. Full parameters of shotcrete lining. |

***Table 6. Simulation stages for tunnel Section B numerical analysis.***

| Stage | Description |
|---|---|
| 1. *Geostatic* | Simulation of the initial ground conditions, without tunnel construction |
| 2. *Relaxation Top Heading – Temp Invert (x= 0m)* | Relaxation of the Top Heading and Temporary Invert area, with relaxation material at the tunnel face (x = 0m). |
| 3. *Relaxation Top Heading – Temp Invert (x= -1m)* | Relaxation of the Top Heading and Temporary Invert area, with relaxation material in a distance x= 1m from the tunnel face. Installation of steel sets and shotcrete: 50% of total thickness and 25% of total strength. |
| 4. *Relaxation Heading – Temp Invert (x= -2m)* | Relaxation of the Top Heading and Temporary Invert area, with relaxation material in a distance x= 2m from the tunnel face. Hardening of shotcrete: 100% of total thickness and 50% of total strength. Installation of fully bonded bolts. |
| 5. *Support Top Heading – Temp Invert* | Ground material remove from the Top Heading and Temporary Invert area. Full parameters of shotcrete lining. |
| 6. *Relaxation Bench (x= 0m)* | Relaxation of the Bench area, with relaxation material at the tunnel face (x = 0m). |

| Stage | Description |
|---|---|
| *7. Relaxation Bench (x= -1m)* | Relaxation of the Bench area, with relaxation material in a distance x= 1m from the tunnel face. Installation of steel sets and shotcrete: 50% of total thickness and 25% of total strength. |
| *8. Relaxation Bench (x= -2m)* | Relaxation of the Bench area, with relaxation material in a distance x= 2m from the tunnel face. Hardening of shotcrete: 100% of total thickness and 50% of total strength. Installation of fully bonded bolts. |
| *9. Support Bench* | Ground material remove from the Bench area. Full parameters of shotcrete lining. |
| *10. Relaxation Final Invert (x= 0m)* | Relaxation of the Final Invert area, with relaxation material at the tunnel face (x = 0m). |
| *11. Relaxation Final Invert (x= -1m)* | Relaxation of the Final Invert area, with relaxation material in a distance x= 1m from the tunnel face. Installation of steel sets and shotcrete: 50% of total thickness and 25% of total strength. |
| *12. Relaxation Final Invert (x= -2m)* | Relaxation of the Final Invert area, with relaxation material in a distance x= 2m from the tunnel face. Hardening of shotcrete: 100% of total thickness and 50% of total strength. Installation of fully bonded bolts. |
| *13. Support Final Invert* | Ground material remove from the Final Invert area. Full parameters of shotcrete lining. |

### 2.7. Relaxation method

In order to takes into account on the numerical analyses, the effect of the third -dimension, as the tunnel pre-convergence starts a lot of meters in front of the tunnel face, the ground relaxation method used.

Based on this method, the material on the excavation area, is simulated as relaxation material with reduced ground modulus (E) and the same strength parameters with the rockmass material. The reduced ground modulus (E) for the relaxation material, depends on the deconfinement factor (λ) and can be calculated as follow:

$$\frac{E}{E_o} = \frac{(1 - 2 \times \nu) \times (1 - \lambda)}{(1 - 2 \times \nu) + \lambda}$$

Where, E: is the ground modulus of the relaxation material, $E_o$; is the ground modulus of the rockmass, λ: is the deconfinement factor and v: is the Poisson ratio.

Based on *Chapter 2.6*, ground relaxation is simulated in three (3) steps, based on the simulation distance from the tunnel face. On the following ***Figure 5***, the relaxation stages for the Top Heading excavation area of the tunnel Section B, are presented.

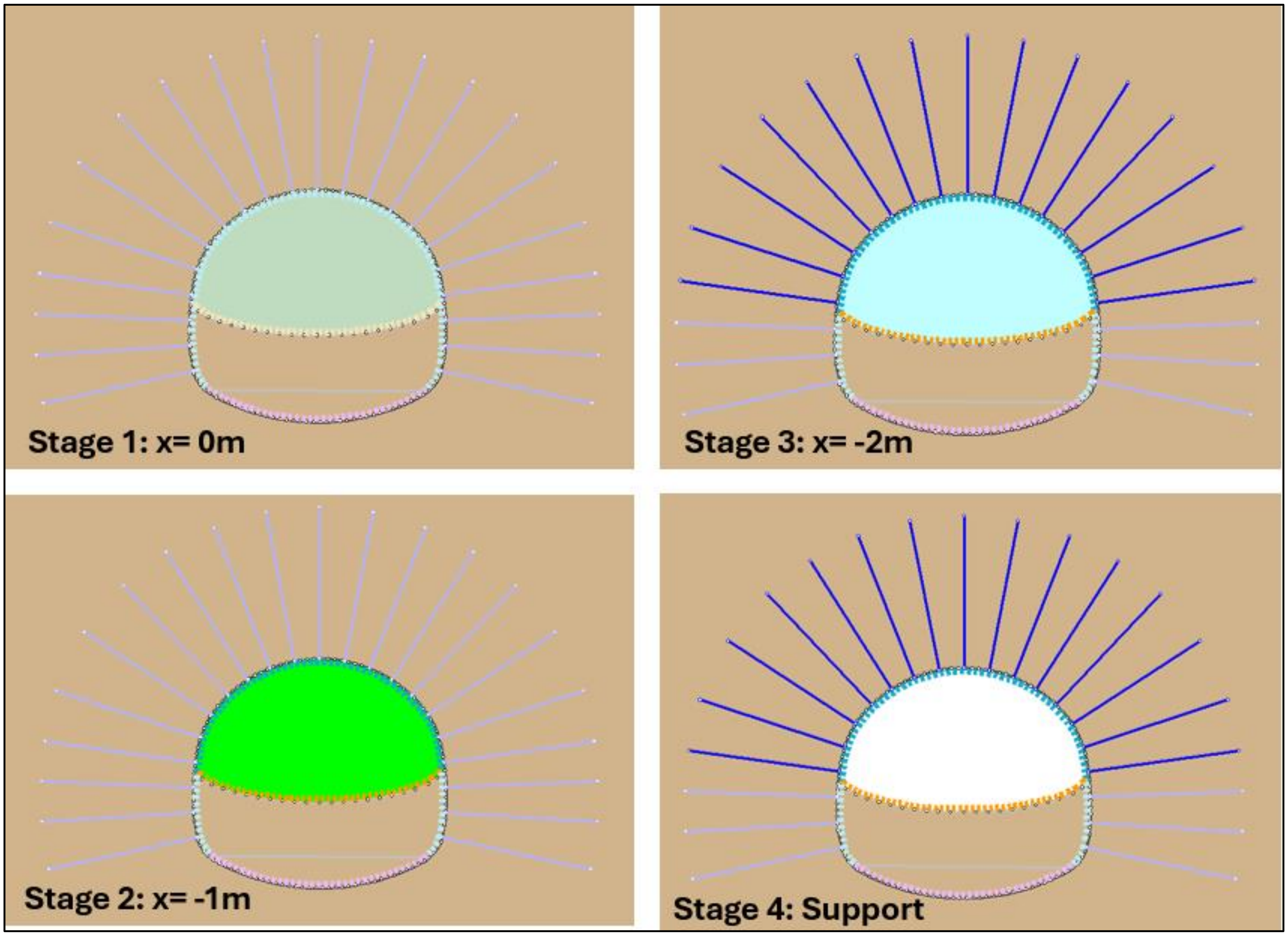


***Figure 5. Relaxation stages for Top Heading area, in tunnel Section B.***

In order to calculate the deconfinement factor (λ) and the equivalent ground relaxation modulus (E), for using in the numerical analyses, the longitudinal displacement profile (LDP) method by *Chern et al. 1998* and the convergence – confinement method by *Kavvadas M. 2004*, used.

On the following Figures, the convergence confinement curve and the tunnel longitudinal displacement profile (LDP) for the two engineering geological units, are presented. Also, on the following Tables, characteristics values from the convergence – confinement curve, the deconfinement factor (λ) and the ground relaxation modulus (E), are presented.

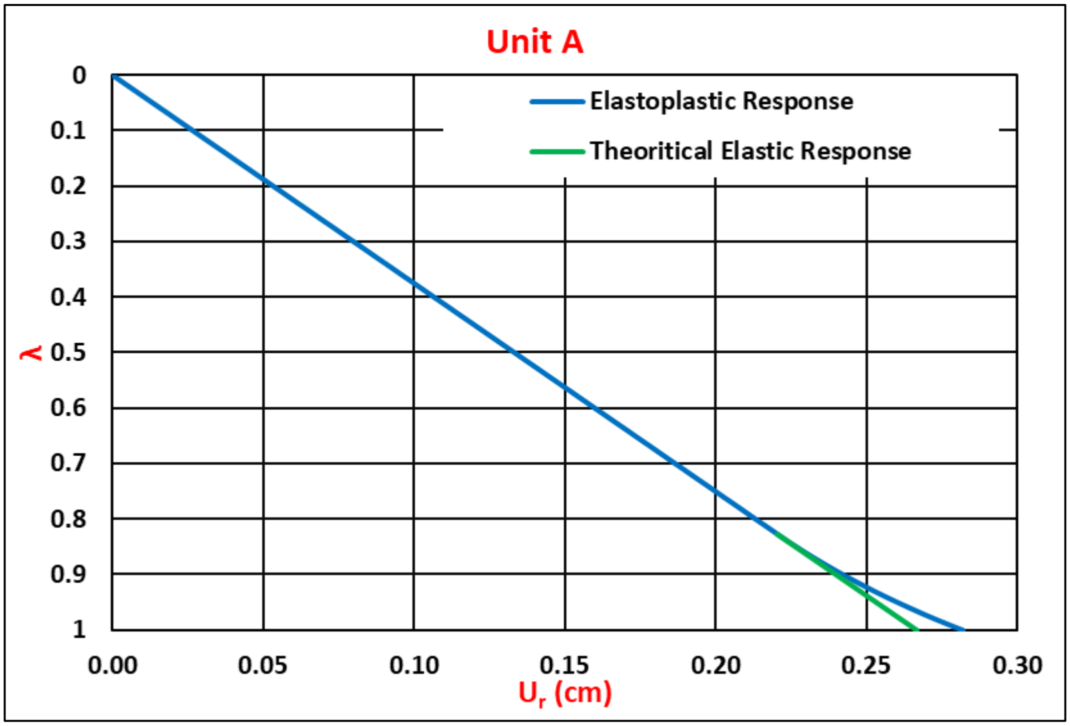


*Figure 6. Ground convergence – confinement curve, for engineering geological unit A.*

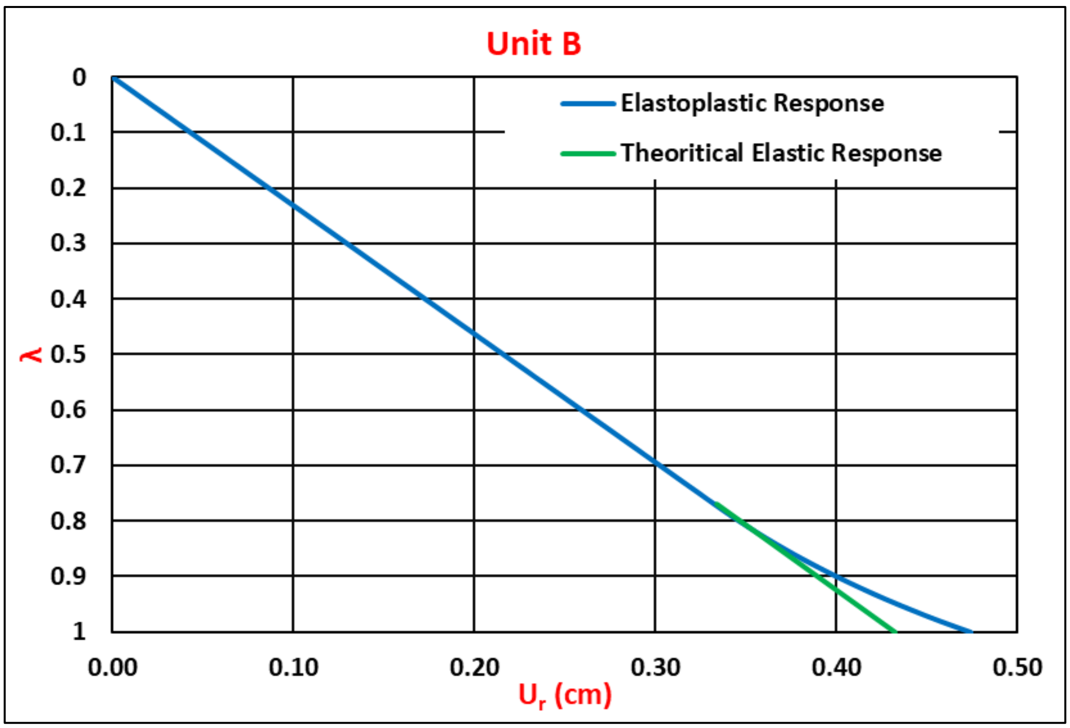


*Figure 7. Ground convergence – confinement curve, for engineering geological unit B.*

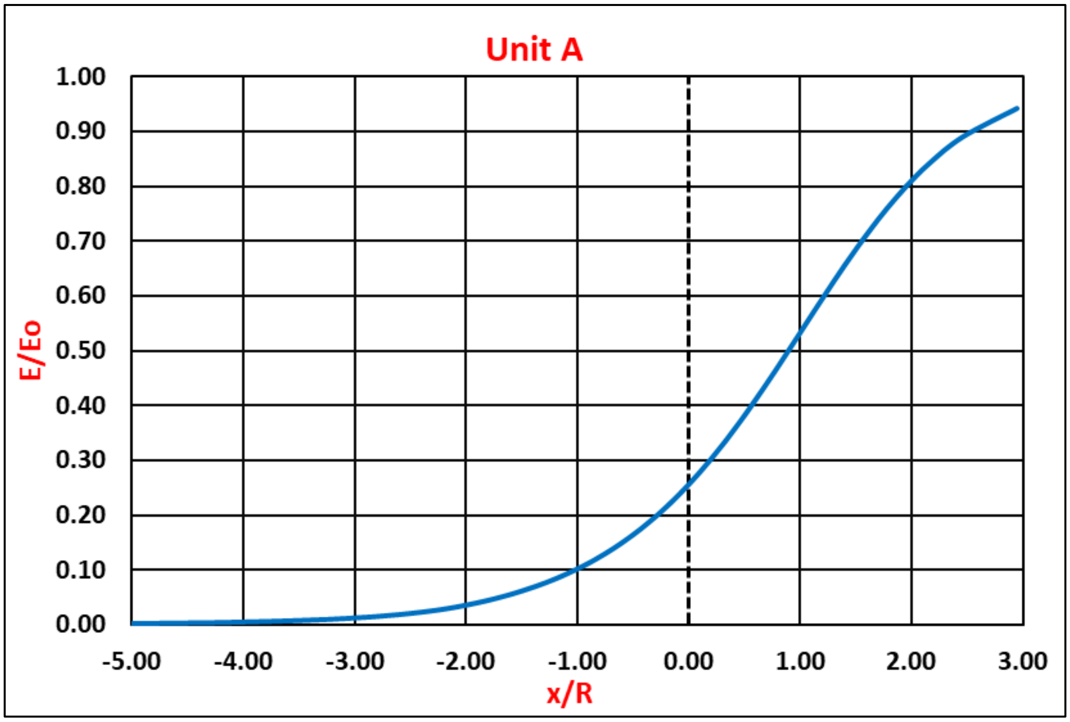


*Figure 8. Longitudinal displacement profile (LDP), for engineering geological unit A.*

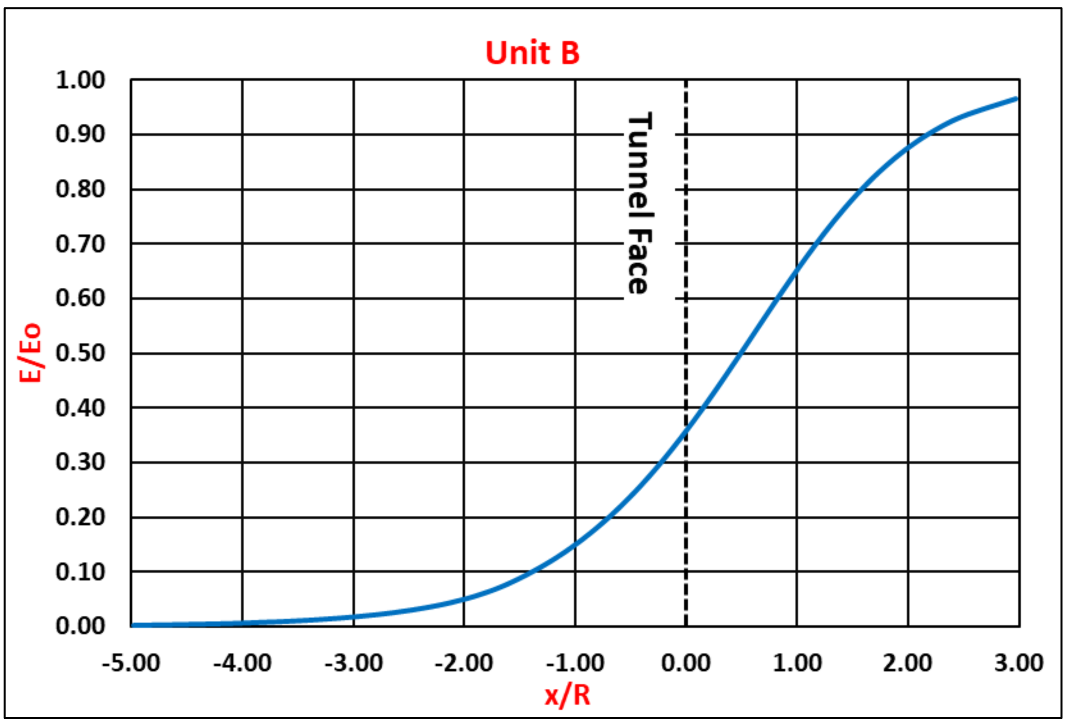


*Figure 9. Longitudinal displacement profile (LDP), for engineering geological unit B.*

***Table 7.Deconfinement characteristics values, for engineering geological unit A.***

| Parameter | Value |
|---|---|
| Geostatic field stress ($p_o$) | 4,55 MPa |
| Ground strength ($\sigma_{cm}$) | 5,4 MPa |
| Overload factor ($N_s$) | 1,69 |
| Critical deconfinement factor ($\lambda_{cr}$) | 0,83 |
| Deconfinement factor at the tunnel face (λ, x=0m) | 0,33 |
| Deconfinement factor at excavation 1 x advance length (λ, x=-3m) | 0,51 |
| Deconfinement factor at excavation 2 x advance length (λ, x=-6m) | 0,68 |
| Relaxation modulus at the tunnel face (E, x=0m) | 2718MPa |
| Relaxation modulus at excavation 1 x advance length (E, x=-3m) | 1484 MPa |
| Relaxation modulus at excavation 2 x advance length (E, x=-6m) | 782 MPa |

***Table 8.Deconfinement characteristics values, for engineering geological unit B.***

| Parameter | Value |
|---|---|
| Geostatic field stress ($p_o$) | 0,89 MPa |
| Ground strength ($\sigma_{cm}$) | 0,96 MPa |
| Overload factor ($N_s$) | 1,85 |
| Critical deconfinement factor ($\lambda_{cr}$) | 0,77 |
| Deconfinement factor at the tunnel face (λ, x=0m) | 0,34 |
| Deconfinement factor at excavation 1 x advance length (λ, x=-1m) | 0,40 |
| Deconfinement factor at excavation 2 x advance length (λ, x=-2m) | 0,46 |
| Relaxation modulus at the tunnel face (E, x=0m) | 427 MPa |
| Relaxation modulus at excavation 1 x advance length (E, x=-1m) | 359 MPa |
| Relaxation modulus at excavation 2 x advance length (E, x=-2m) | 301 MPa |

Note, that in all excavation phases, the same deconfinement ratio (λ) and equivalent ground relaxation modulus (E), is used.

### 2.8. Loading

In order to simulate the tunnel overburden height (H) on both examined cases, as the upper numerical model is lower that the real tunnel overburden height, an additional vertical load (P) is added on the upper model limit (see *Figures 3* and *4*), in order to simulate the real overburden loading on the tunnel axis. The additional load (P) on the upper model limit, is calculated as follow:

**$P= \gamma \times (H-H_{model})$**, where γ: is the rockmass unit weight, H: the tunnel overburden height measured from the tunnel axis and $H_{model}$: the vertical distance between the tunnel axis and the numerical model upper limit. On both numerical models, the $H_{model}$= 45m. For the Section A numerical model, the additional load **P= 5,330 MPa** and for the Section B numerical model, the additional load **P= 0,23 MPa**.

### 2.9. Restrains

On the numerical models, the following restrains were used:

- Rollers on the sides and bottom limits
- Pins on the two corners of the bottom limit
- Free the upper surface

# 3. Results – Tunnel Section A

## 3.1. Tunnel primary lining design – Support bearing capacity

Based on the limitation of the minimal shotcrete thickness t= 15cm, numerical analysis with the previous shotcrete thickness done, in order to check the lining bearing capacity, according to EC2 EN 1992-1. Due to the good rockmass conditions, only Swellex bolts placed on the tunnel perimeter and no steel sets used. From the numerical analysis, it is observed that the minimal shotcretes thickness t=15cm, it is acceptable according to EC2 EN 1992-1, as the combination between lining bending moment (M) and thrust (N), is inside the lining capacity envelope in all simulation stages. On the following ***Figure 10*** is presented the support capacity envelope for the shotcrete lining on the Top Heading excavation phase and on ***Figure 11***, is presented the support capacity envelope for the shotcrete lining on the Bench excavation phase.

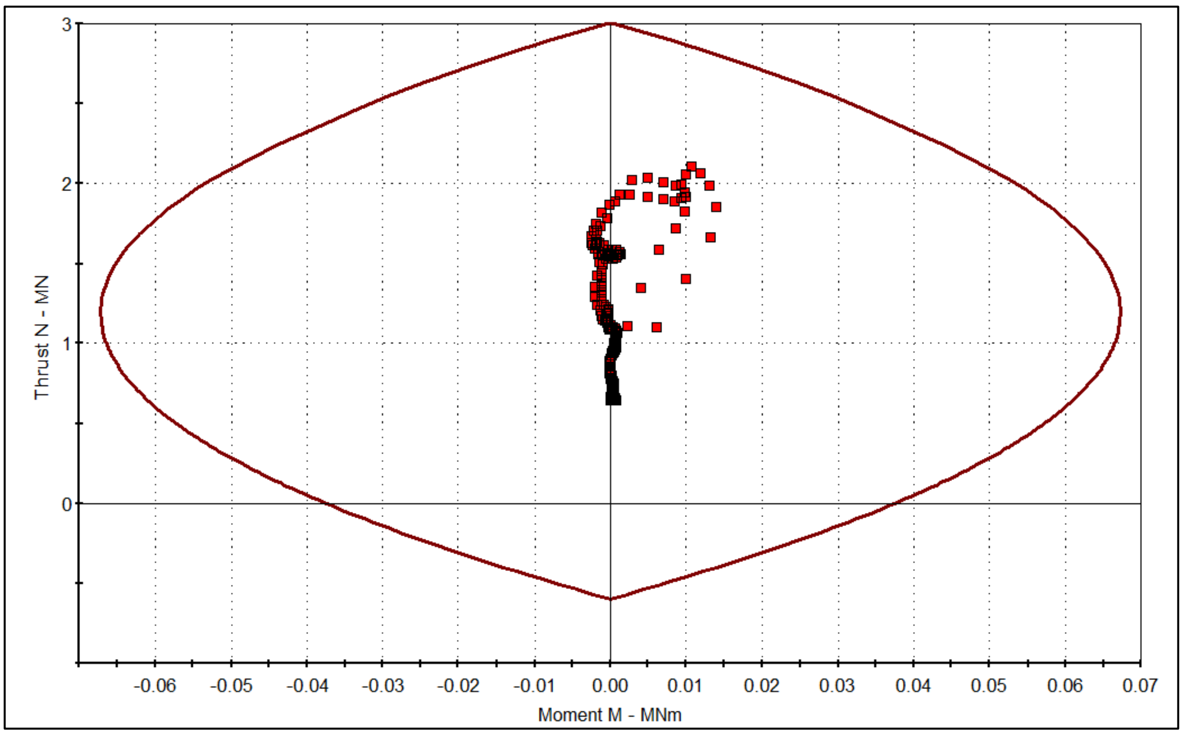


***Figure 10. Support capacity plot for the shotcrete lining on the Top Heading excavation phase, of tunnel Section A.***

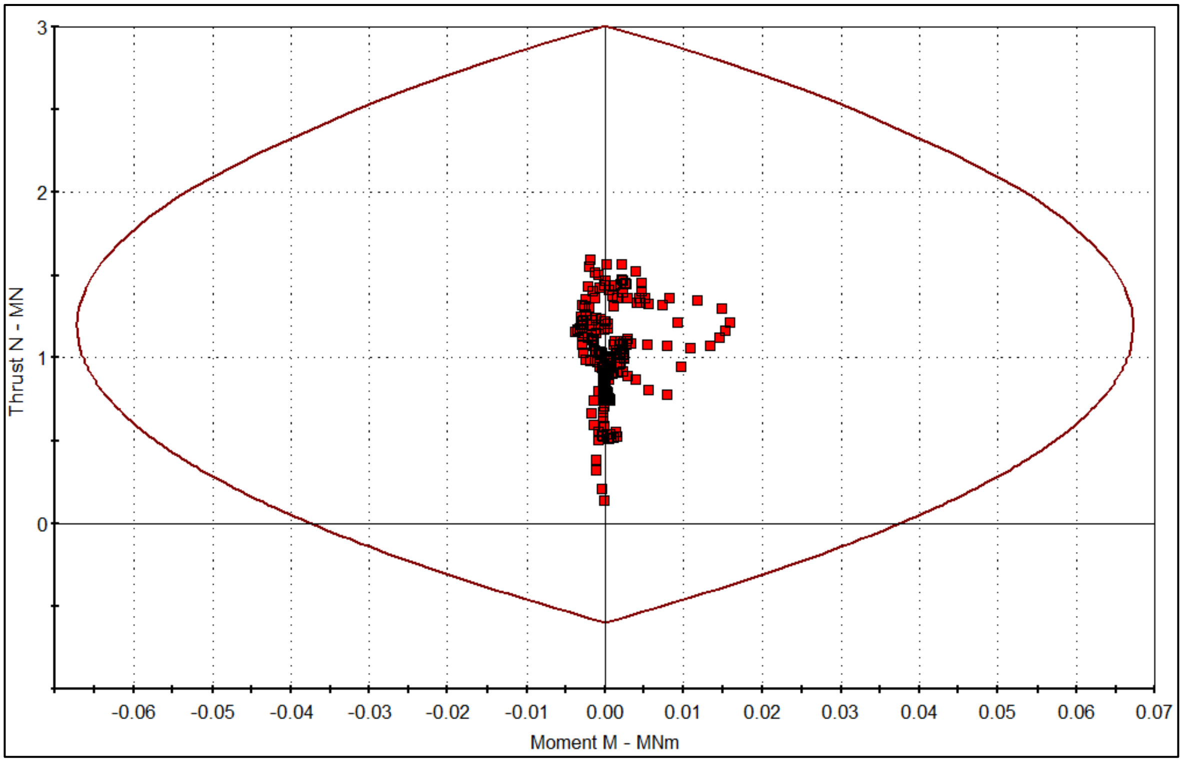


***Figure 11. Support capacity plot for the shotcrete lining on the Bench excavation phase, of tunnel Section A.***

Moreover, as it is presented on the following ***Figure 12,*** the maximal axial force on Swellex bolts, is F= 15 kN, which means that bolts are not yielded and the safety factor (SF) of bolts under tension loading, taken into account the baring capacity of them $P_y$= 140 kN, is SF= (140 kN/ 15 kN)= **9,33.**

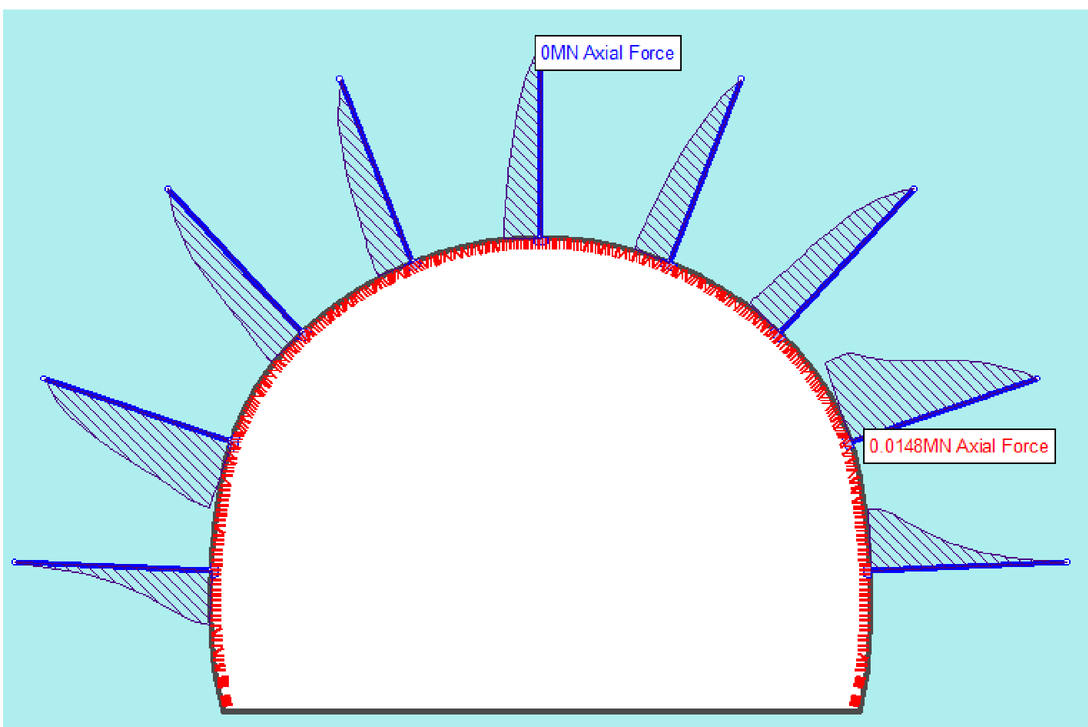


***Figure 12. Axial force on tunnel perimeter Swellex bolts, for tunnel Section A,***

***Thus, the proposed tunnel primary lining, consist of shotcrete with total thickness t=15cm and Swellex bolts Dextra DM160, placed in a pattern 3 x 3m (longitudinal x radial).***

### 3.2. Tunnel displacements

Based on the proposed tunnel primary lining, as described on *Chapter 3.1*, on the following ***Table 9***, total displacements on the tunnel crown every excavation step, are presented. Moreover, on the following ***Figure 13***, total displacements around excavation perimeter on the final excavation step, are presented.

***Table 9. Total displacement on the tunnel crown, for tunnel Section A.***

| Phase | Total displacement |
|---|---|
| Top Heading | 5,1 mm |
| Bench | 5,6 mm |

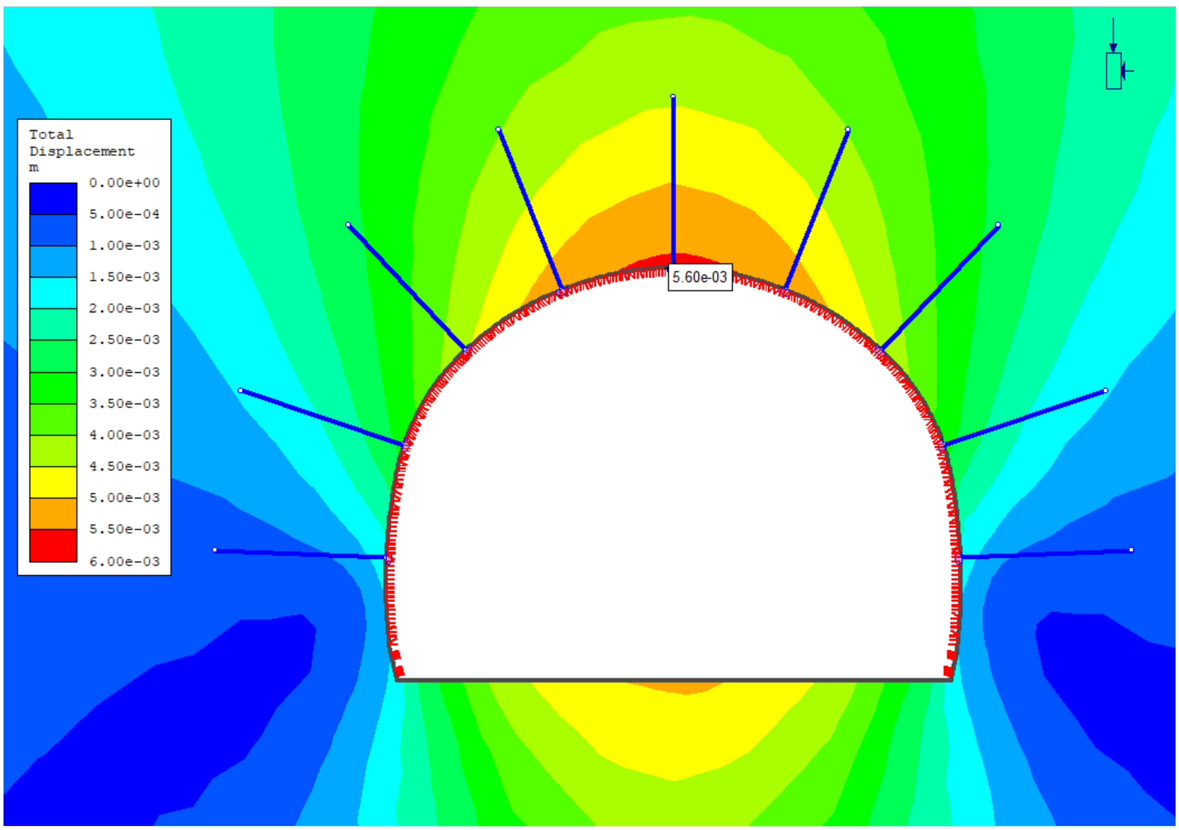


***Figure 13. Total displacements on the final excavation stage for tunnel Section A.***

### 3.3. Plastic zone

Based on *Table 7*, as the tunnel overload factor Ns= 1,69 > 1, a plastic zone around the excavation is expected to be formed. On the following ***Figure 15***, the formation of yield – plastic zone around the excavation due to the tunnel construction, is presented. The maximal length of plastic zone, measured from the excavation perimeter, is estimated **L= 5m** on the tunnel bottom and **L=1,9** on the tunnel sides.

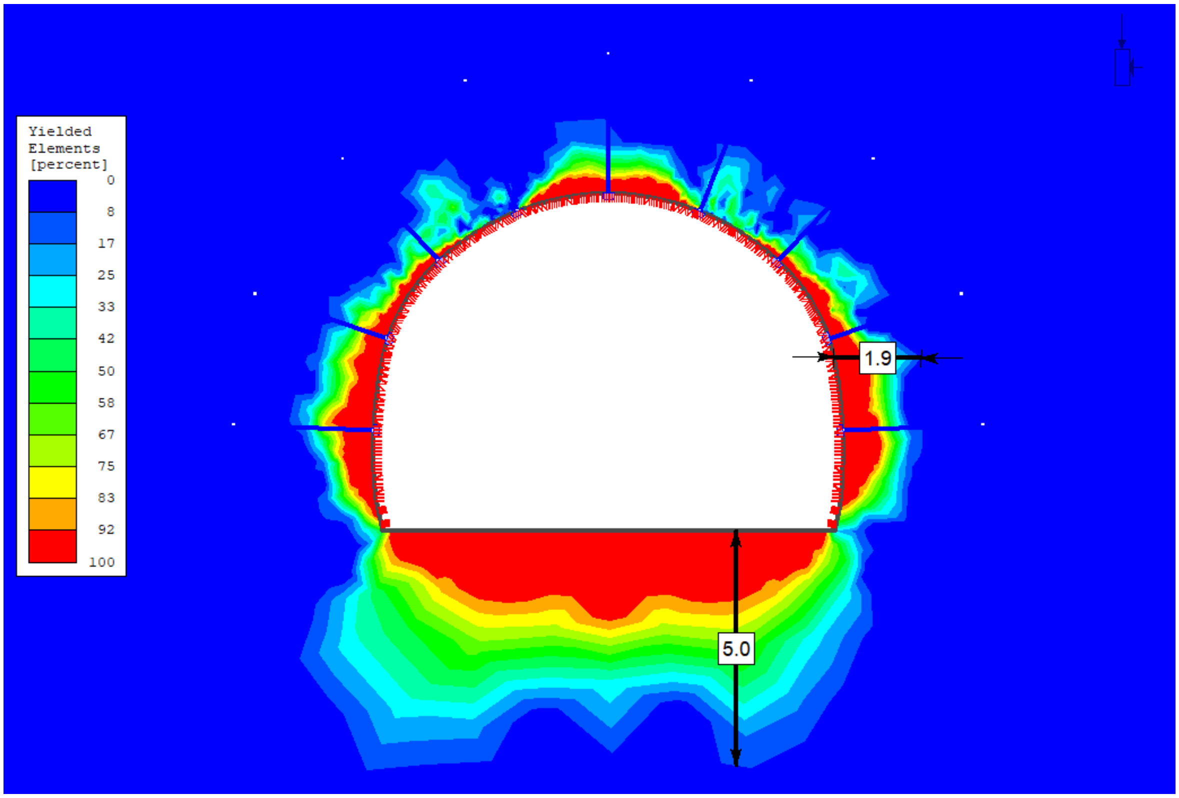


*Figure 14. Plastic zone formation on the final excavation stage for tunnel Section A.*

### 3.4. Proposed tunnel primary lining

The proposed tunnel primary lining and the excavation phases for tunnel Section A, based on the numerical analysis, is presented on the following Table.

*Table 10. Tunnel primary lining. For tunnel Section A*

| Excavation Phase | Excavation advance length | Shotcrete | Wire mesh | Bolts | Steel sets |
|---|---|---|---|---|---|
| Top Heading | 3 m | C30/37, t=15 cm | 1 layer T188 | 7 Swellex bolts, L= 3m, s= 3m, every excavation length | - |
| Bench | 3 m | C30/37, t=15 cm | 1 layer T188 | 2 Swellex bolts, L= 3m, s= 3m, every excavation length | - |

# 4. Results – Tunnel Section B

## 4.1. Tunnel primary lining design – Support bearing capacity

Based on the limitation of the minimal shotcrete thickness t= 15cm, numerical analysis with the previous shotcrete thickness done, in order to check the lining bearing capacity, according to EC2 EN 1992-1. Due to the poor rockmass conditions, the excavation perimeter shotcrete lining, is reinforced by rockbolts and steel sets. From the numerical analysis, it is observed that the minimal shotcretes thickness t=15cm, it is acceptable according to EC2 EN 1992-1. On the following Figures, are presented the support capacity envelopes for the shotcrete and reinforced lining in all excavation phases.

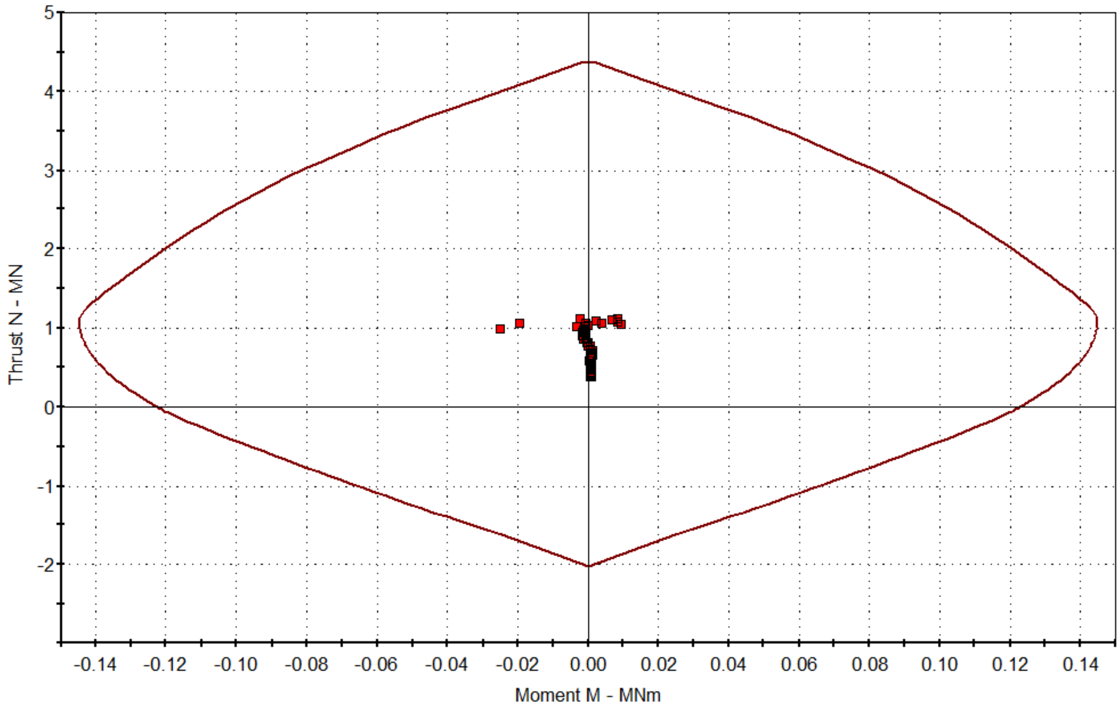


***Figure 15. Support capacity plot for the shotcrete lining on the perimeter of the Top Heading area at the Top Heading and Temp Invert excavation phase, of tunnel Section B.***

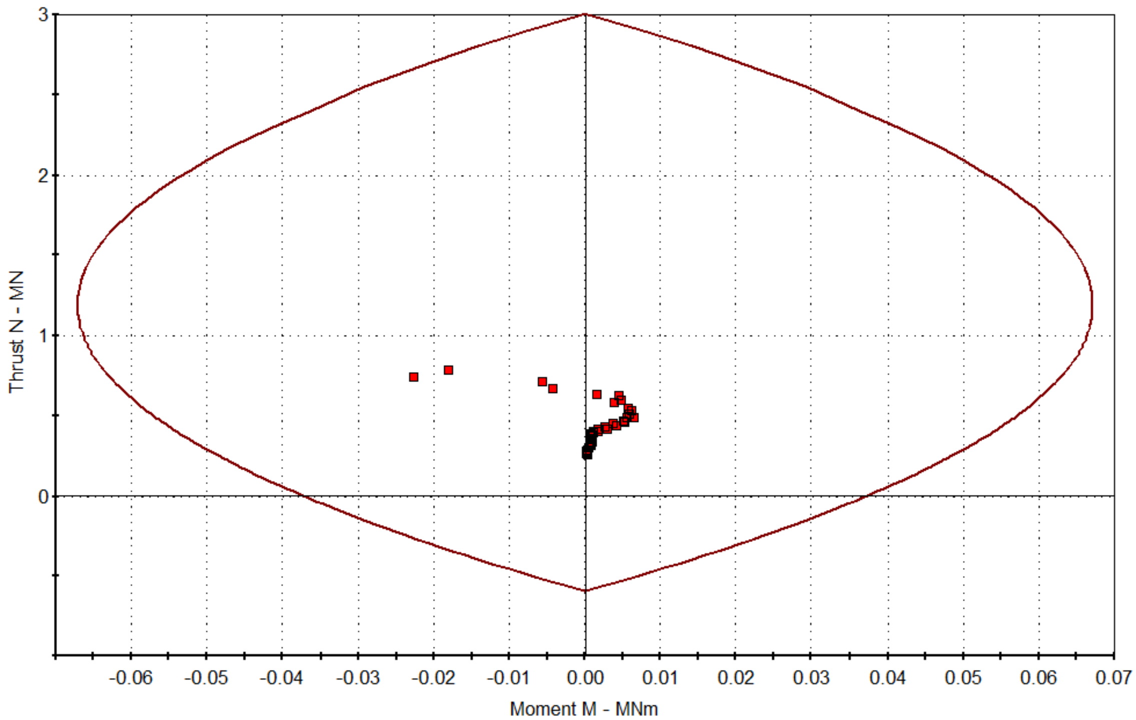


***Figure 16. Support capacity plot for the shotcrete lining on the Temporary Invert area at the Top Heading and Temp Invert excavation phase, of tunnel Section B.***

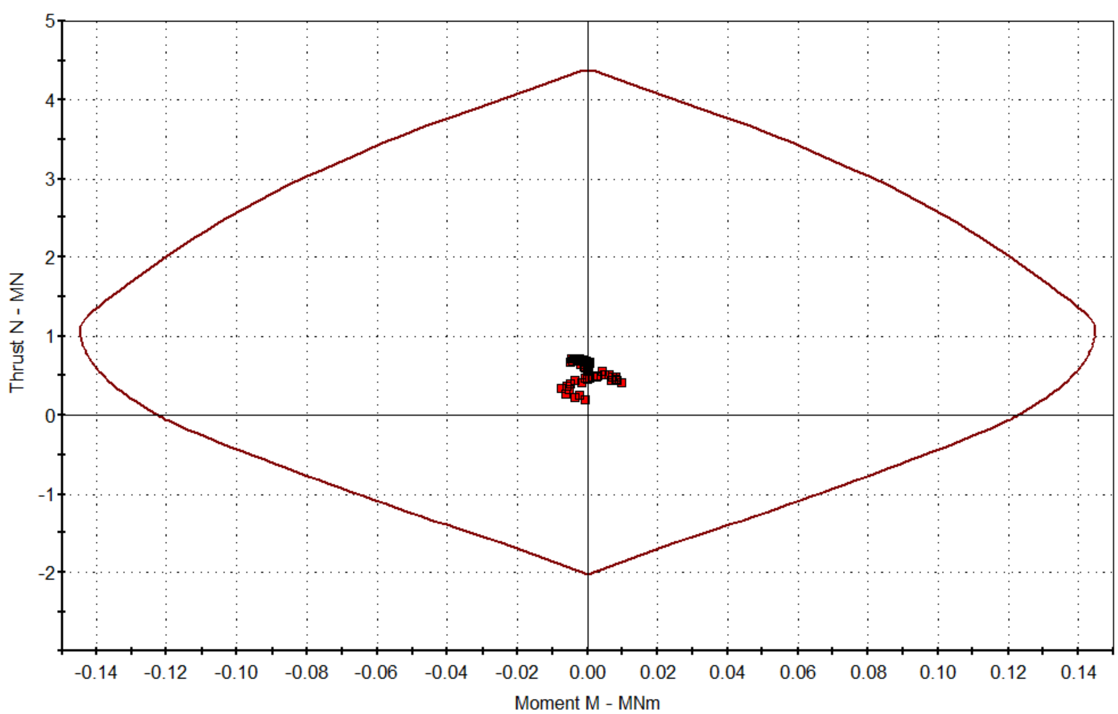


***Figure 17. Support capacity plot for the shotcrete lining on the perimeter of the Top Heading and Bench area at the Bench excavation phase, of tunnel Section B.***

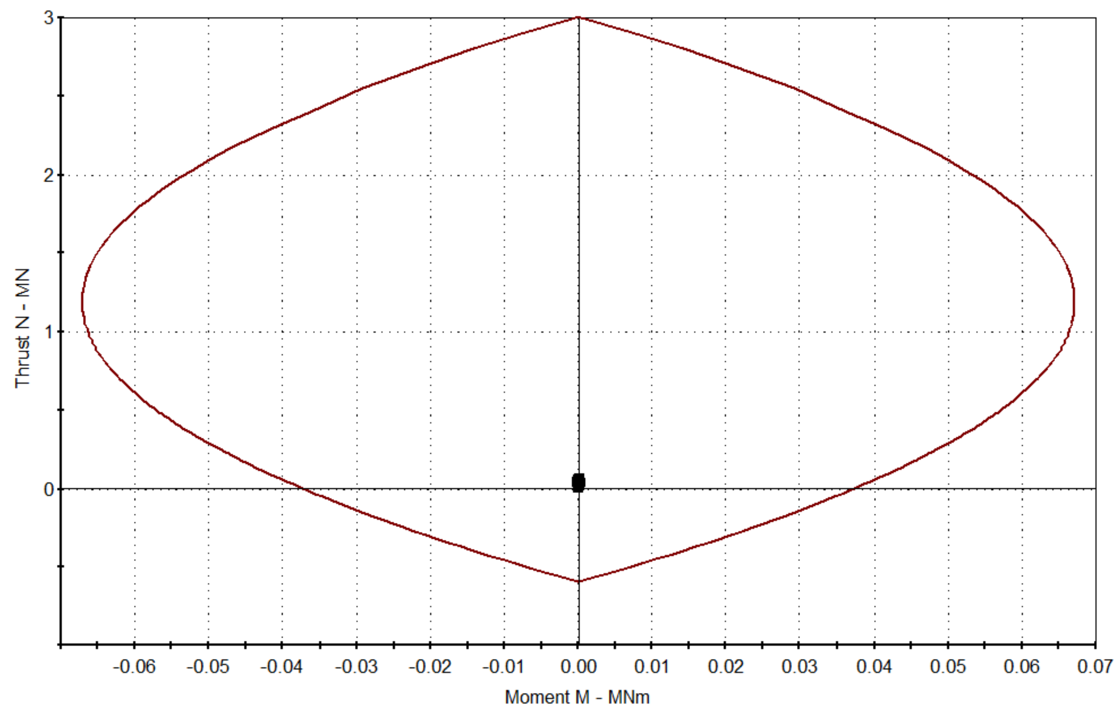


***Figure 18. Support capacity plot for the shotcrete lining on the Final Invert area at the Final Invert excavation phase, of tunnel Section B.***

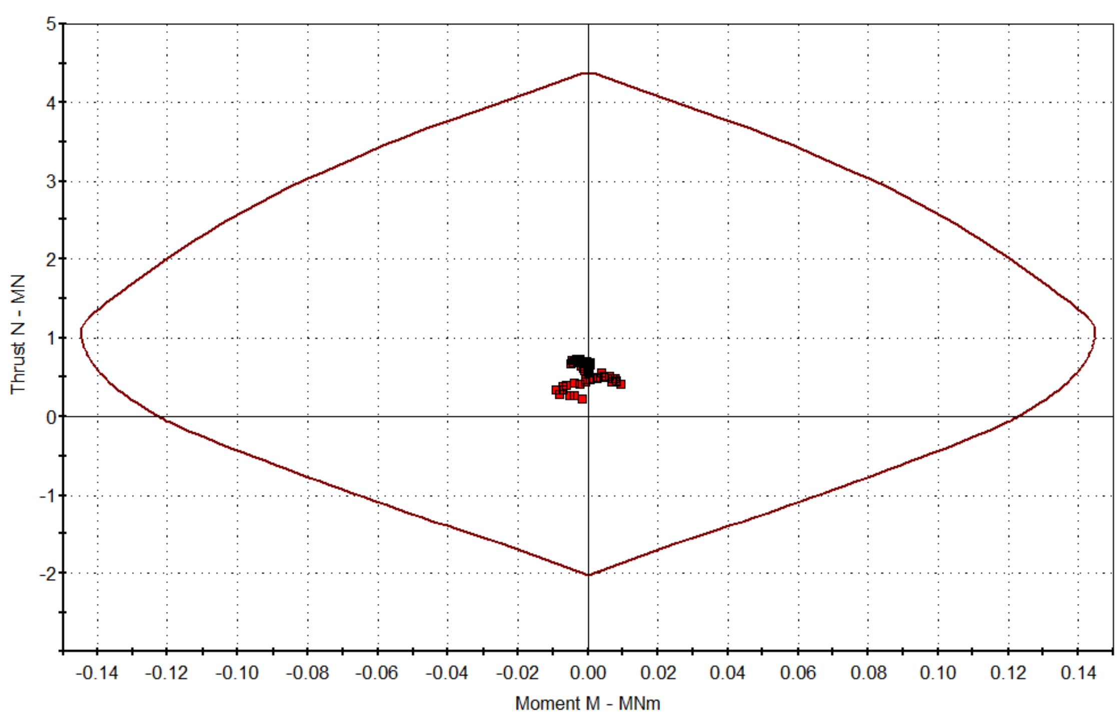


***Figure 19. Support capacity plot for the shotcrete lining on the perimeter of the Top Heading and Bench area at the Final Invert excavation phase, of tunnel Section B.***

Moreover, as it is presented on the following ***Figure 20,*** the maximal axial force on rockbolts, is F= 111 kN, which means that bolts are not yielded and the safety factor (SF) of bolts under tension loading, taken into account the baring capacity of them $P_y$= 240 kN, is SF= (240 kN/ 111 kN)= **2,16.**

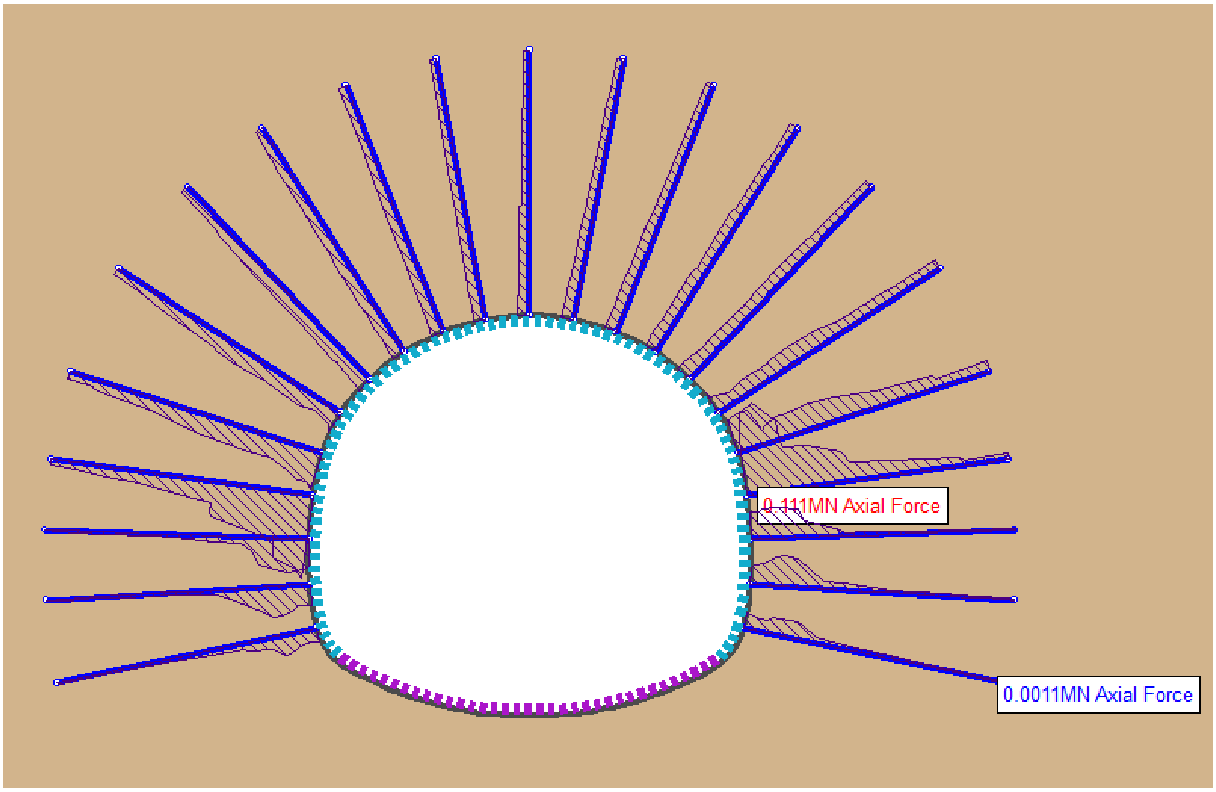


*Figure 20. Axial force on tunnel perimeter rockbolts Φ25, for tunnel Section B.*

***Thus, the proposed tunnel primary lining, consist of shotcrete with total thickness t=15cm, steel sets HEB 140 on the Top Heading and Bench area, fully bonded rockbolts Φ25 placed in a pattern 1 x 1m (longitudinal x radial), Temporary Invert consists of shotcrete with total thickness t=15cm and Final Invert consists of shotcrete with total thickness t=15cm.***

### 4.2. Tunnel displacements

Based on the proposed tunnel primary lining, as described on *Chapter 4.1*, on the following ***Table 11***, total displacements on the tunnel crown every excavation step, are presented. Moreover, on the following ***Figure 21***, total displacements around excavation perimeter on the final excavation step, are presented.

*Table 11. Total displacement on the tunnel crown, for tunnel Section B.*

| Phase | Total displacement |
|---|---|
| Top Heading & Temp Invert | 7,5 mm |
| Bench | 8,5 mm |
| Final Invert | 8,5 mm |

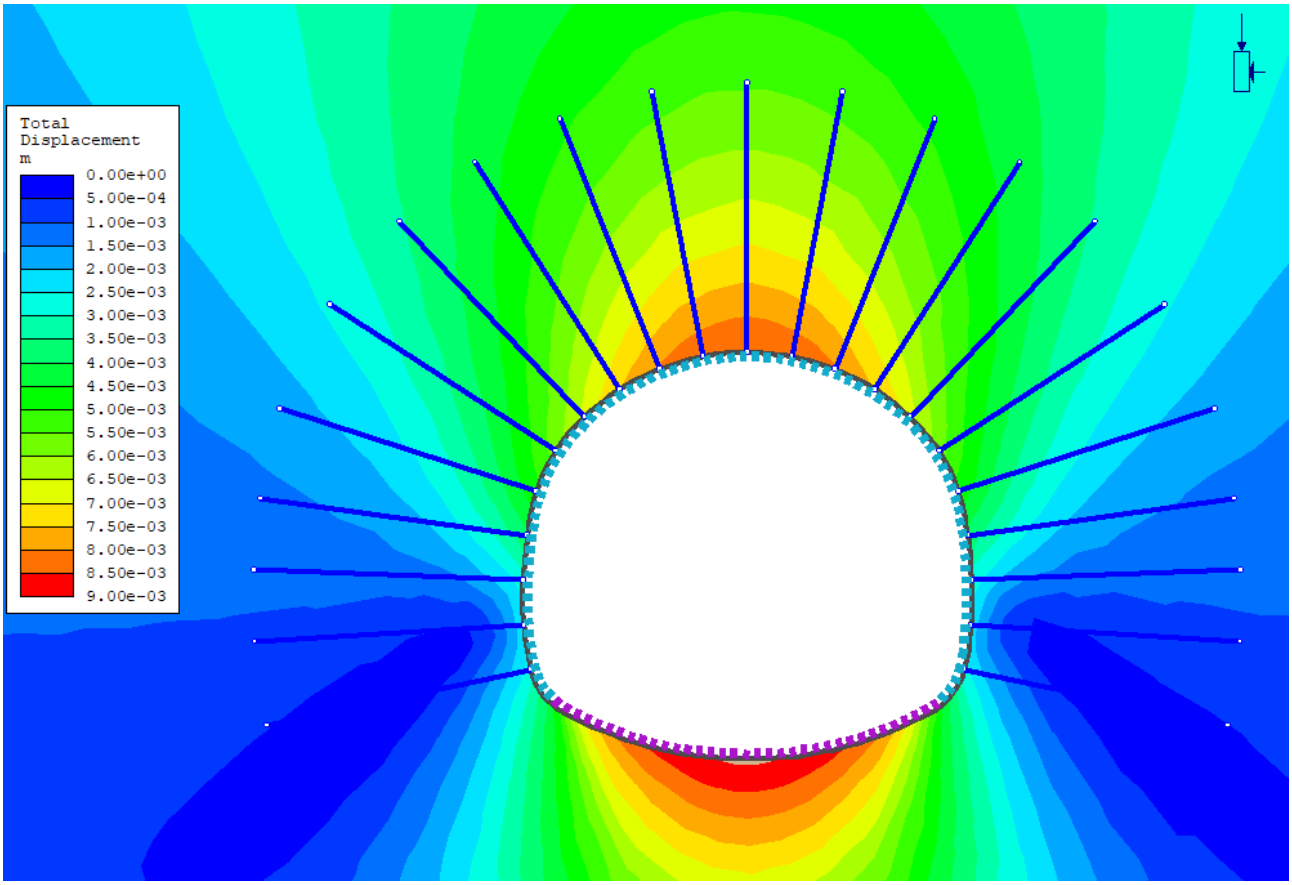


***Figure 21. Total displacements on the final excavation stage for tunnel Section B.***

## 4.3. <u>Plastic zone</u>

Based on *Table 8*, as the tunnel overload factor Ns= 1,85 > 1, a plastic zone around the excavation is expected to be formed. On the following ***Figure 22***, the formation of yield – plastic zone around the excavation due to the tunnel construction, is presented. The maximal length of plastic zone, measured from the excavation perimeter, is estimated **L= 4.3m** on the tunnel bottom and **L= 2.8m** on the tunnel sides.

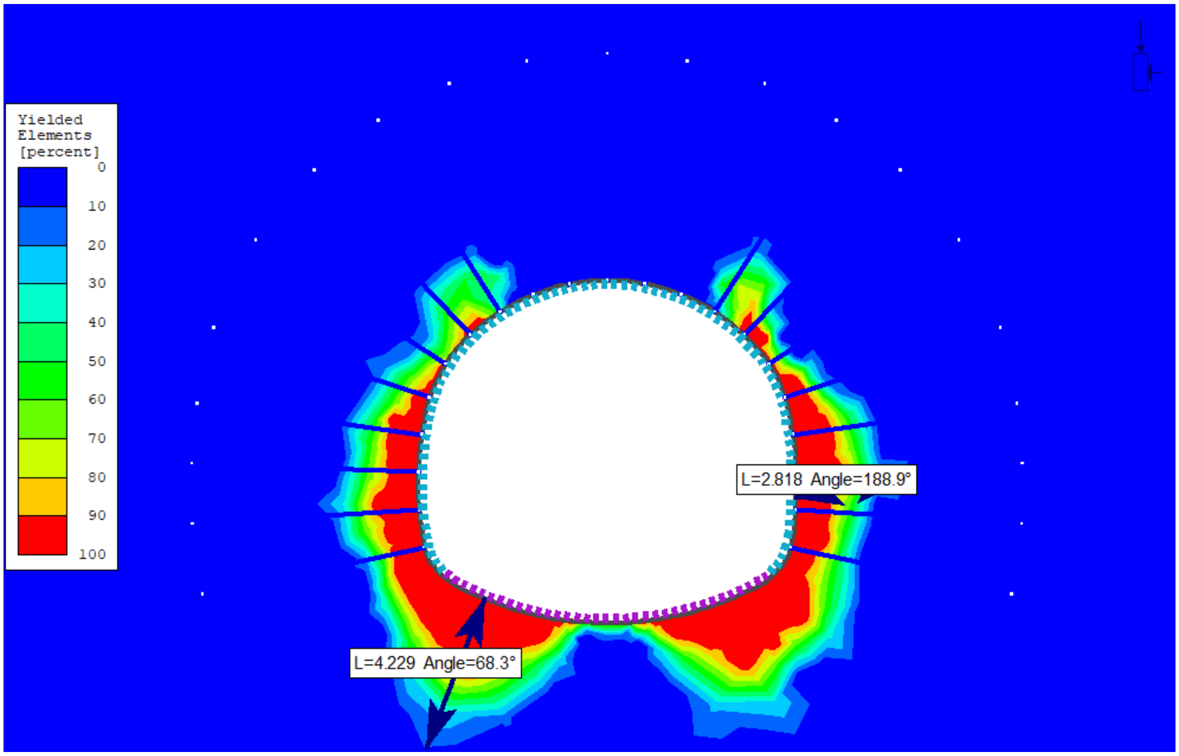

*Figure 22. Plastic zone formation on the final excavation stage for tunnel Section B.*

### 4.4. Proposed tunnel primary lining

The proposed tunnel primary lining and the excavation phases for tunnel Section B, based on the numerical analysis, is presented on the following Table.

*Table 12. Tunnel primary lining. For tunnel Section B*

| Excavation Phase | Excavation advance length | Shotcrete | Wire mesh | Bolts | Steel sets |
|---|---|---|---|---|---|
| Top Heading | 1 m | C30/37, t=15 cm | 2 layers T188 | 15 fully bonded rockbolts Φ25, L= 8m, s= 1m, every excavation length | HEB 140, every excavation length |
| Temporary Invert | 1 m | C30/37, t=15 cm | 2 layers T188 | - | - |
| Bench | 1 m | C30/37, t=15 cm | 2 layers T188 | 6 fully bonded rockbolts Φ25, L= 8m, s= 1m, every excavation length | HEB 140, every excavation length |
| Final Invert | 1 m | C30/37, t=15 cm | 2 layers T188 | - | - |