Numerical modelling of tunnel excavation using the NATM method

Program: FEM - Tunnel

File: Demo_manual_26.gmk

The objective of this manual is to describe numerical modelling of a single-track railway tunnel using the Finite Element Method.

Problem specification

Develop a model and assess the primary lining of a single-track railway tunnel for speeds ranging from 160 to 230 km/h. The tunnel cross-section is designed on the basis of the respective SZDC (Railway Infrastructure Administration, state organisation) Standard Sheet see *the picture*).
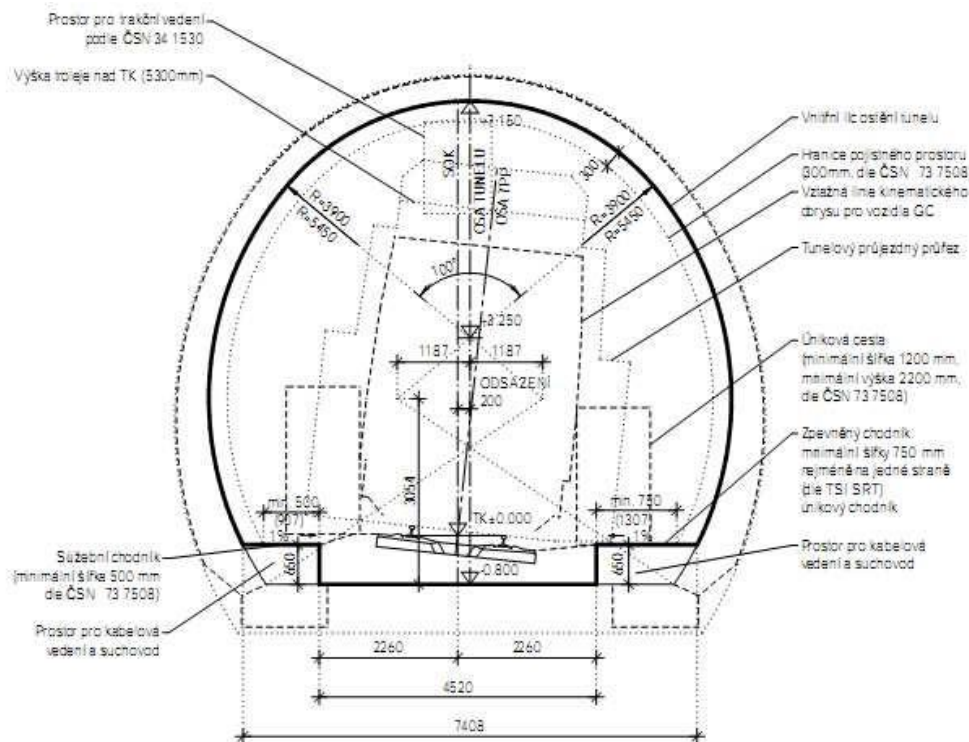
Net tunnel profile for a single-track railway tunnel according to the SZDC Standard Sheet

The tunnel will be driven using a conventional tunnelling method (the New Austrian Tunnelling Method, the Sequential Excavation Method) with the excavation sequence consisting of a top heading, a bench and an invert (the so-called horizontal sequence). The overburden is approximately 14 meters high. The 200 mm thick primary lining is in C 20/25 sprayed concrete. The excavation crown is supported with hydraulically expanded rockbolts (HUIS, type WIBOLT EXP) with the capacity of 120kN.

We assume on the basis of the assessment of the stages of survey operations that the geological layers are parallel with the terrain surface. The composition of the geological profile can be seen in *Table 1*.

Table 1 – Parameters of soils and rocks

Soil, rock (specification)	Profile $[\text{m}]$	γ $[\text{kN}/m^3]$	φ_{ef} $[°]$	c_{ef} $[\text{kPa}]$	ν $[-]$	E_{def} $[\text{MPa}]$	E $[\text{MPa}]$	γ_{sat} $[\text{kN}/m^3]$
Silty sand (S4 / SM)	0 – 3	19,5	29	10	0,3	10	30	22
Silty gravel (G4 / GM)	3 – 5	19,5	33	8	0,3	70	210	22
Heavily weathered slate (R5)	5 – 10	24	29	30	0,33	45	135	25
Slightly weathered slate (R3)	over 10	26	38	250	0,25	350	1050	26
Anchored region (R5)	–	24	29	63	0,33	45	135	29

Solution

We will use the GEO5 – FEM program to analyse this problem. In the text below, we will describe the solution to this example step by step:

– Topology: the problem settings and modelling (contact elements, modelling of the lining)

– Modelling the construction procedure: primary tunnel lining material, Excavation steps

– Construction stage 1: primary geostatic stress state of the rock massif

– Construction stage 2: modelling the top heading excavation, activation of the unsupported excavated opening

– Construction stage 3: supporting the top heading vault with an immature concrete primary lining

– Construction stage 4: improving material characteristics of mature concrete (top heading)

– Construction stage 5: modelling the tunnel bench excavation, activation of the unsupported excavated opening
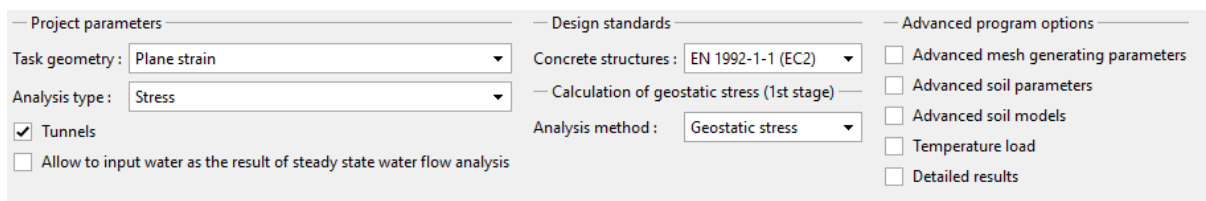
- Construction stage 6: supporting the bench side-walls with an immature concrete primary lining

- Construction stage 7: improving material characteristics of mature concrete (bench)

- Results, conclusion: terrain surface settlement trough, rock massif deformation, distribution of internal forces and displacement of the primary tunnel lining, forces in anchors.

Note: Modelling in GEO5 – FEM program consists of two parts: In the first part, it is necessary to define the magnitude of the numerical model itself in the topology mode, specify the interfaces between soils and rocks, define the tunnel structure geometry using points and lines and assign them to respective interfaces of the model (for more details visit Help – F1).

In the second part, individual construction stages are defined and calculations are carried out. In individual construction stages, our aim is to model the actual course of the real construction of the particular underground structure by activating, deactivating or changing materials in pre-circumscribed regions of the model, by adding or removing beam elements representing the structures (e.g. the tunnel lining) or by changing their parameters (material, dimensions). We will get a numerical model for which we assume that its behaviour will be identical with the future behaviour of the real underground structure and which will be used to dimension the tunnel structure.

Topology (Part 1): specifying the problem (profile) interfaces and soil parameters

In the "Settings" frame, we will leave the analysis of Construction Stage 1 to be in geostatic stress state. The "*Stress*" analysis type is applied. In addition, we will switch the "Tunnels" mode, which allows us to model the course of the primary tunnel lining construction realistically.
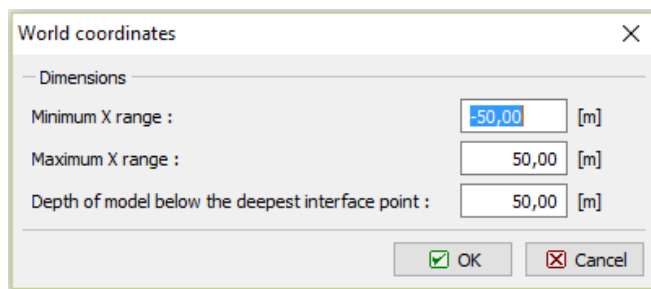
Project parameters		Design standards		Advanced program options
Task geometry : Plane strain		Concrete structures : EN 1992-1-1 (EC2)		☐ Advanced mesh generating parameters
Analysis type : Stress		Calculation of geostatic stress (1st stage)		☐ Advanced soil parameters
☑ Tunnels		Analysis method : Geostatic stress		☐ Advanced soil models
☐ Allow to input water as the result of steady state water flow analysis				☐ Temperature load
				☐ Detailed results

"Settings" frame

Note: In case the "Tunnels" mode is selected, it is possible to use the program for modelling, for example, the Excavations (modelling the 3D effect of the excavation face using the New Austrian Tunnelling Method), specifying and analysing the degradation of beams, the thermal loads acting on

beams and regions, the loads acting on the regions induced by swelling and lastly to conduct the monitoring of results (for more details visit Help – F1).

Next we will specify the magnitude of the numerical model of the problem being solved and the terrain interface. Regarding this particular problem, we will select model dimensions $\langle -50\ m;\ 50\ m \rangle$ and specify the thickness of the layer being investigated as 50 m.

World coordinates			✕
Dimensions			
Minimum X range :		-50,00	[m]
Maximum X range :		50,00	[m]
Depth of model below the deepest interface point :		50,00	[m]
		☑ OK	✕ Cancel

"World coordinates" dialogue window

Note: The interface of the problem being analysed, or the coordinates of the world, must be selected sufficiently large so that the stress state and rock massif deformations in the location of the structure being analysed (or in the regions of interest) are not affected by the boundary conditions of the model. The guidance values of the recommended dimensions of the boundaries of the models are presented for individual cases of the solutions and described in a more detailed way in the program Help (for more details visit F1).

Interface 1		Interface 2		Interface 3		Interface 4	
x [m]	z [m]	x [m]	z [m]	x [m]	z [m]	x [m]	z [m]
-50,0	22,0	-50,0	19,0	-50,0	17,0	-50,0	12,0
50,0	22,0	50,0	19,0	50,0	17,0	50,0	12,0

List of points for individual interfaces between soils and rocks

In the "Soils" frame, we will define the parameters of soil or the rock layers as well as the parameters of the rock in the region in which the rockbolts are located (see the *note*). We applied the Mohr-Coulomb material model to model the problem. It allows us to take the regions of local or global failures into consideration (for more details visit Help).

Note: The rockbolts are introduced into the numerical model using a method in which the region of the rock mass reinforced with rockbolts in the vicinity of the excavated opening corresponding to the

length of rockbolts is replaced with rock exhibiting better material parameters. In such cases an increase in the rock cohesion is usually assumed. The overall cohesion of rock increased by the action of rockbolts is given by:

$$c_{h+s} = c_h + c_s \ [\text{kPa}]$$

where: c_{h+s} *overall cohesion of rock increased by the action of rockbolts,*

                c_h *original cohesion of rock,*

                c_s *increase in cohesion by the action of rockbolts.*

The increase in cohesion by the action of rockbolts is calculated in accordance with the following relationship:

$$c_s = \frac{N_u}{A_k} \cdot \frac{1 + sin\,\phi_{ef}}{2 \cdot cos\,\phi_{ef}} \cdot \frac{1}{\gamma_{kc}} = \frac{120}{2.058} \cdot \frac{1 + sin\ 29°}{2 \cdot cos\ 29°} \cdot \frac{1}{1,5} = 33.0 \ \text{kPa}$$

where: N_u *rockbolt capacity* $[\text{kN}]$,

                A_k *region allotted to one rockbolt* $[m^2]$,

                ϕ_{ef} *angle of internal friction of rock* $[°]$,

                γ_{kc} *anchoring reliability factor* $[-]$.

*In this problem, we take **10 pieces of HUIS rockbolts with the capacity of 120 kN, spaced at 3.5 m,** into consideration. The resultant shear strength, or cohesion, in the region reinforced with anchors corresponds to R5 rock type:*

$$c_{h+s} = c_h + c_s = 30 + 33 = 63 \ \text{kPa}$$

The modulus of elasticity E $[\text{MPa}]$ was not determined directly by a geological survey. For that reason, its value was derived from the modulus of deformation E_{def} $[\text{MPa}]$ using a general relationship $E = 3 \cdot E_{def}$.

We will take zero dilatancy angle ψ $[°]$ into consideration for all layers of soils and rocks. Subsequently we will assign the soils and rocks into individual regions (see the following *picture*).
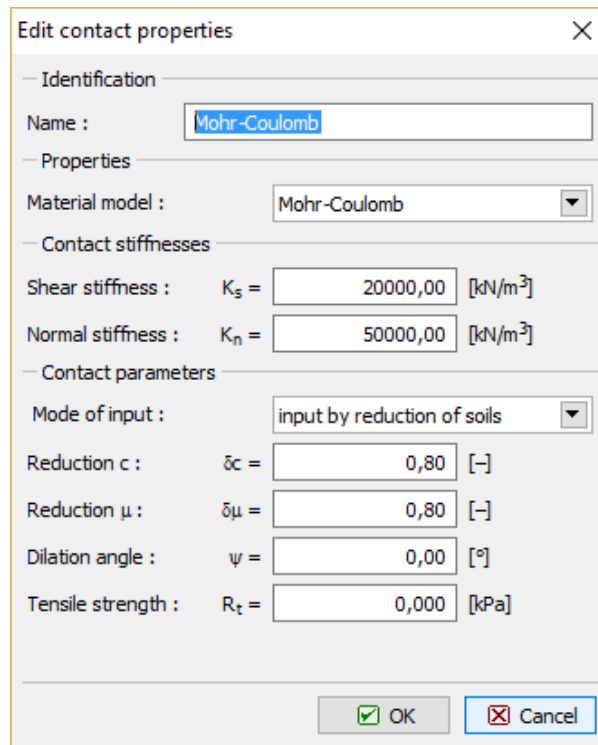
"Add new soils" dialogue window
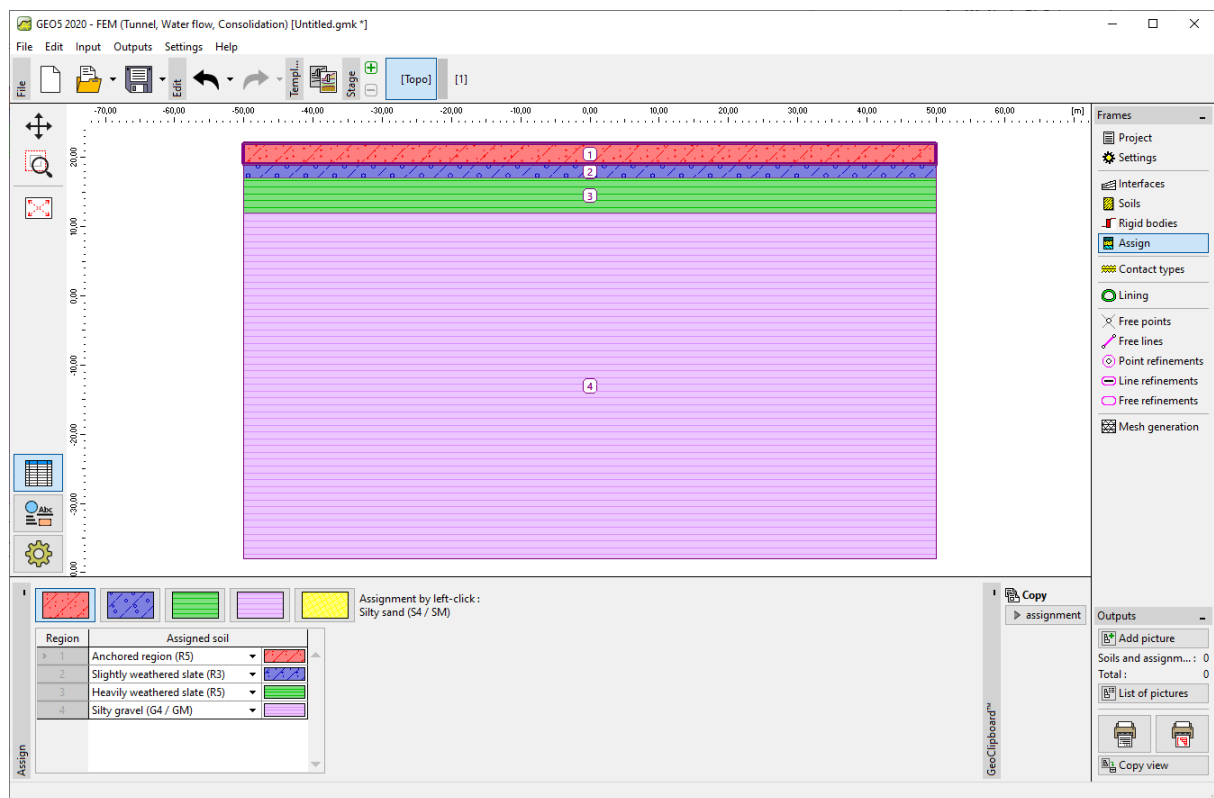
"Assign" frame

The next step is to specify the type of contact elements, which are introduced at the interface between the lining and the soil or rock in the "Contact types" frame. We assume the following parameters of contacts to exist at the interface:

- Shear strength: $K_s = 20,000 \ \text{kN}/m^3$,

- Normal stiffness: $K_n = 50,000 \ \text{kN}/m^3$,

- Reduction for soils: $\delta c = \delta \mu = 0.8$.

"New contact types" dialogue window

Note: The contact elements allow for making provisions for the interaction between materials found along the interface between the soil and the structure, or between individual soil types etc. The thickness of a contact element is zero. The element expresses the relationship between contact stresses and relative changes in displacements along the contact (for more details visit Help – F1).

In this case we consider the contact elements to be located at the interface between the primary lining and the rock, i.e., we consider a certain possibility of the primary lining shifting on the surface of the excavated opening.

Contact elements are generally introduced in less competent soils; they can be disregarded, with some caution, for fresh unbroken rocks (in the cases of tunnel structures). The problems and the method of introducing contact elements have been described in a more detailed way in Chapter 24 Numerical solution to a bracing structure (for more details see http://www.finesoftware.eu/engineering-manuals/). The guidance values of stiffness K_s and K_n [kN/m^3] are presented in Help (for more details visit F1).

This way the basic specification of the problem (the interface modelling, soil parameters, and contact types) is finished. Now we will continue to the modelling of lining of the primary tunnel and, subsequently, to the specification of the region reinforced with anchors.

## Topology (Part 2): modelling of the lining and the region reinforced with rockbolts

We will switch to the "Lining" frame and, using the "Add" button, will specify the primary tunnel lining points, the excavation geometry and its location in the region that is being solved. We will assume a lining thickness of 200 mm, taking into consideration the particular type of the structure (the lining of a railway tunnel is being modelled).

Note: We can specify the tunnel lining in the program by means of individual points and lines or we can define it as a so-called macro-element. The advantage of the latter solution lies in the fact that when the geological profile changes, we can shift the lining as a whole in an arbitrary way (horizontally or vertically). For more details visit our Help – F1.

The excavated cross-section geometry is specified in the "Lining – FEM" module by means of ten free points (see *Table* 2), which are connected by free lines (see *Table 3*).

Table 2 – Free points of an excavation (primary lining)

Point No.	Location $x \ [m]$	Location $y \ [m]$
1	4.81	2.25
2	3.41	6.11
3	-3.41	6.11
4	-2.62	-0.80
5	2.62	-0.80
6	-4.81	2.25
7	2.62	-1.30
8	4.17	-1.30
9	-2.62	-1.30
10	-4.17	-1.30
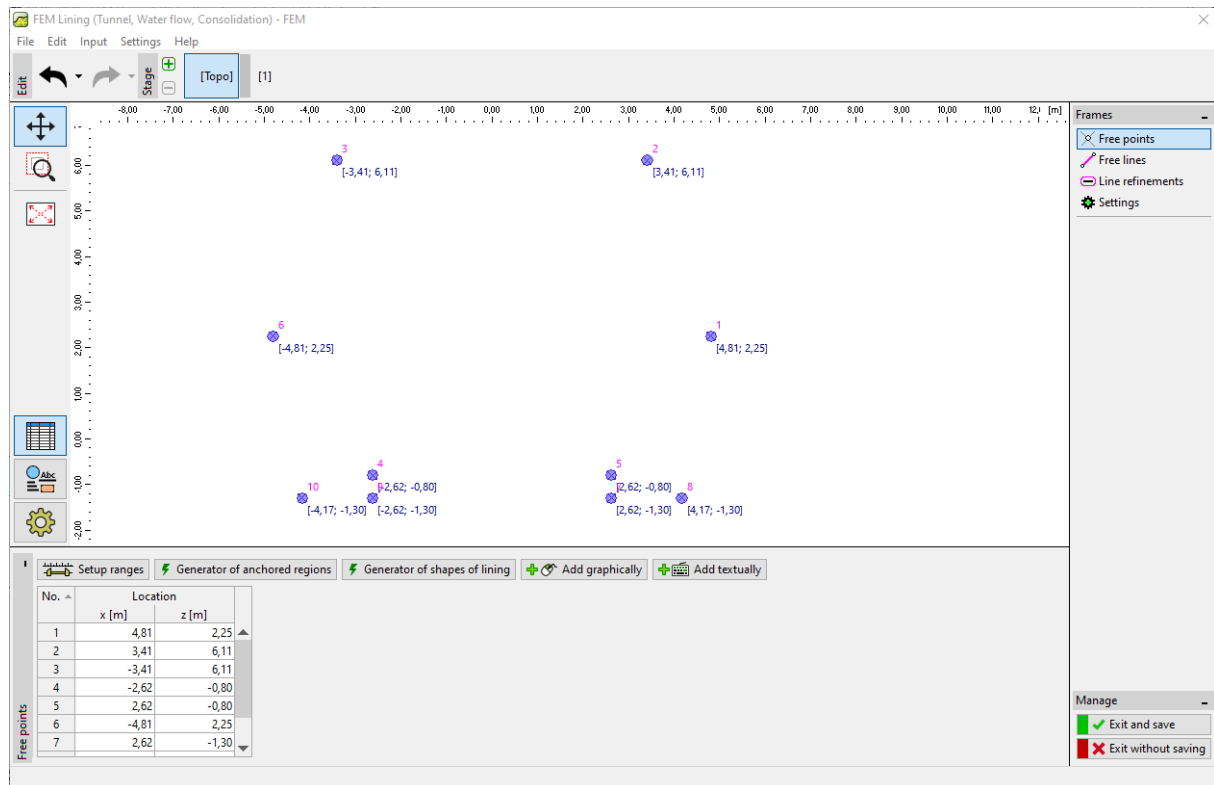
"Lining" dialogue window

Note: The generators of the lining geometries generate respective elements according to the parameters. The elements are subsequently worked with independently, without any possibility of subsequent change of their parameters. If the generation parameters are correct, the current graphical form of the generated elements is shown when the parameters are being modified (for more details visit Help – F1).

Table 3 – Free lines of excavation (primary lining)

Line No.	Type of line	Mode of input	Lines topology
1	arc	center	Origin – point 1, end – point 2 center (-1,19; 2,25), orientation positive
2	arc	center	Origin – point 2, end – point 3, center (0,00; 3,25), orientation positive
3	segment	–	Origin – point 4, end – point 5
4	arc	center	Origin – point 3, end – point 6, center (1,19; 2,25), orientation positive

5	segment	–	Origin – point 7, end – point 8
6	arc	center	Origin – point 1, end – point 8, center (-5,39; 2,25), orientation negative
7	segment	–	Origin – point 5, end – point 7
8	segment	–	Origin – point 9, end – point 10
9	arc	center	Origin – point 10, end – point 6, center (5,39; 2,25), orientation negative
10	segment	–	Origin – point 4, end – point 9
11	segment	–	Origin – point 6, end – point 1

The free points on the excavation contour line for the primary lining are drawn in the following picture.
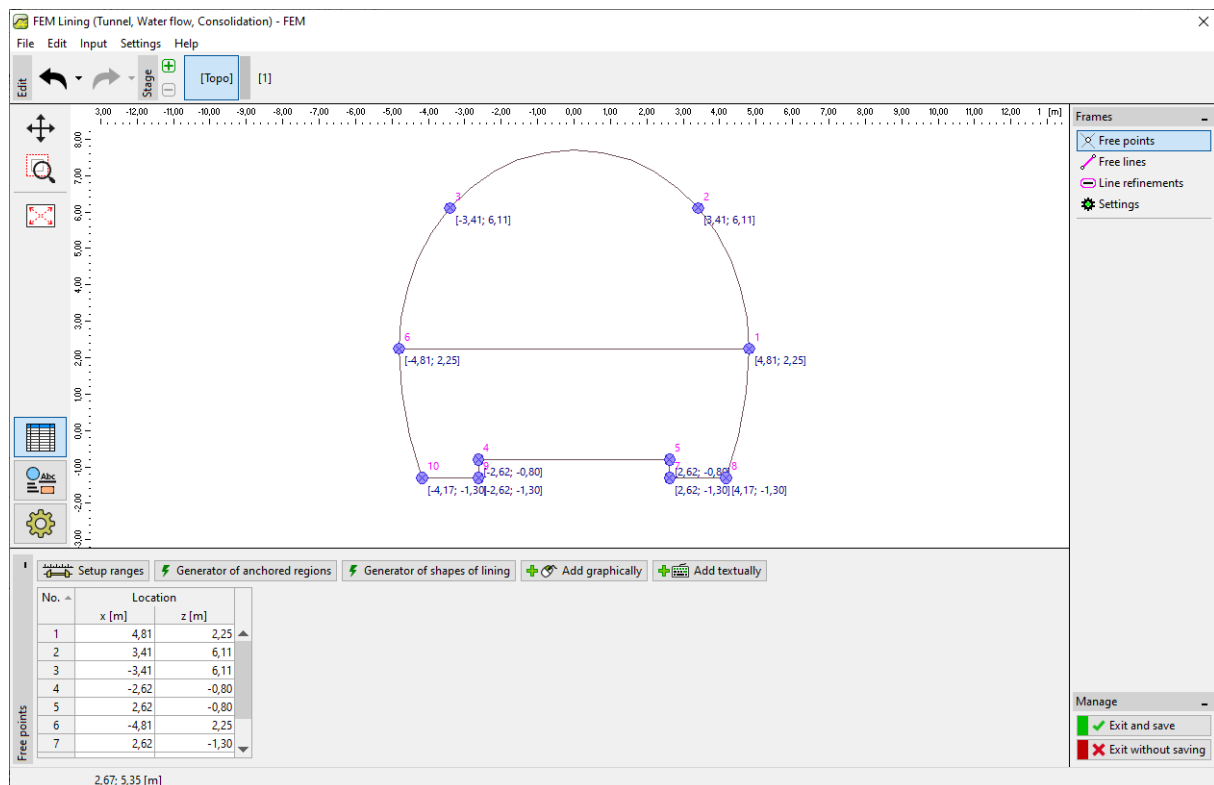
"Lining" module – FEM" – Free lines of excavation (with horizontal sequencing)

The excavation crown support using rockbolts is taken into consideration during the construction of the underground structure. This support is usually modelled in engineering practice as the improvement of the parameters of the rock, which is found in that particular region. For that reason,

it is in this case also necessary to specify the region reinforced with rockbolts – by means of free points (see *Table 4*) and free lines (see *Table 5*).

Table 4 – Free points near anchored region with hydraulically expanded rockbolts

Point No.	Location x [m]	Location y [m]
11	7.81	2.25
12	5.71	8.04
13	-5.71	8.04
14	-7.81	2.25

Table 5 – Free lines near anchored region with hydraulically expanded rockbolts

Line No.	Type of line	Mode of input	Lines topology
12	arc	radius	Origin – point 14, end – point 13 Radius – 9,0 m, orientation – negative Angle – acute
13	arc	radius	Origin – point 13, end – point 12 Radius – 7,45 m, orientation – negative Angle – acute
14	arc	radius	Origin – point 12, end – point 11 Radius – 9,0 m, orientation – negative Angle – acute
15	segment	–	Origin – point 14, end – point 6
16	segment	–	Origin – point 11, end – point 1

Then we will add a new free point No. 15 with the coordinates [0,0; 2,25] in the "Lining" module and will subsequently increase the density of the mesh of finite elements around it (see *Topology – Part 3*).
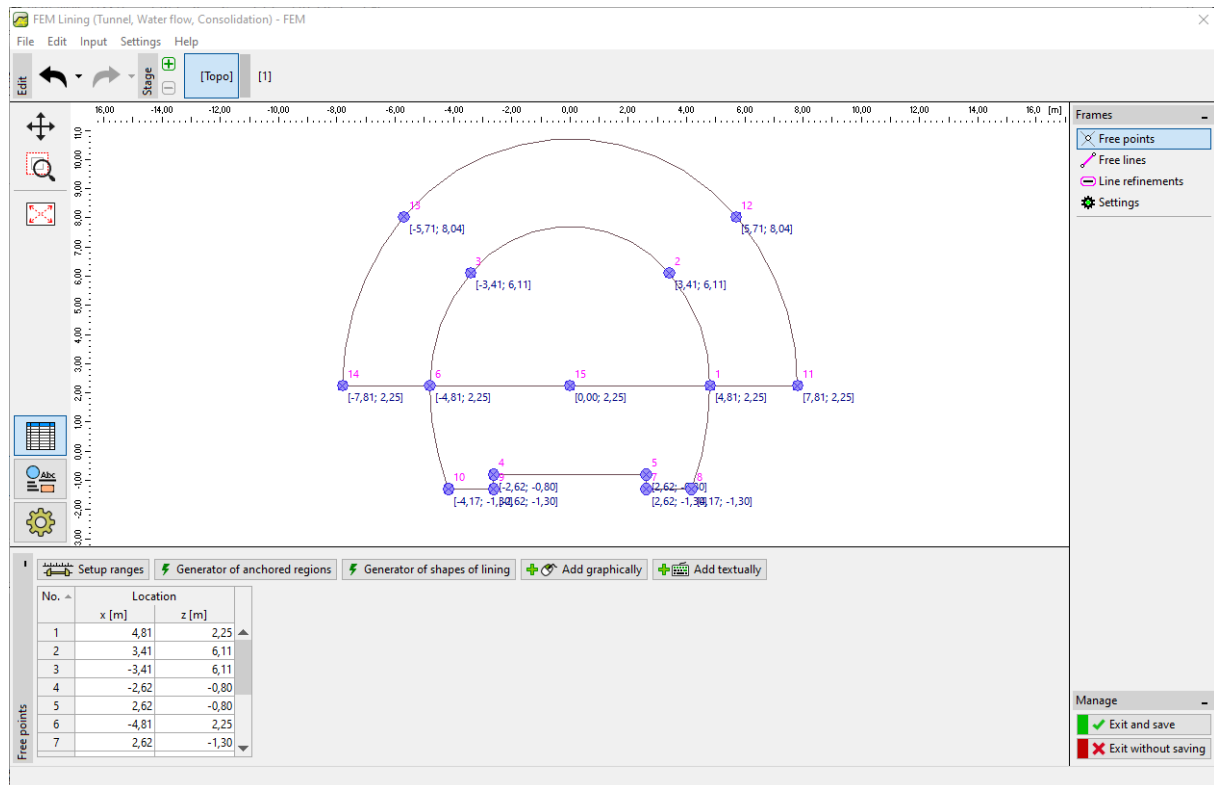
Free points near anchored region and free points of primary lining

Now we will examine the resultant geometry of the primary lining of the tunnel being modelled, together with the region reinforced with rockbolts. We will place the lining in the space of the region being solved to the coordinate system origin, i.e. to the [0,0] coordinate, using the "Settings" frame. We will confirm the end of the specification of the points in the "Lining" module by clicking the "Exit and Save" button.

In the last part of the structure topology settings we will generate the finite element mesh and increase its density.

Topology (Part 3): generation of the finite element mesh and increasing its density

The finite element mesh significantly affects the resultant calculation values. Prior to the mesh generation itself, we will increase the density in the excavated space (around point No. 15) with the element edge length $l = 0.5\ m$ and the reach radius $r = 28\ m$.

Note: Through this step we will provide a sufficiently dense mesh in the surroundings of the region of interest (the excavated opening). The process of increasing the density of free points or lines has been described in more detail in Chapter 23. Collector lining analysis (for more details see http://www.finesoftware.eu/engineering-manuals/).
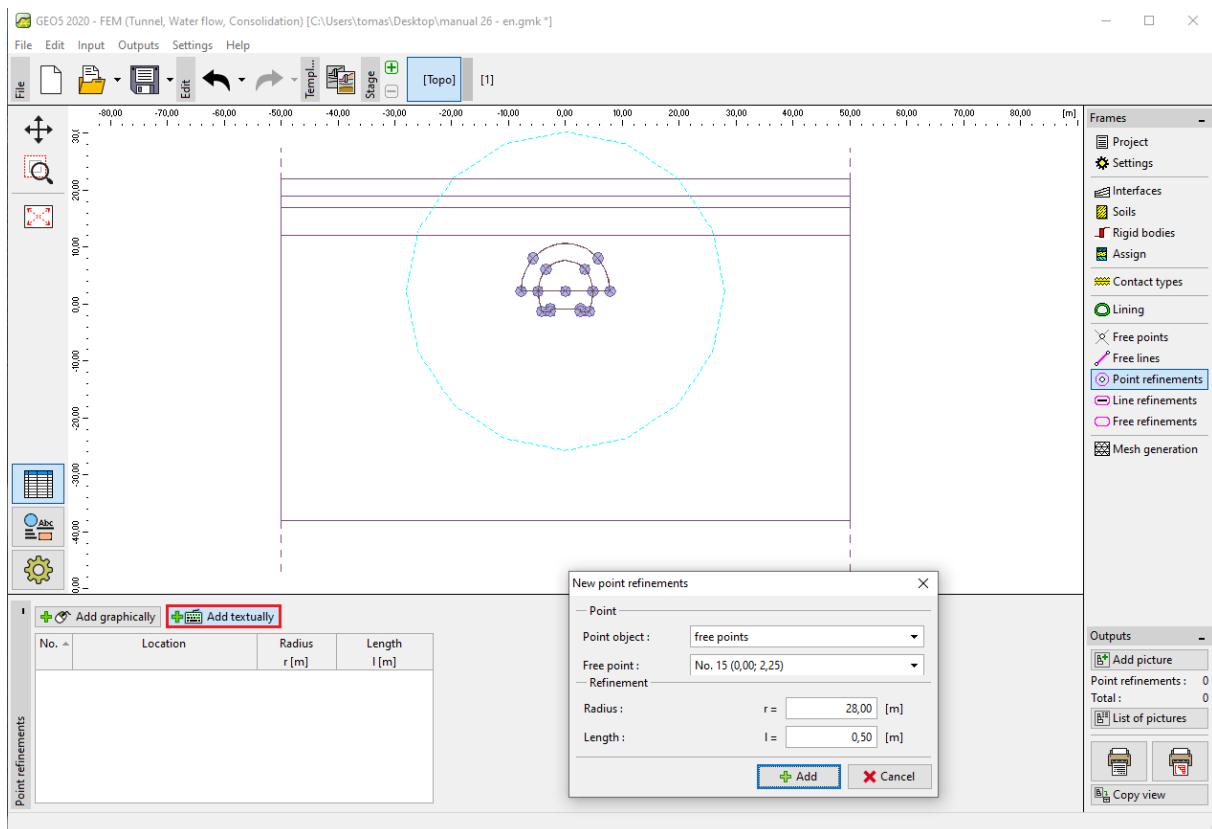
"New point refinements" dialogue window

Subsequently we will continue directly to the generation of the FEM mesh. In the "Mesh generation" frame, we will set the length of the element's edge at 2.0 m and will select the "Mesh smoothing" option.
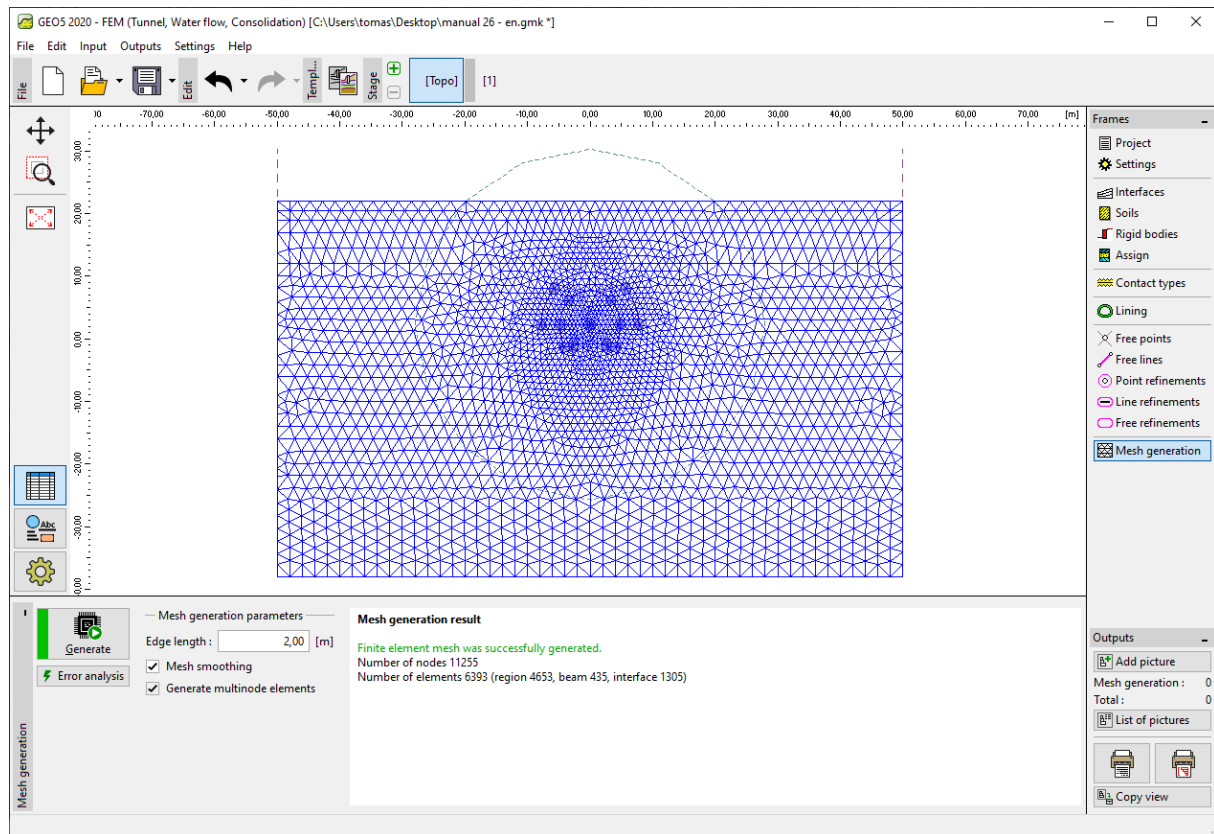
"Mesh generation" frame– Refinement of points near excavation region (length 0.5 m)

Notes on the modelling of the construction procedure:

In this part of the manual we present important notes relating to the construction procedure itself for easy reference – the primary tunnel lining material, the excavation sequence (individual excavations). This information is useful for the numerical modelling of our example because some input data is repeated (e.g. the excavations).

Note: The construction stages take into consideration the tunnelling process. To be able to compile individual construction stages, we need to know the primary tunnel lining material, the excavation sequence and hydro-geological conditions to be encountered during the course of the tunnel excavation.

*We will design the **primary lining** to be 200 mm thick, in C 20/25 sprayed concrete. We will only introduce sprayed concrete and the influence of the strength, or the modulus of elasticity increasing with time (see Table 6) into the numerical model.*

Table 6 – Values of modulus of elasticity for sprayed concrete (development with time)

Maturation of sprayed concrete	Modulus of elasticity E_{cm} [MPa]	Shear modulus G [MPa]
Immature concrete	2 900	1 134
Mature concrete	29 000	11 340

Note: The tunnel excavation is modelled as a 2D problem, which does not fully allow for the spatial changes in the stress state of the rock mass, which take place during the course of the excavation in the region of the excavation face. During the course of the excavation operation, the temporarily unsupported excavated opening is supported by the face-advance core (the longitudinal and transverse rock arch) and by the part of the excavated opening previously provided with the support. This behaviour can be described only by a 3D model; in a 2D model the behaviour in the direction of excavation progress is solved only approximately.

The method, which is most frequently used in the engineering practice (generally called the λ method or the β method), assumes that the primary stress state of the massif, i.e. the original stress σ_0 acting before the excavation in the surroundings of the future excavated opening, gradually changes with time according the relationship$(1 - \beta) \cdot \sigma_0$ (for the primary stress state $\beta = 1$). If we model a change in the primary stress at 2 calculation stages (construction stages), the unsupported excavated opening is loaded by the value of $(1 - \beta) \cdot \sigma_0$ at the first stage and the remaining load of $\beta \cdot \sigma_0$ is taken into consideration at the second stage.

In the case of the sequential excavation system, this procedure has to be applied separately to each partial heading. The value of coefficient β depends on rock mass geology, the advance per round and the size of the excavated profile; it is relatively hard to determine. In GEO5 – FEM, this method is represented by the so-called Excavation. We have estimated its value for the purpose of numerical modelling as$\beta = 0.6$ for the single-track profile for both the top heading and the bench.

Construction stage 1: primary geostatic stress state

After generating the FE mesh we will switch to construction stage 1 and will carry out the analysis of the primary geostatic stress state of the massif. We will maintain the "Standard" analysis setting for all construction stages (for more details visit Help – F1).
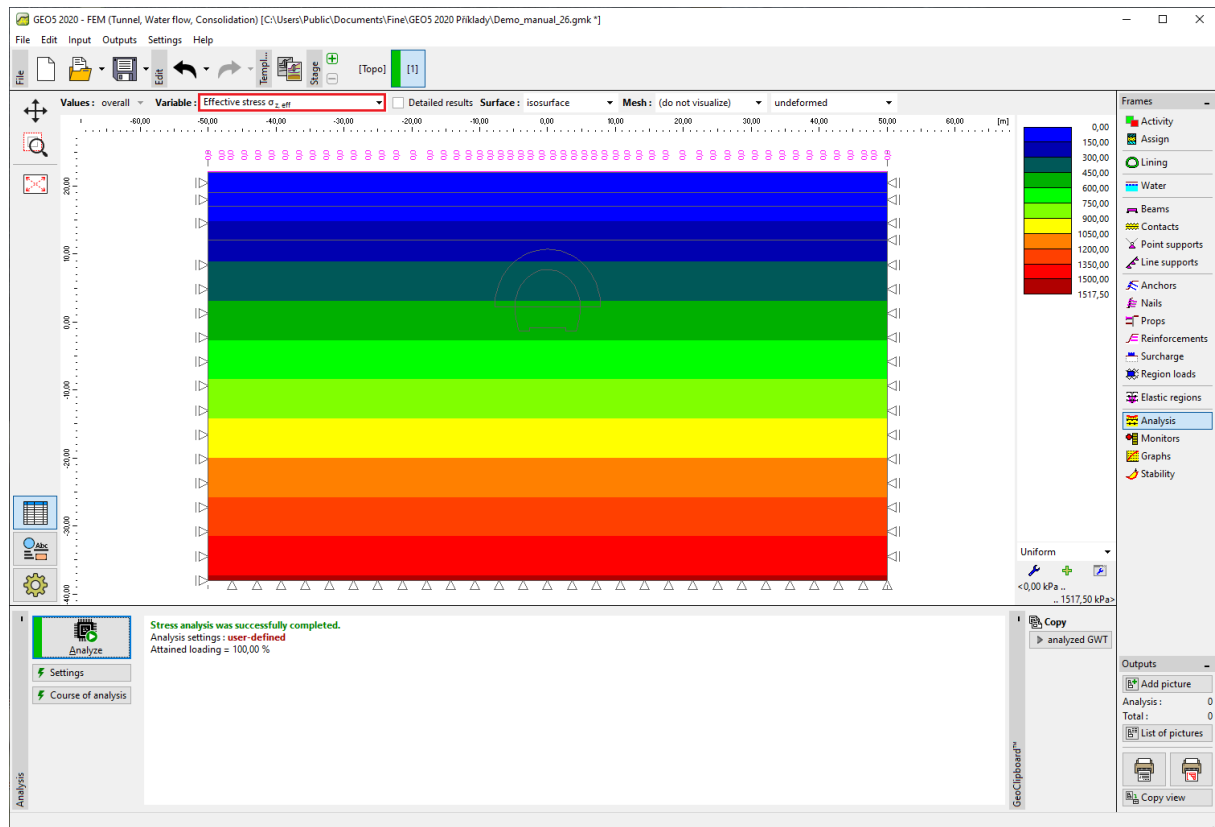
"Analysis" frame– Construction stage 1 (primary geostatic stress $\sigma_{z,eff}$)

Construction stage 2: top heading excavation, activation of the unsupported excavation

In the next step, we will add construction stage 2. Then we will model the top heading excavation in the "Activation" frame and will carry out the Excavation for region No. 6 (using the "Add" button).
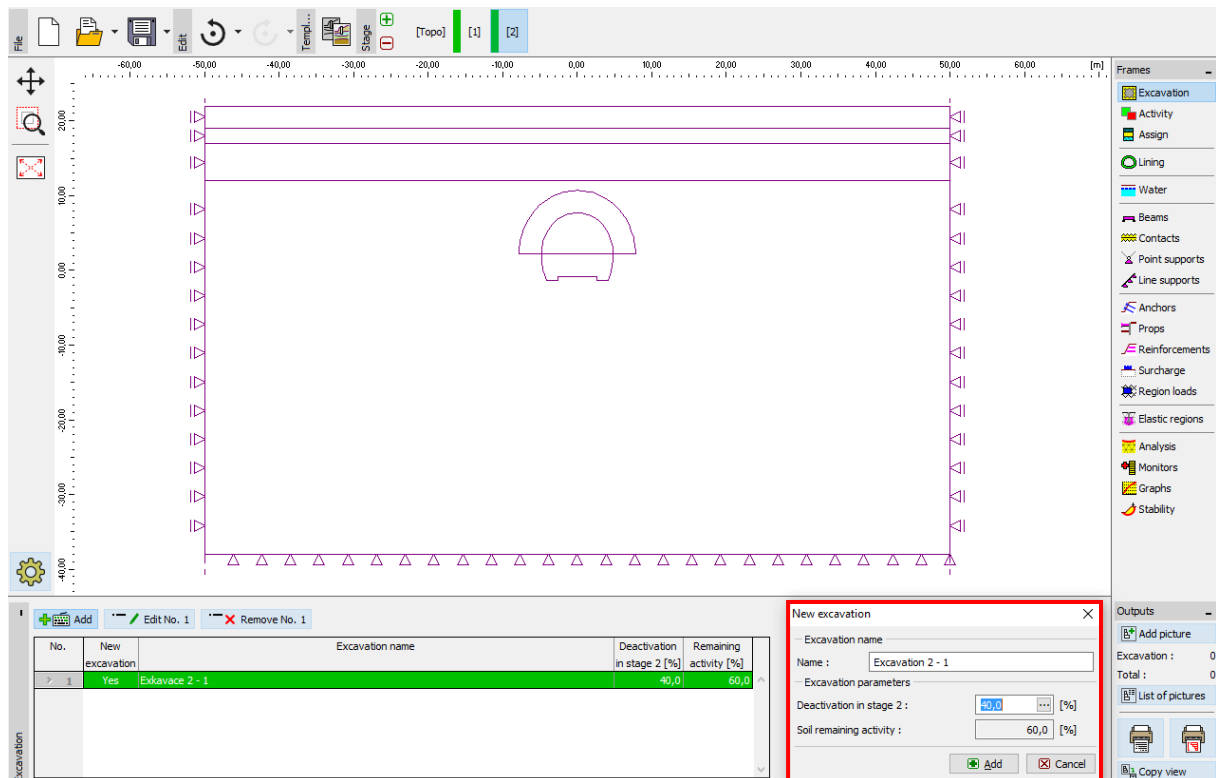
"New excavation" dialogue window – Construction stage 2

Note: In the engineering practice the excavation sequence (individual excavations) is specified by the percentage of the rock deactivation relative to the remaining rock action. In this example we take the following proportions of the excavations for individual tunnel construction stages:

− top heading excavation, activation of the unsupported excavated opening: 40 % / 60 %,

− top heading vault support with the immature concrete primary lining: 30 % / 30 %,

− improvement of material properties of mature concrete (top heading): 30 % / 0 %.

− modelling of tunnel bench excavation, activation of the unsupported excavated opening: 40 % / 60 %,

− supporting of bench sidewalls by immature concrete primary lining: 30 % / 30 %,

− improvement of material properties of mature concrete (bench): 30 % / 0 %.

The above-mentioned percentage proportions are based on years of experience and provide relatively reliable results. In the program it is possible to set various percentage proportions of the Excavations for particular construction stages (e.g. 25/75, 30/45, 30/15 a 15/0) for the top heading or bench excavation.

In essence, it is the case of the activation of the percentage proportion of the load acting on the unsupported top heading. In this stage we take the 40 % deactivation of soil (see *the picture)* into consideration.
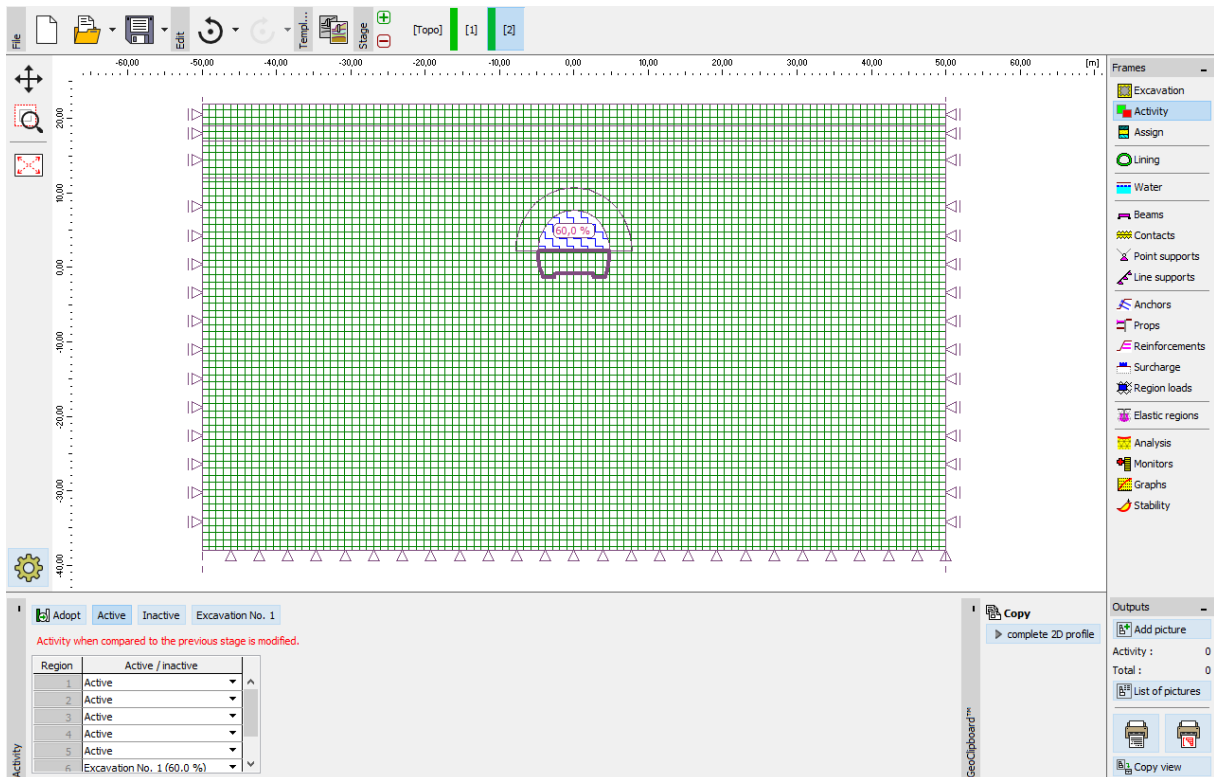
"Activity" frame – Construction stage 2 (activity of 40 % of loading on excavation of top heading)
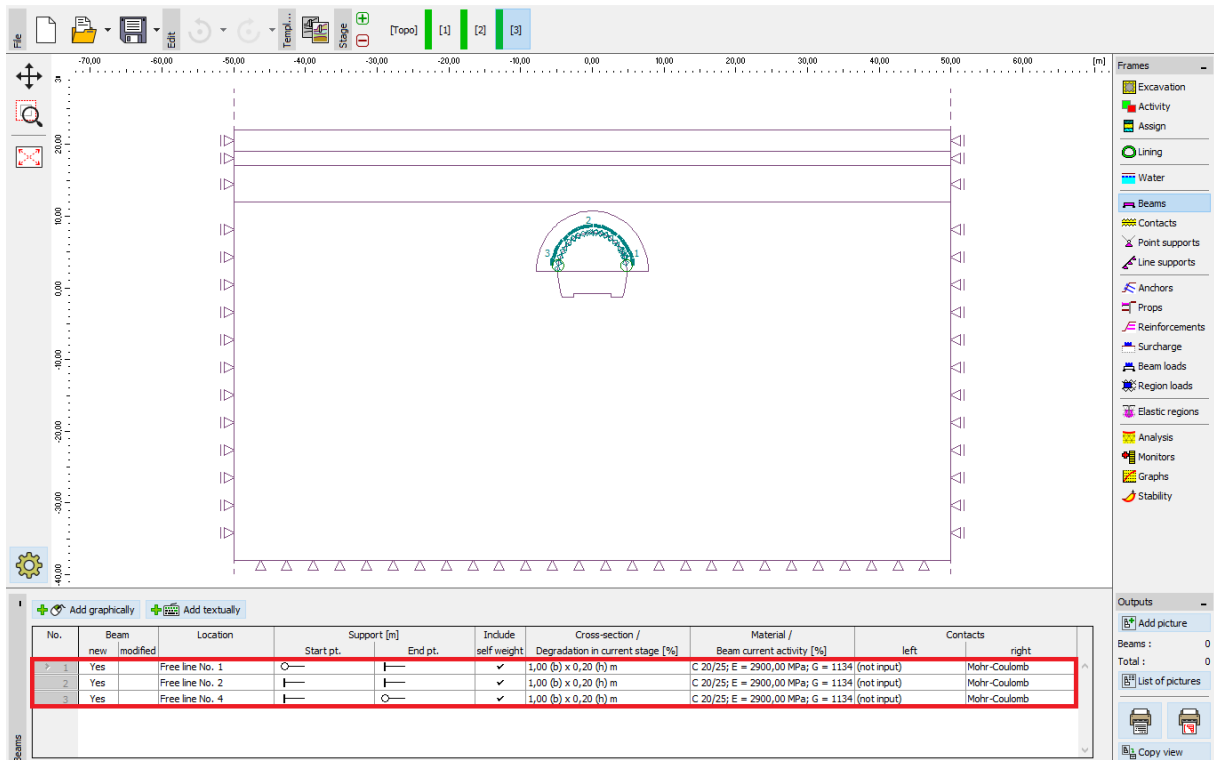
Now we will carry out the analysis and examine the results for vertical displacement d_z [mm]. To better understand the behaviour of the excavation, we will show the deformed mesh and the settlement trough.
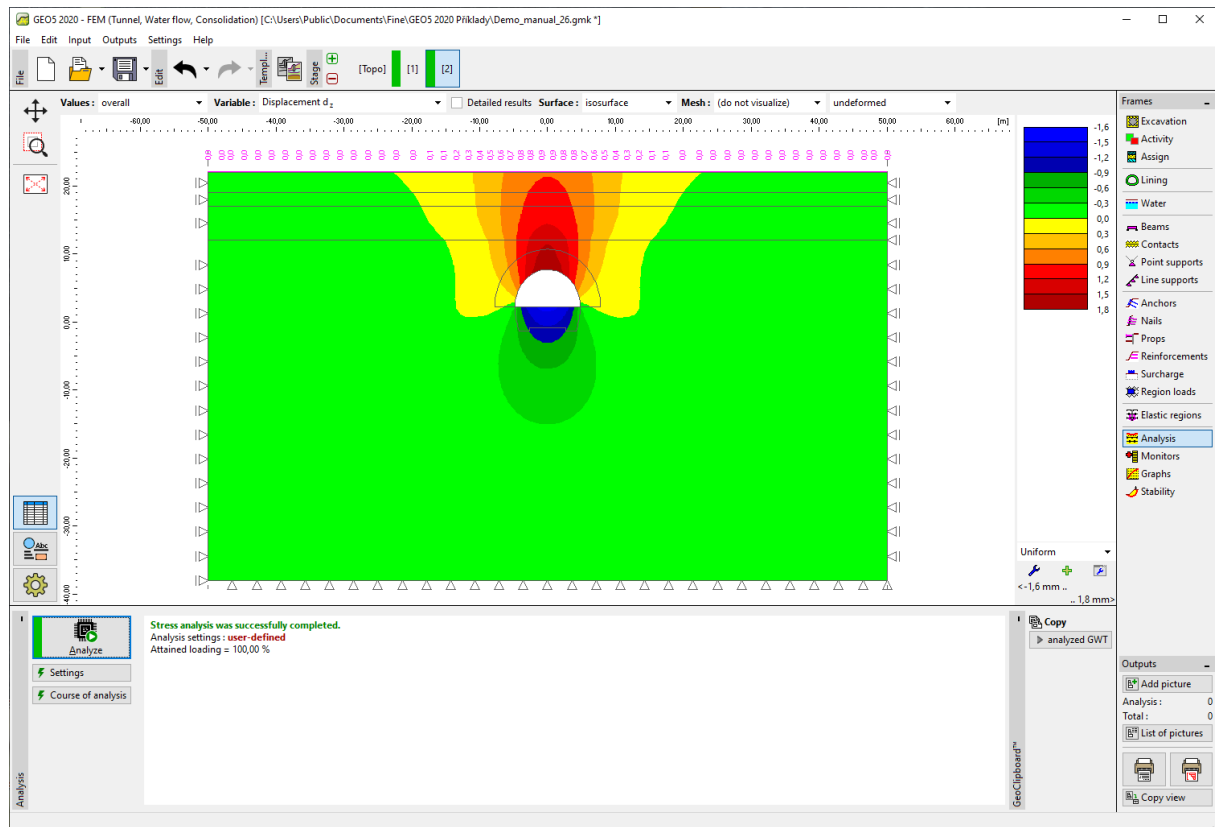
"Analysis" frame – Construction stage 2 (vertical displacement d_z with settlement trough)

Construction stage 3: supporting the top heading vault with an immature concrete primary lining

In the next step we will add construction stage 3. First of all, we will model the top heading vault support with a 200 mm thick immature concrete primary lining in the "Beams" frame.

Input of primary lining of top heading with new beams – Construction stage 3 (immature concrete)

*Note: We consider the beams to have a rotational degree of freedom at both ends, which means that bending moments at the bottom ends of the beams are zero. In some cases, the bearing of the ends of beams is modelled by means of a special type of the so-called **foot**, which ensures stability and convergence in the analysis (for more details visit Help – F1).*

In the "Assign" frame we will change the rock in region No. 5 (to the "anchored R5" option), in which we will take the anchoring with hydraulically expanded steel rockbolts into consideration (see the *picture*).
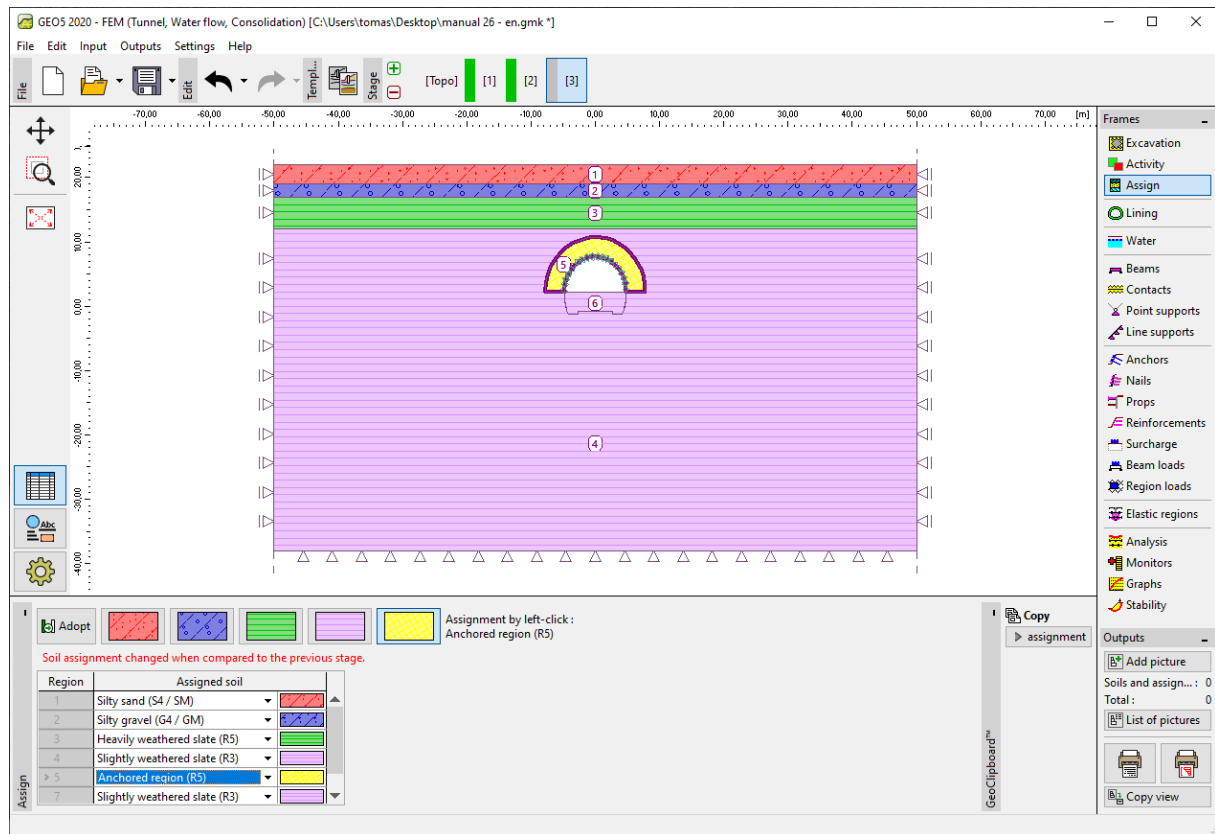
"Assign" frame – Constr. stage 3 (region anchored with hydraulically expanded rockbolts)

Further on we will activate the rockbolts in the rock mass reinforced with anchoring in the surroundings of the top heading excavation and will edit the excavation properties by adding 30 % of the load (using the "Edit" button).
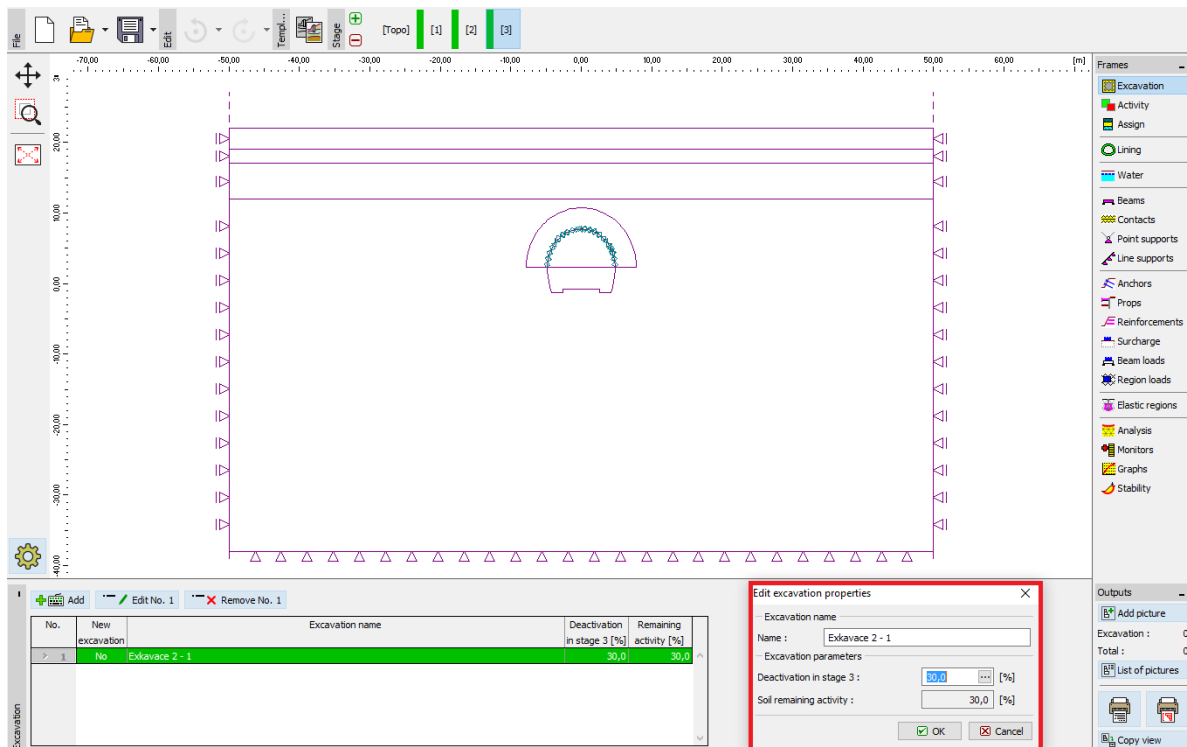
"Edit excavation properties" dialogue window – Construction stage 3
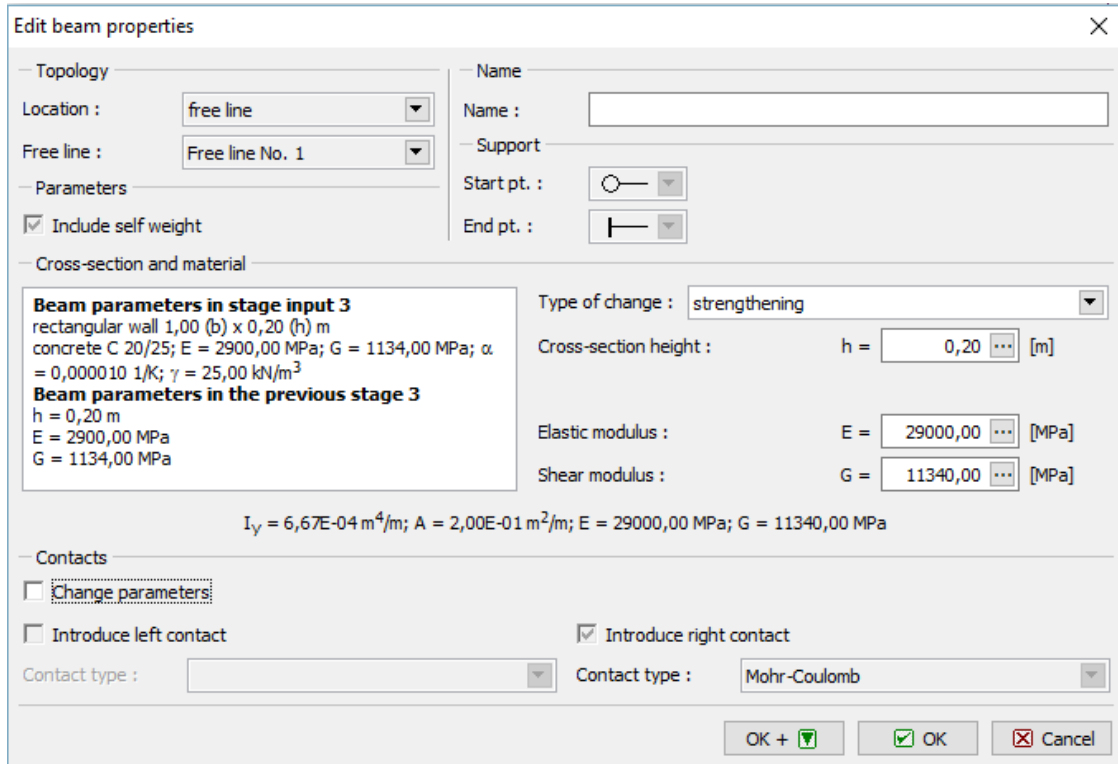
Then we will again carry out the analysis.
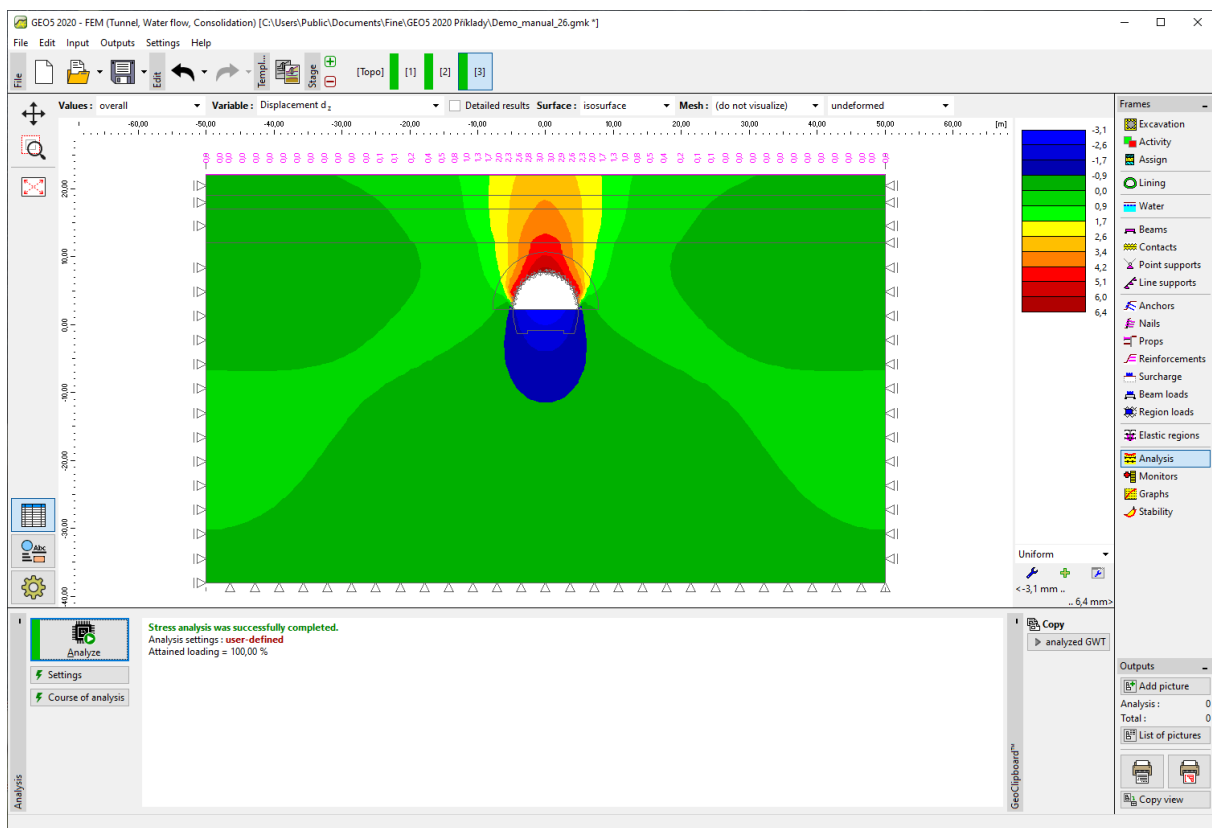
"Analysis" frame– Construction stage 3 (vertical displacement d_z with settlement trough)

Construction stage 4: improving material characteristics of mature concrete (top heading)

In construction stage 4, we will improve the material characteristics of the already mature concrete supporting the top heading. In the dialogue window "Modify beam properties", we will select the "Strengthening" option and will set the respective values of the modules of elasticity. We will leave the other parameters unchanged.

"Modify beam properties" dialogue window – Construction stage 4 (beam no. 2)
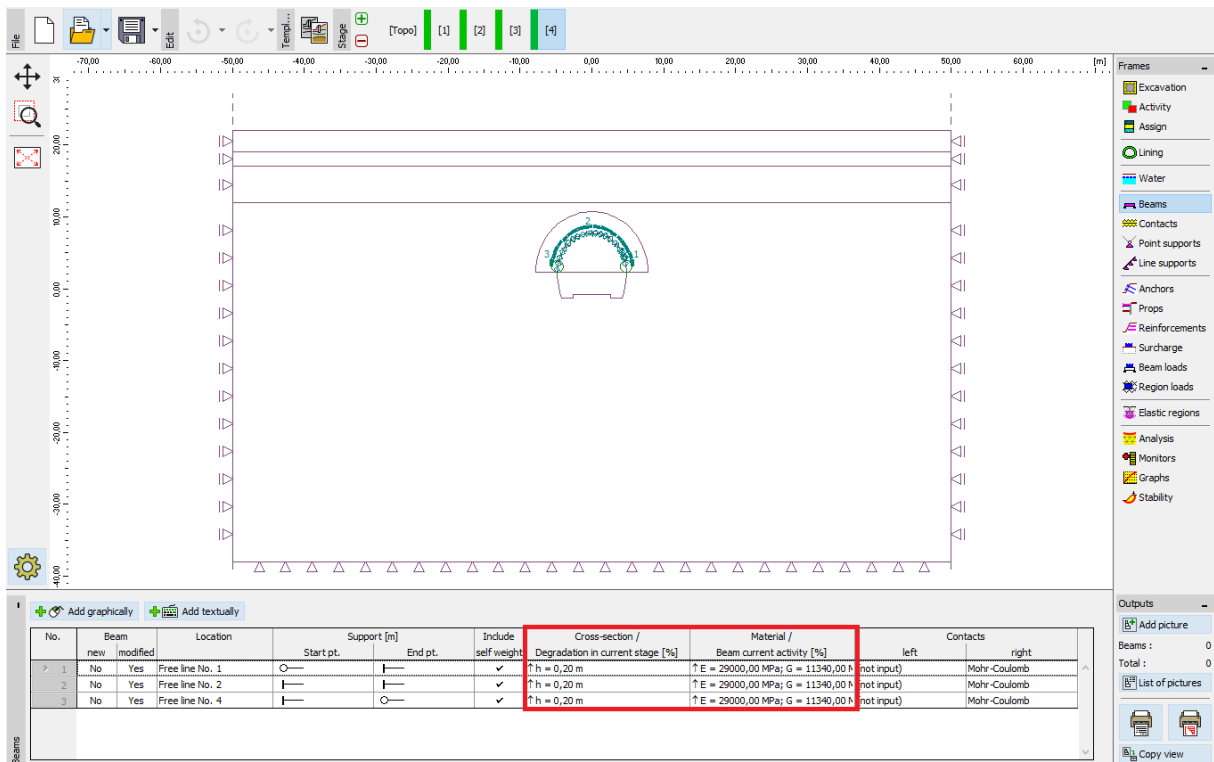
Modify properties of primary lining (top heading) – Construction stage 4

(mature sprayed concrete)

We will activate the remaining 30 % of the load acting on the rock mass. The procedure of editing the properties of the excavation is similar to that used in the previous construction stages.
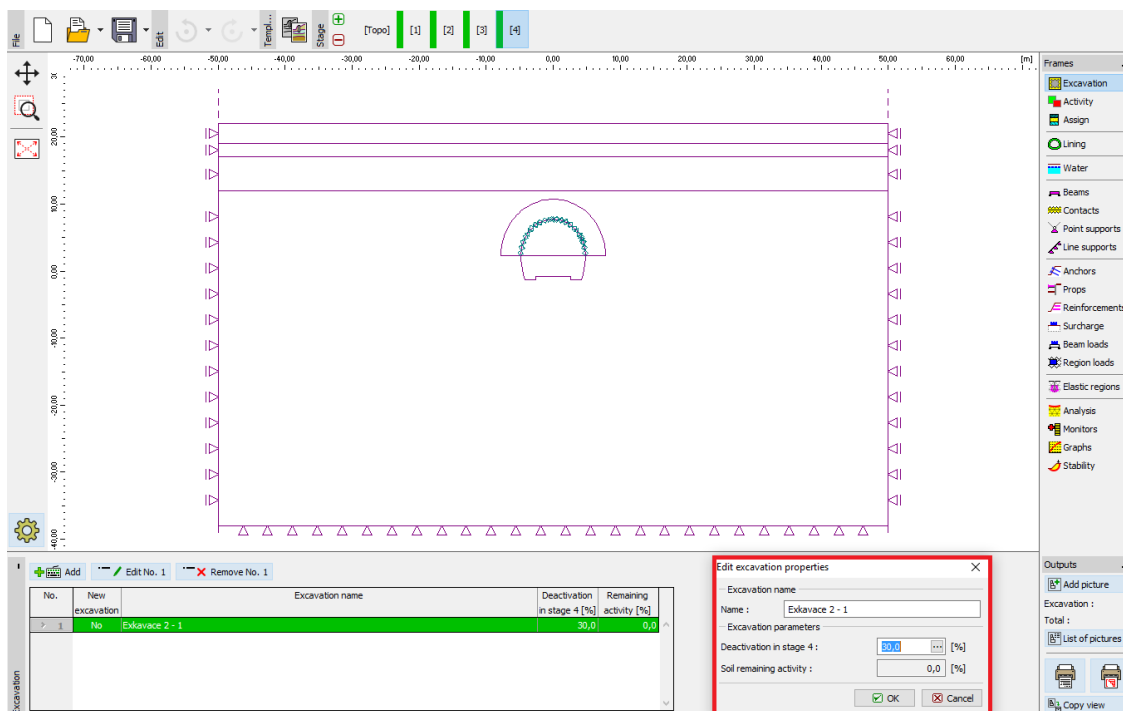
*"Edit excavation properties" dialogue window – Construction stage 4*

Subsequently, we will carry out the analysis and examine the bending moment curve along the top heading contour line.
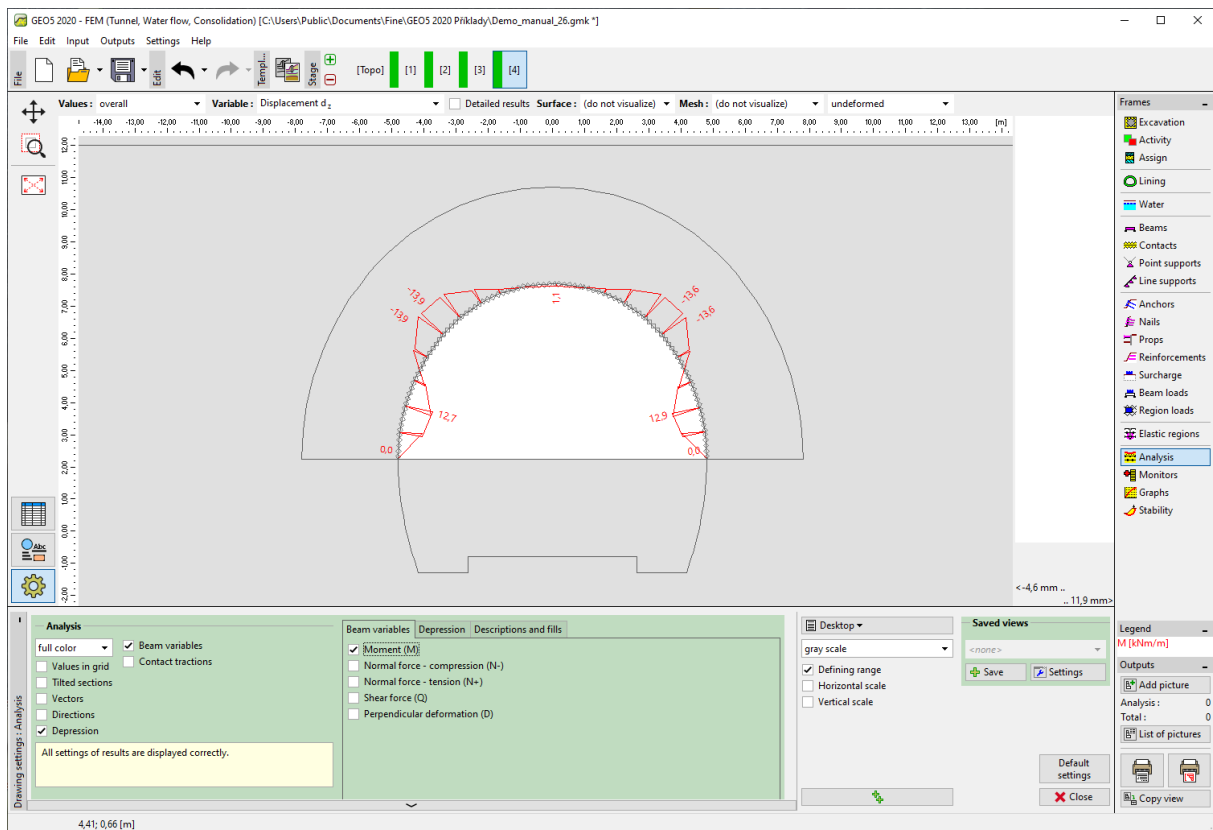
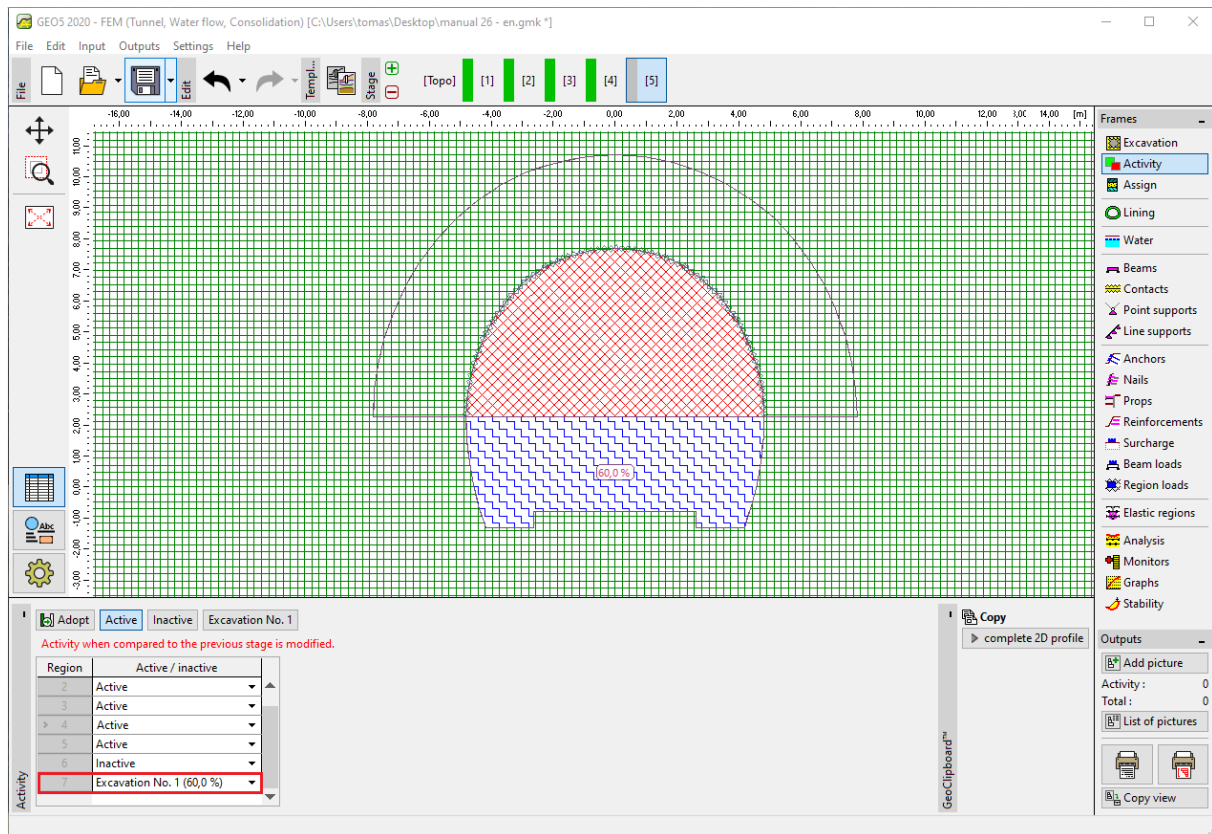*"Analysis" frame – Construction stage 4 (bending moment M $[\mathrm{kNm}/m]$)*

Construction stage 5: modelling of the tunnel bench excavation, activation of the unsupported excavated opening

In the next step, we will add construction stage 5. In this construction stage we will take the deactivation of soil, or the action of 40% of the load, into consideration. The remaining action of soil, or the massif in the vicinity of the tunnel bench excavation, is therefore 60 %.
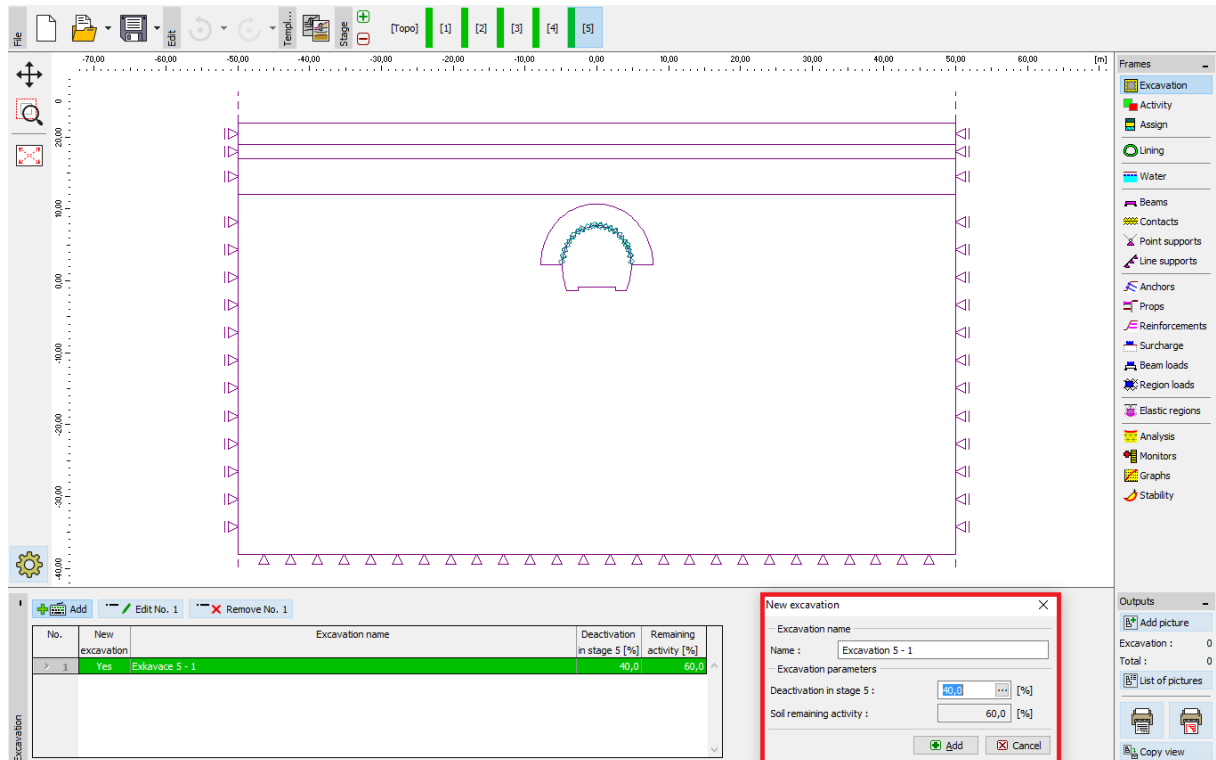
"New excavation" dialogue window – Construction stage 5

Note: The modelling of this problem to be applied to the subsequent construction stages is similar. First of all, the primary lining of the tunnel bench is carried out using immature sprayed concrete. The next percentage proportion of the load will be activated subsequently. In the following stage the material characteristics of the already mature sprayed concrete will be improved and the remaining proportion of the load will be activated.

"Activity" frame – Constr. stage 5 (activity of 40 % of loading on excav. of tunnel bench)

Subsequently we will carry out the analysis.
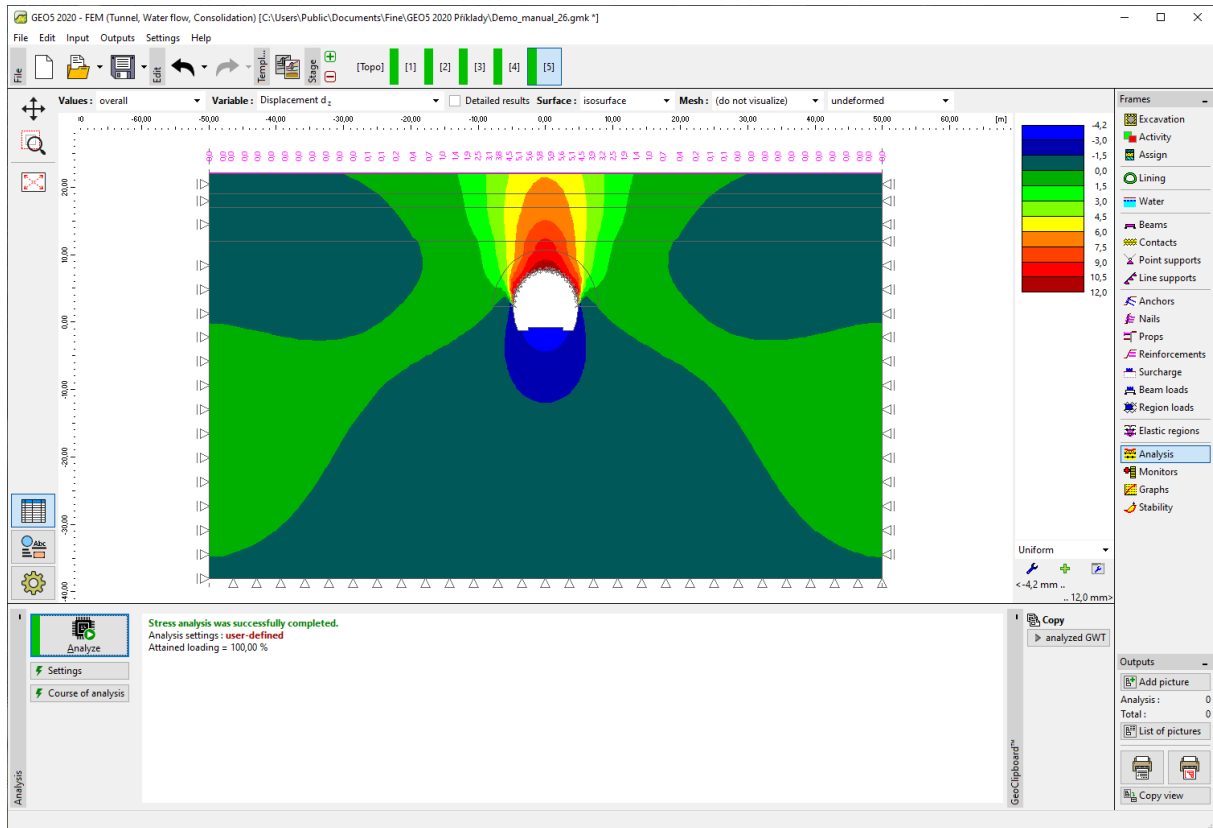
"Analysis" frame – Construction stage 5 (vertical displacement d_z with settlement trough)

Construction stage 6: supporting the bench side-walls with an immature concrete primary lining

In construction stage 6 we will set the support of the bench side-walls with a 200 mm thick immature sprayed concrete primary lining. The top heading lining will remain unchanged in the subsequent stages.
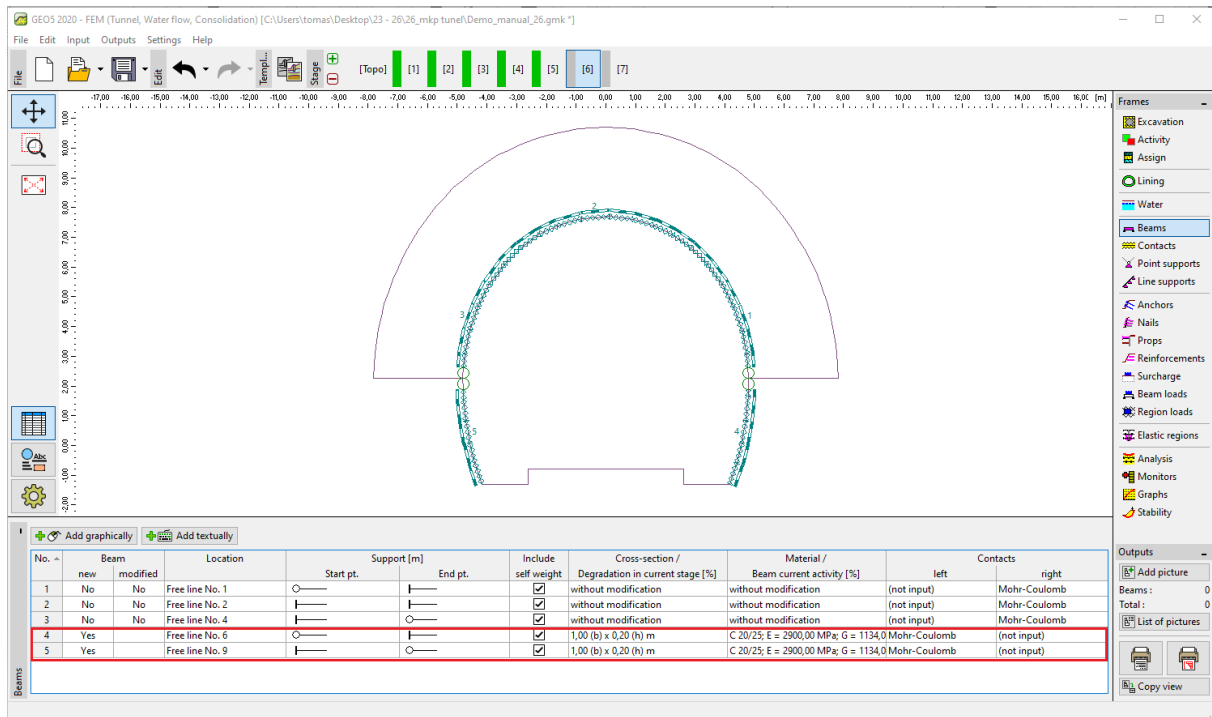
*Input of primary lining of tunnel bench with new beams – Constr. stage 6 (immature concrete)*

Note: We again consider the beams to have a rotational degree of freedom at both ends; the contact between the top heading and the bench is not capable of transferring the loading by a bending moment (it is not the case of fully continuous joints). The dimensions of the bench cross-section are identical with those of the top heading walls, i.e. $b = 1.0\ m,\ h = 0.2\ m$. But we must set the contacts at the new beams in a reverse way (for more details see the picture) because the orientation of the beams (bench side-walls) is negative.

In this stage, we will activate the additional 30 % of the loading induced by the rock massif.
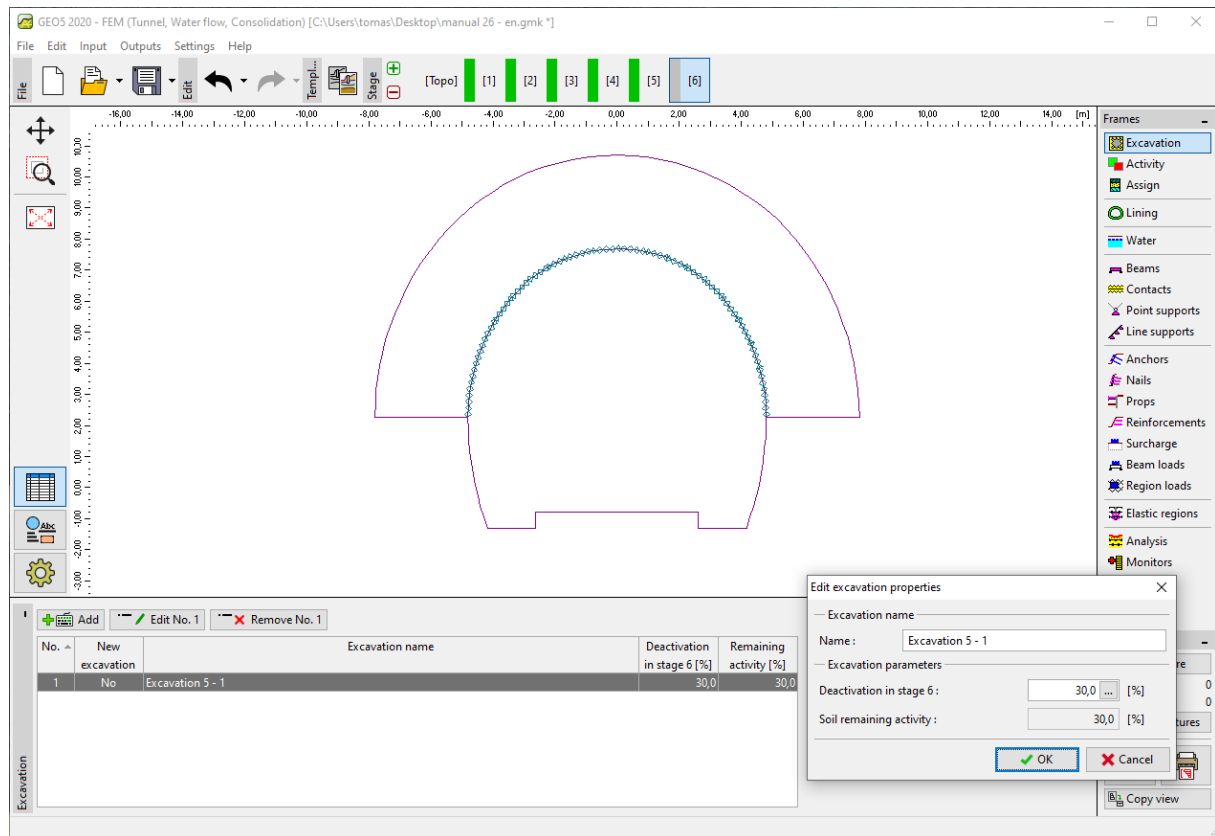
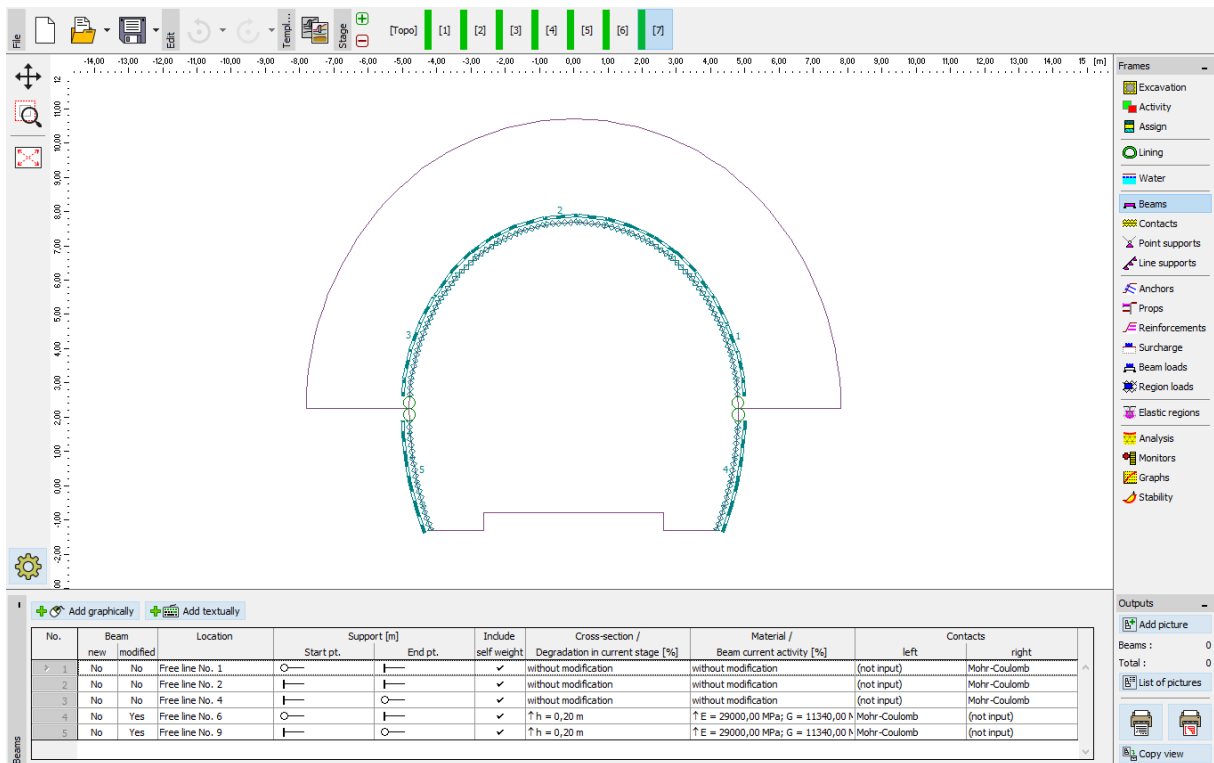*"Edit excavation properties" dialogue window – Construction stage 6*

In the last part of this stage we will again carry out the analysis.
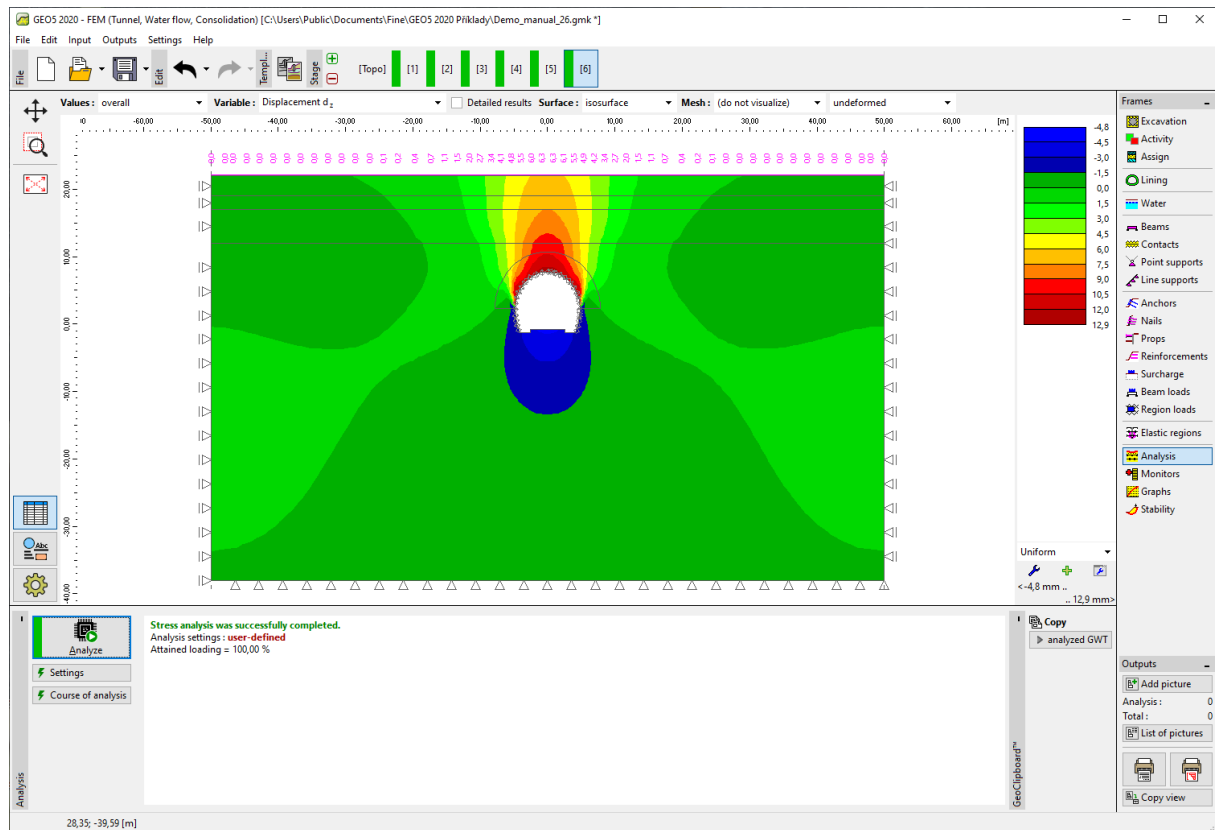
"Analysis" frame – Construction stage 6 (vertical displacement d_z with settlement trough)

Construction stage 7: improving material characteristics of mature concrete (bench)

In the last construction stage we will improve the material characteristics of the already mature concrete supporting the tunnel bench excavation.


Modify properties of primary lining (tunnel bench) – Stage 7 (mature sprayed concrete)

The procedure of increasing the capacity of the beams is similar to that used in construction stage 4. We will activate the remaining 30% of the load induced by the rock massif. By taking this step, we remove all soils from the excavation space and the loading therefore acts on the primary tunnel lining (inclusive of the top heading and bench walls) at 100 %. Subsequently we will carry out the analysis of the last construction stage.
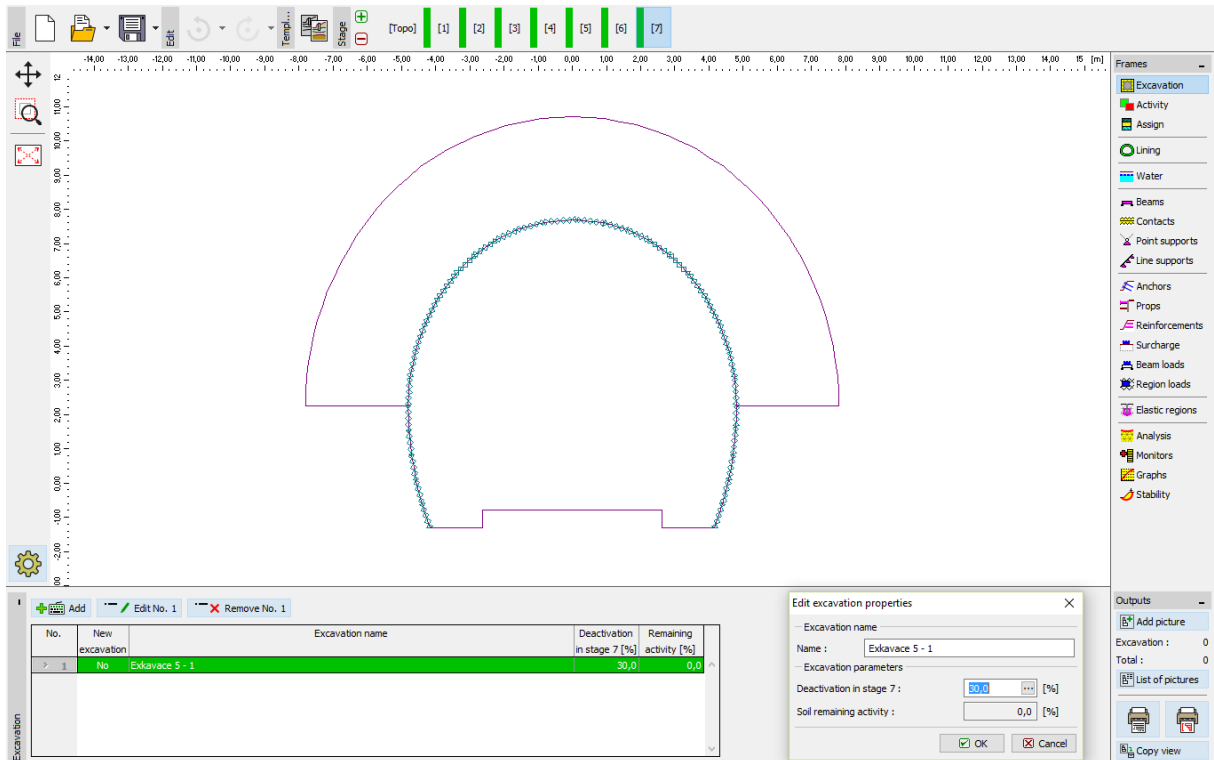
*"Edit excavation properties" dialogue window – Construction stage 7*

Now we will carry out the analysis of the last construction stage.
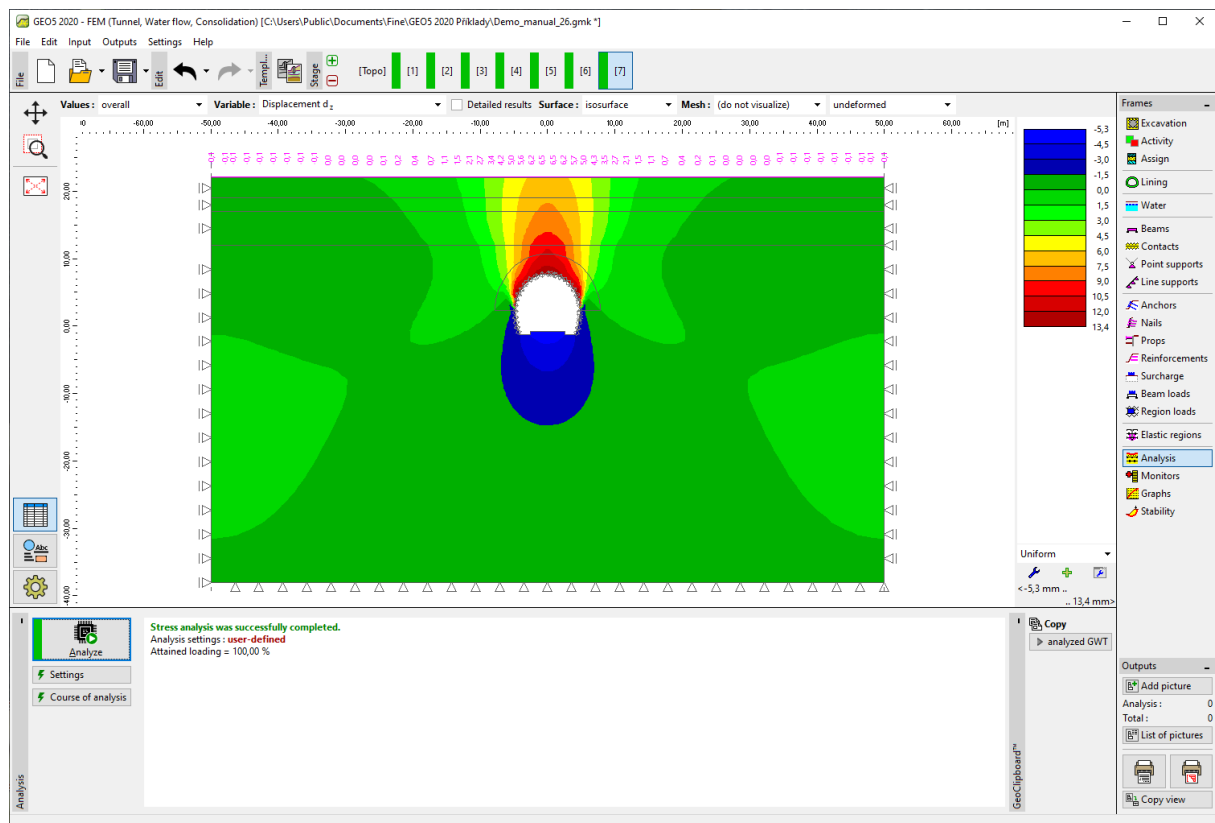
"Analysis" frame – Construction stage 7 (vertical displacement d_z with settlement trough)

Further on in this stage, we will show the equivalent plastic deformations $\varepsilon_{eq.,pl.}$ and the distribution of internal forces for bending moments and normal forces (the "Show" button, "Distribution" tab sheet). We will record the results in a summary table.
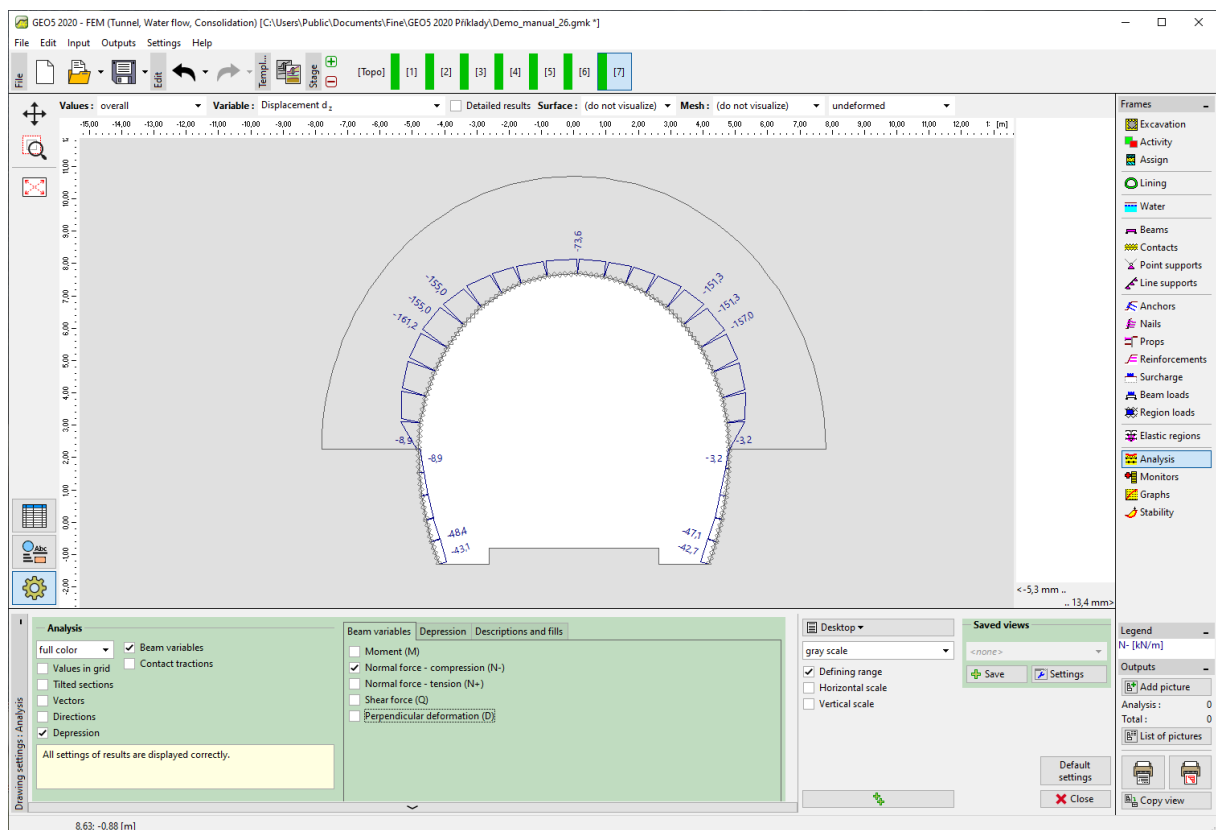
It seems from the following picture that the equivalent plastic deformations $\varepsilon_{eq.,pl.}$ are not zero, which corresponds to the structure behaviour according to the non-linear material model (Mohr – Coulomb).
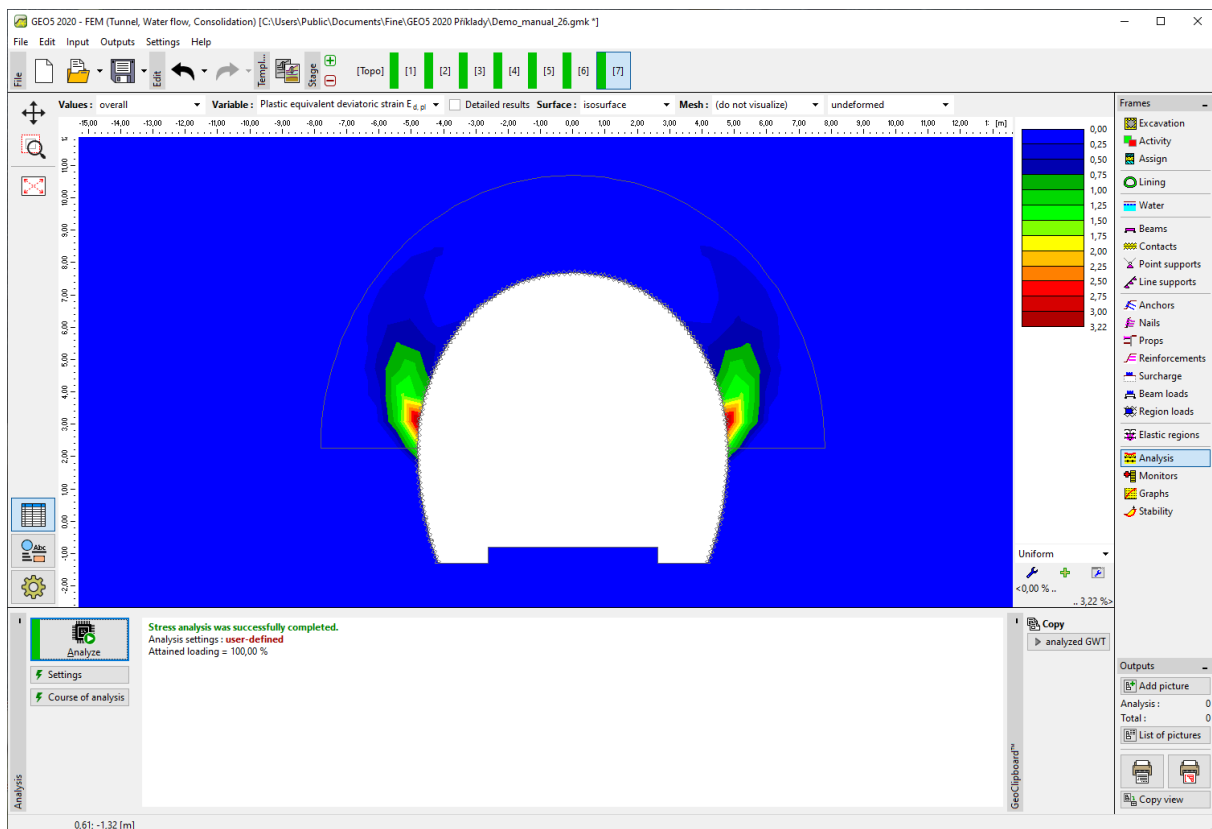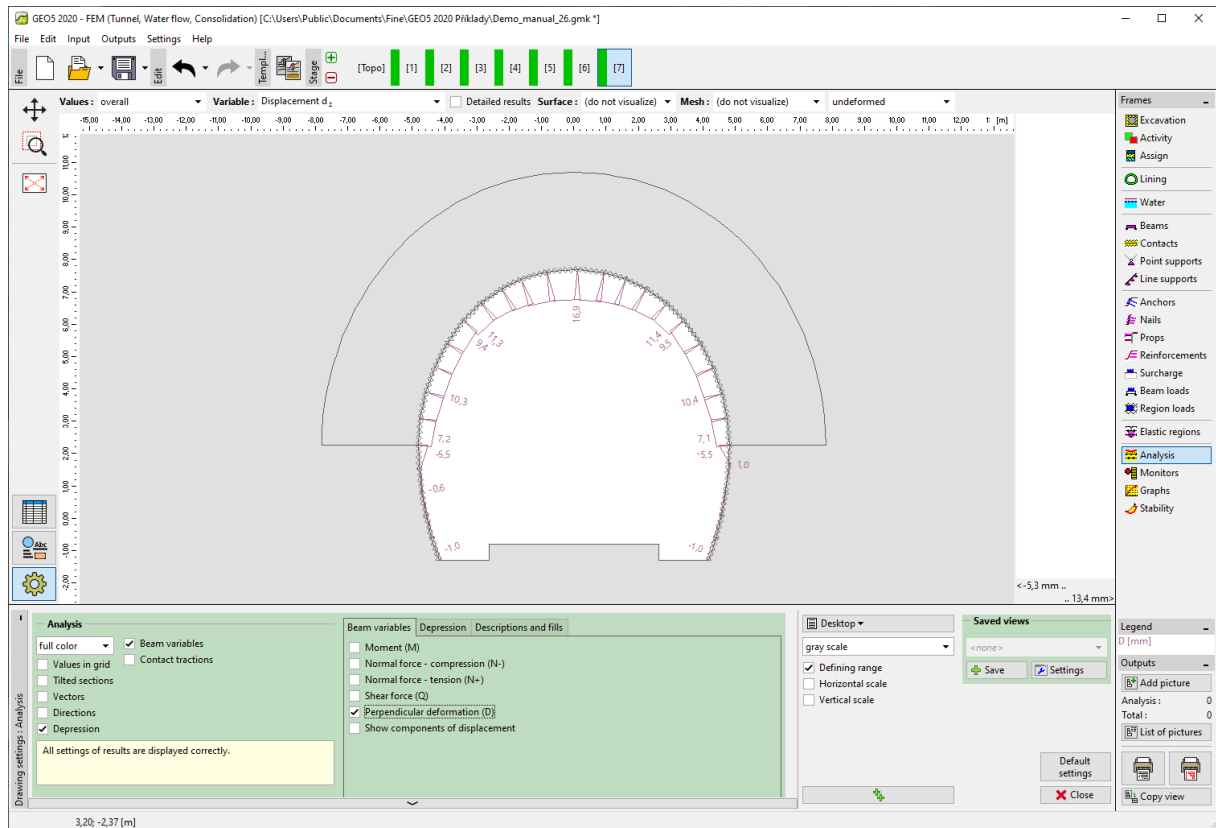

"Analysis" frame – Construction stage 7 (equivalent plastic strain $\varepsilon_{eq.,pl.}$ according to Mohr-Coulomb model)
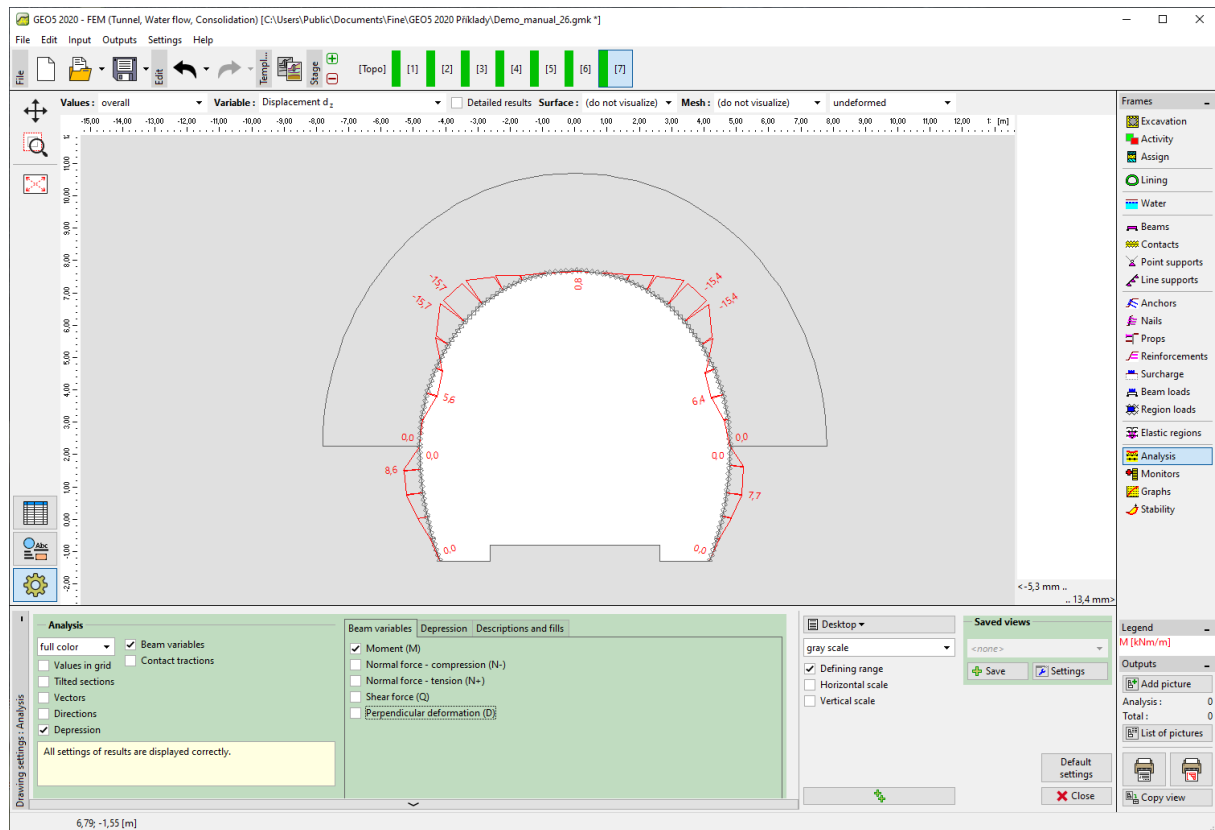
"Analysis" frame – Construction stage 7 (bending moment M $[\text{kNm}/m]$*)*

"Analysis" frame – Construction stage 7 (normal force – compression N^- [kN/m])

"Analysis" frame – Construction stage 7 (perpendicular deformation)

Assessment of the results:

The following table shows the values of the extremes of internal forces (bending moments, shear forces and normal forces) acting on the beams (the primary tunnel lining) for construction stage 7. We carried out this analysis for the plastic material model (Mohr – Coulomb) with locally increased density of triangular elements.

Material model	Construction stage 7 – Internal forces		
	N [kN/m]	M [kNm/m]	Q [kN/m]
Mohr – Coulomb	− 161,2	− 15,7	− 1,0
	− 3,2	+ 6,4	+ 16,9

Extreme values of internal forces in primary lining – Construction stage 7

This table presents the overall values of vertical and horizontal displacements d_z, d_x [mm] of the primary tunnel lining for individual construction stages.

Construction stage	Values of overall displacement d_z, d_x [mm]			
	$d_{z,min}$	$d_{z,max}$	$d_{x,min}$	$d_{x,max}$
1	–	–	–	–
2	− 1,6	+ 1,8	− 0,46	+ 0,46
3	− 3,1	+ 6,4	− 2,8	+ 2,8
4	− 4,6	+ 11,9	− 4,8	+ 4,9
5	− 4,2	+ 12,0	− 5,0	+ 5,1
6	− 4,8	+ 12,9	− 5,5	+ 5,5
7	− 5,3	+ 13,4	− 5,7	+ 5,8

Values of displacement d_z, d_x of primary lining (extremes) – All construction stages

Conclusion:

In this problem we demonstrated the modelling of the primary lining of a real tunnel using the Finite Element Method. The tunnel is made using the NATM. The tunnel excavation is divided into certain parts. When the rock is being removed, the massif is being unburdened and the soil or rock is being deformed, with the contour displacement direction heading toward the excavated opening interior.

__The primary lining__ is reinforced with KARI mesh (concrete reinforcing steel mesh welded from steel rods 8mm in diameter, with 150 x 150 mm mesh dimensions) and steel lattice girders with 3 load-bearing rods. The introduction of KARI mesh into the FEM numerical model (the homogenisation of concrete and reinforcement) is disputable; it is mostly taken into consideration only after the separate assessment of the lining.

The primary tunnel lining would be subsequently assessed on the calculated extremes of internal forces, using structural analysis software (e.g. FIN EC – CONCRETE 2D), as a combination of the stress produced on the section by a bending moment and a normal force (according to the interaction diagram).

Note: The analysis of an underground structure without the use of beam and contact elements according to a linear material model (with elastic behaviour) was described in Chapter 23. Collector lining analysis (see http://www.finesoftware.eu/engineering-manuals/).