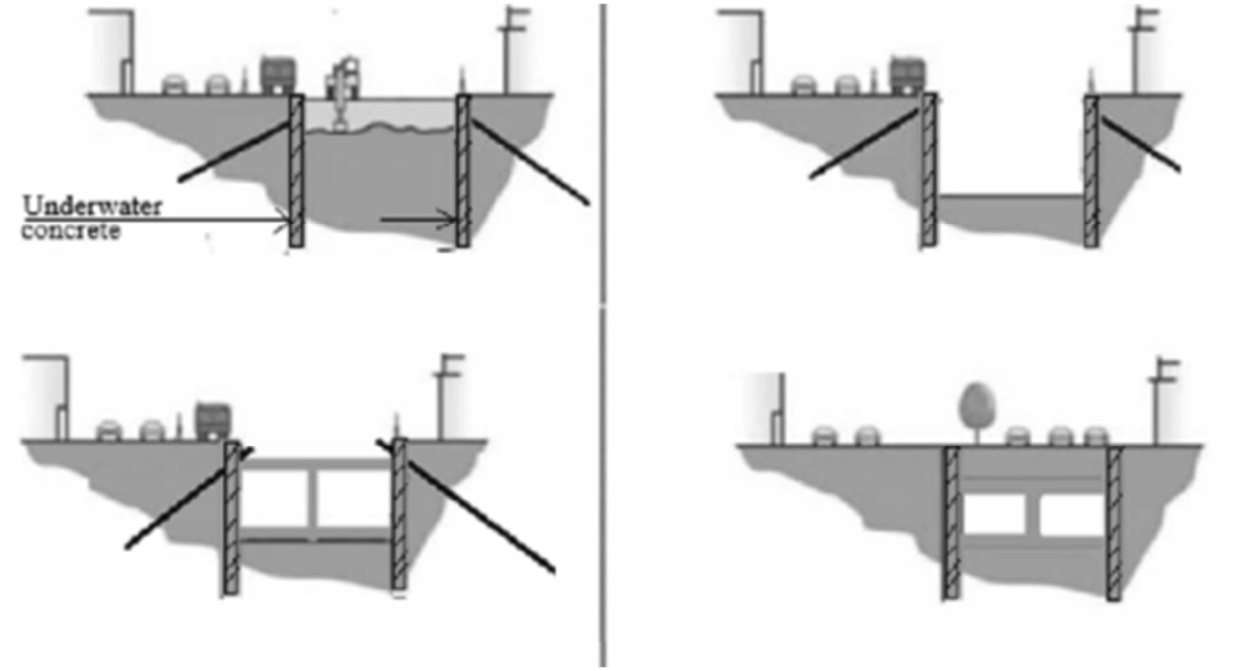
Cut and cover tunnel construction – one anchor level (Using permanent cast-in-place diaphragm wall)

Advanced nonlinear tunnel and geotechnical FEA features:

- *Moving traffic load analysis under nonlinear conditions (linear is also performed).*
- *Geotechnical stability utlitmates state (”Jordbrott).*
- *Staged construction analysis for excavation, tunnel and anchors.*
- *Mohr–Coulomb nonlinear soil model is used for nonlinear conditions.*
- *Initial horsiontal stresses based on Rankine at-rest earth pressure (K_0).*
- *Nonlinear tunnel–soil interface elements to handle slip resistance.*
- *Comparison of linear and nonlinear soil behaviour*

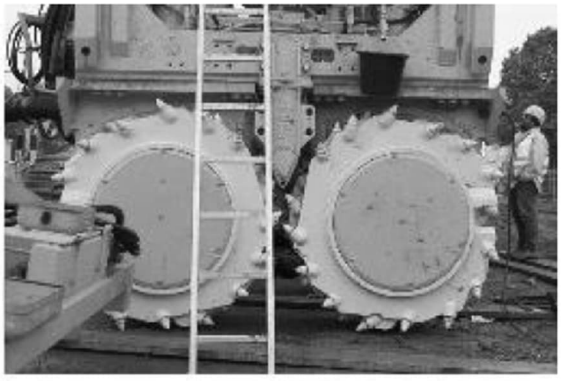
Table of content

0. PREFACE



Principal sketch
Overview

Excavation
Fine grained soil



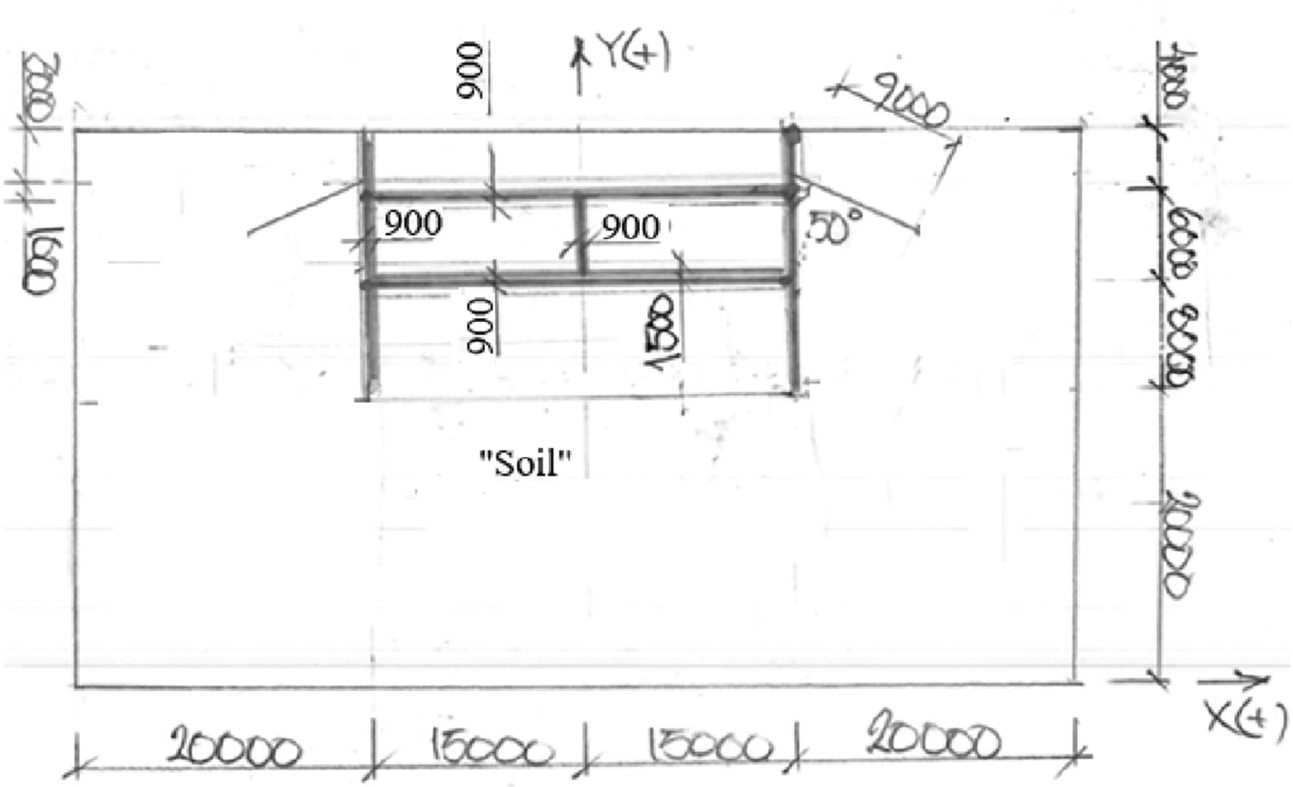
Excavation
Bouldery soil

1. GENERAL

Below is a description of varying stages of design.

1.1 GEOMETRY

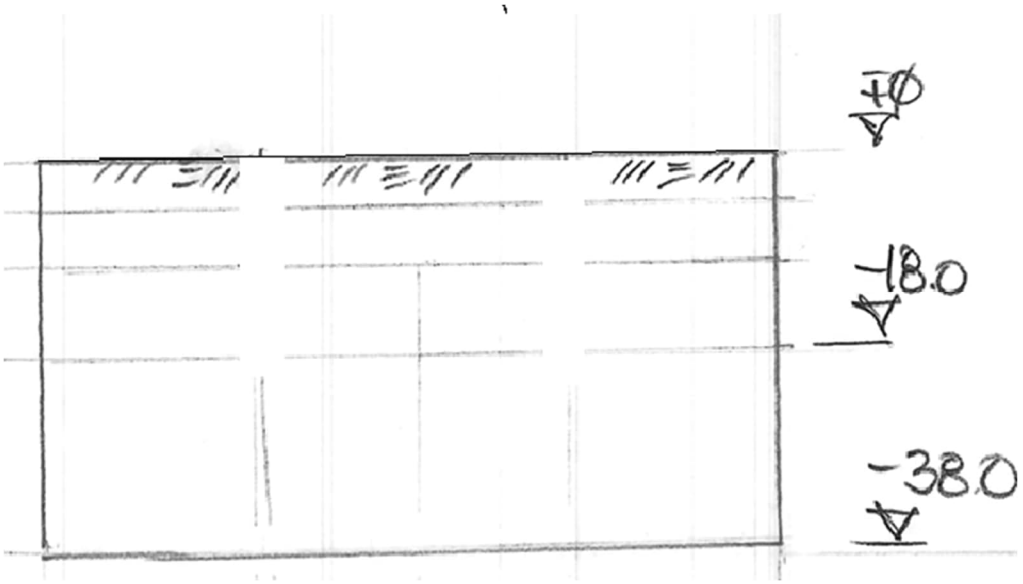
Below are geometries associated to constuction and operational stage.



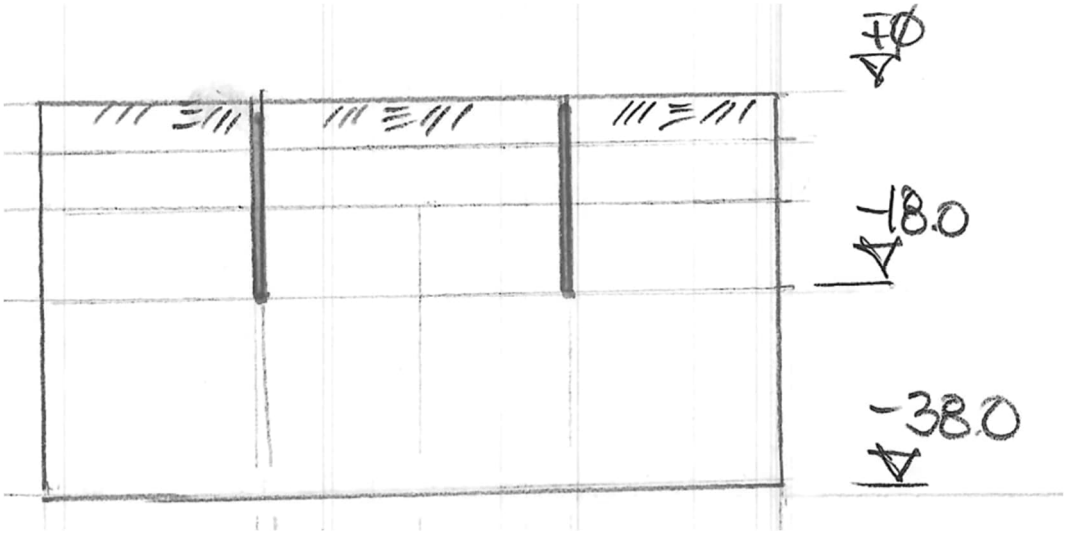
ELEVATION
Overall

1.1.1 Construction stages

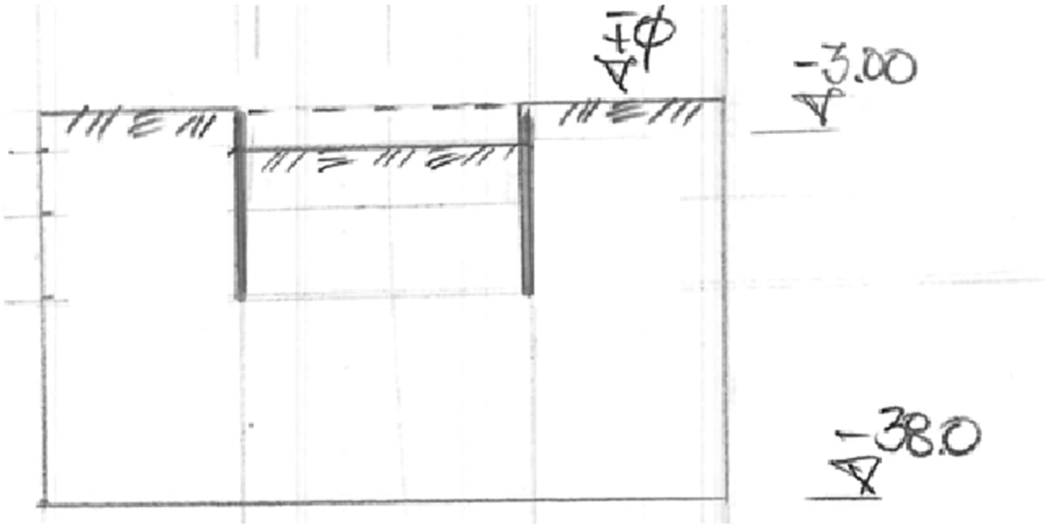
There are a total of 7 construction stages as seen on sketches below.



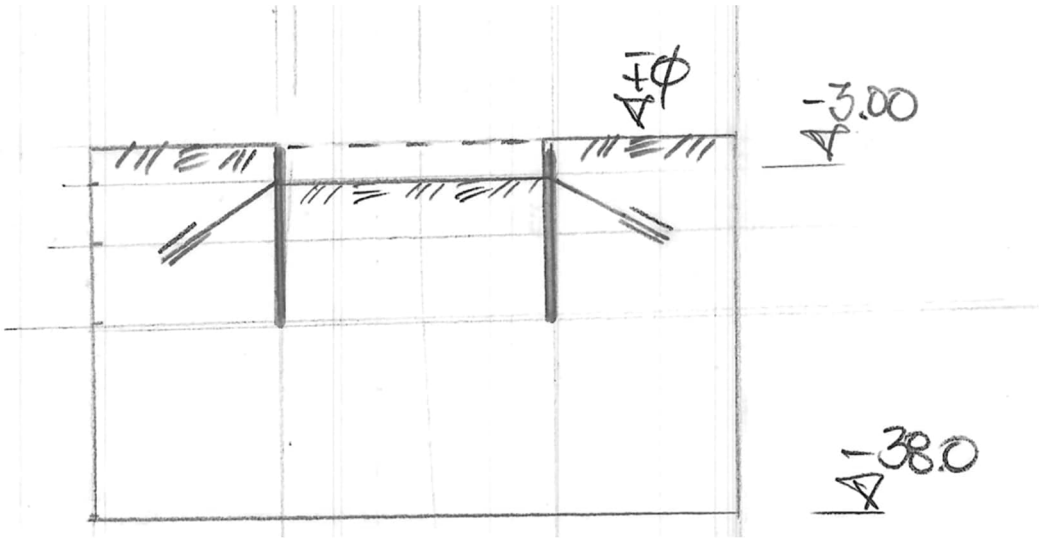
ELEVATION
Stage 1: Initial conditions.



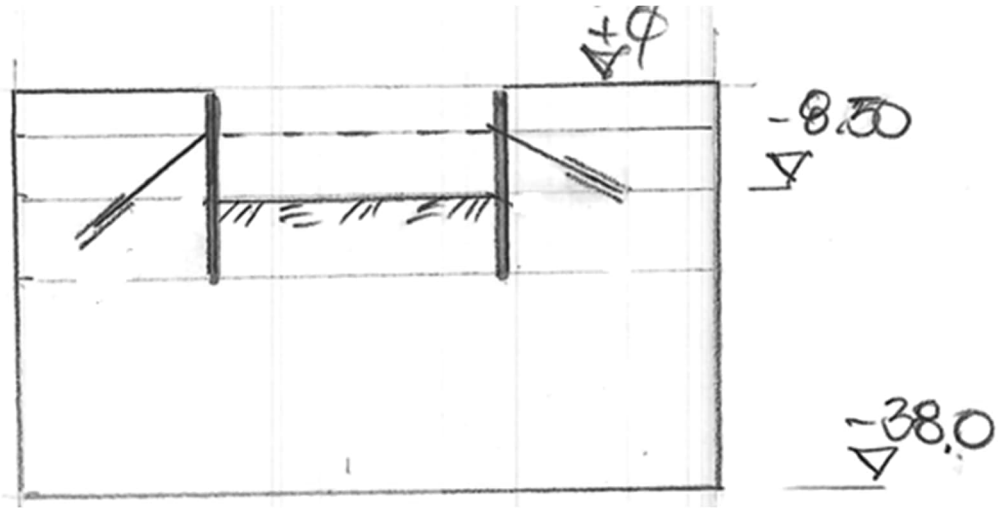
ELEVATION
Stage 2: Installation diaphragm-walls.



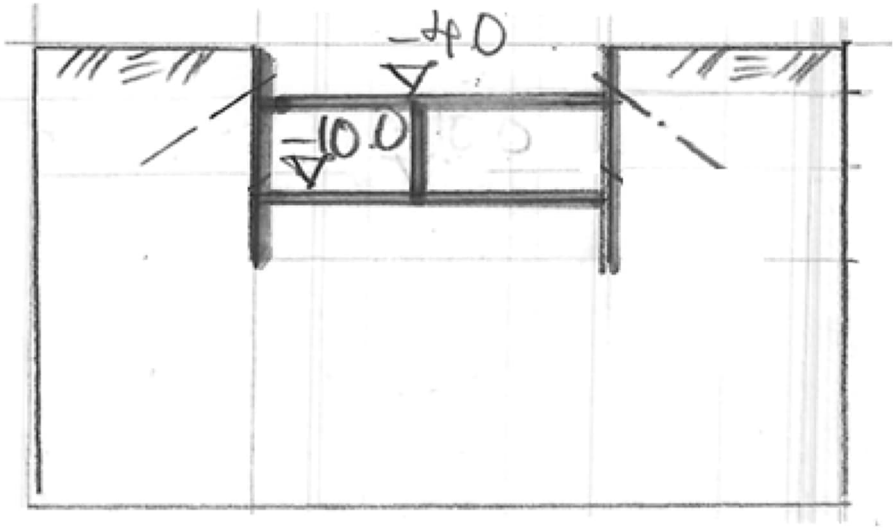
ELEVATION
Stage 3: Excavation 1



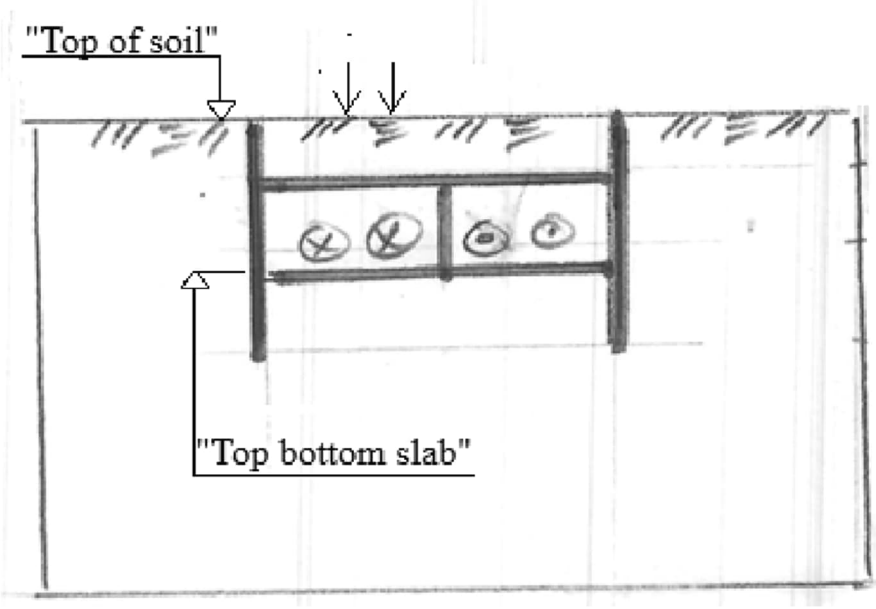
ELEVATION
Stage 4: Installation of anchors at level 1.



ELEVATION
Stage 5: Excavation 2.



ELEVATION
Stage 6: Construction tunnel



ELEVATION
Overall. Stage 7: Filling on top of tunnel

1.2 SOIL PROPROPETIES

1.2.1 Ground water

Ground water level is assumed lower than level ± 0.

1.2.2 Soil material

Geotechnical parameters:

Material	Level	ρ	ρ´	ϕ_k	E_k
”Soil”	± 0→ -38.0	20	11	30	8
”Rock”	± 0	-	-	-	-
-	m	kN/m³	kN/m³	deg	MPa

2. SYSTEM ANALYSIS

2.1 GENERAL

There are 7 construction stages (∴ Stage 1-7) that are analysed using nonlinear analysis. During each construction stage varying structural parts and soil material is activated or deactivated due to excavation and construction of structure.

The soil material is modelled using a elasto-plastic model *Mohr-Coulomb* (called model 65) that is used for soil and rocks.

Soil is modelled using plain strain surface elements (QNP8).

All structural parts of tunnel including diaphragms are modelled as thick beam elements (BMI3).

Analysis using *"branches"*(∴Branch 1-5) is used to perform nonlinear analysis. Each "branch" is a sub-analysis has completed. Using braches means start and end of the previous sub-analysis are indepndependent sub-analysis. Every branch is defined using single loadcases, thus load ing occur 'simultaneously', not 'sequentially'.

When applying gravity load at stage 1 (∴ before excavtion") deformations arisies which do not occur since have allready been "consolidated" over time. These are historic deformation are used by resting formations av stage 1 but maintaining stress.

Safety factor analysis is performed using function *Phi-c Reduction* to determine the most dangerous situation. Considered to arise at Stage 5,

.

Schematic sketch

Analysis 1:

Stage #	Name	Excavation	Loading	Deactivate	Activate
1	Before excavation	Before excavation	Gravity soil *	Tunnel & anchors	-
2	Wall installation	Before excavation	Gravity wall	-	Wall
3	Excavation:1	After excavation 1	-	Excavation:1	-
4	Install anchor:1	After excavation 1	Anchor load:1	-	Anchor:1
5	Excavation:2	After excavation 2	-	Excavation:2**	-
6	Construct tunnel	After excavation 2	Gravity top slab	Anchors	Tunnel
7	Filling at top slab	After filling top slab	Gravity filling top slab	-	Soil top slab

* = Reset deformation is applied to remove historic deformations.

** = Phi-c analysis to determin geotechnical stability (”Jordbrott”).

2.2 NONLINEAR ANALYSIS

Nonlinear analysis is performed using increments using Newton Raphson numerical procedure.

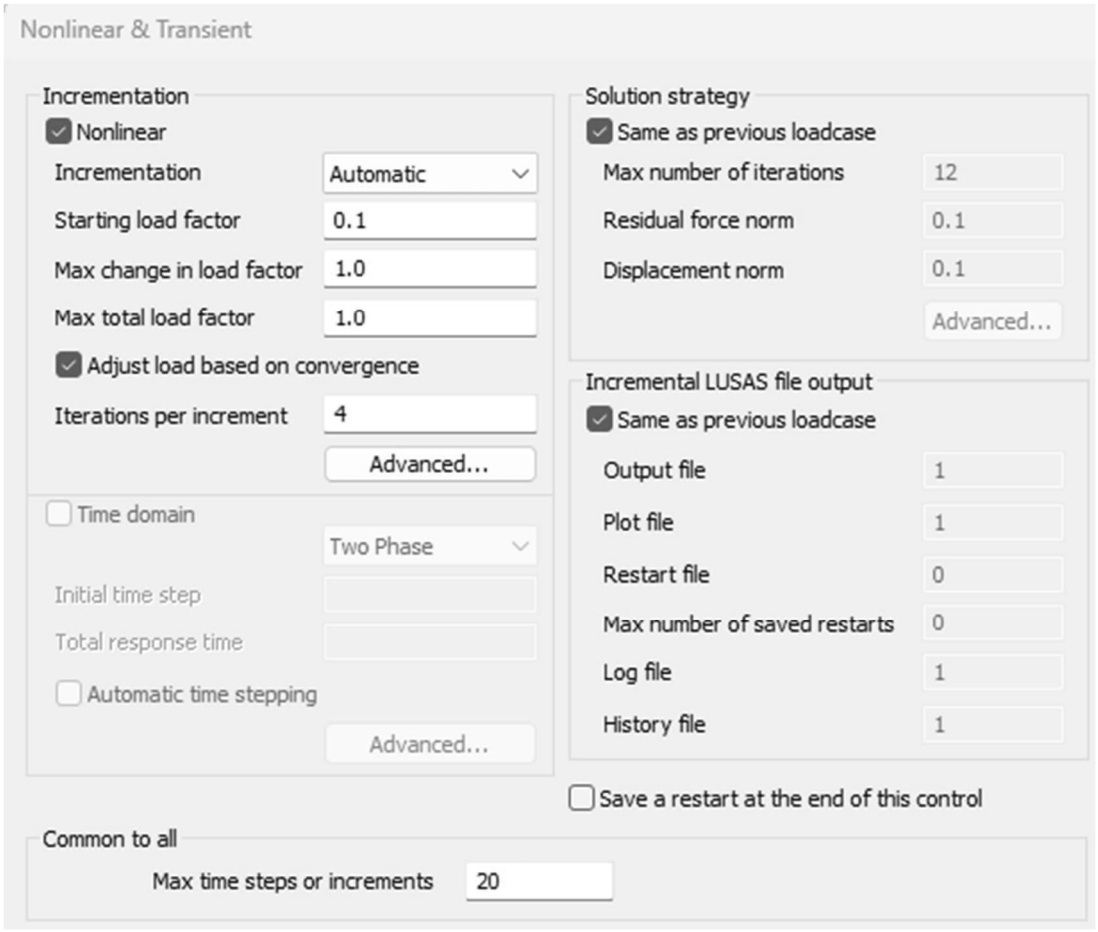
Max number of iterations:
For each load increment if convergence is not achieved.

Residual force norm:
The limit for the sum of the squares of all residual forces as a percentage of the sum of the squares of all external forces, including reactions (rdnrm). By default, only translation degrees of freedom are considered. So for a value of 0.1 the convergence of the solution at each load increment will be achieved when the out of balance forces are as less than 0.1% of the reactions.

Displacement norm:
The limit for the sum of the squares of the iterative displacements as a percentage of the sum of the squares of the incremental displacements (DTNRM). Only translation degrees of freedom are considered

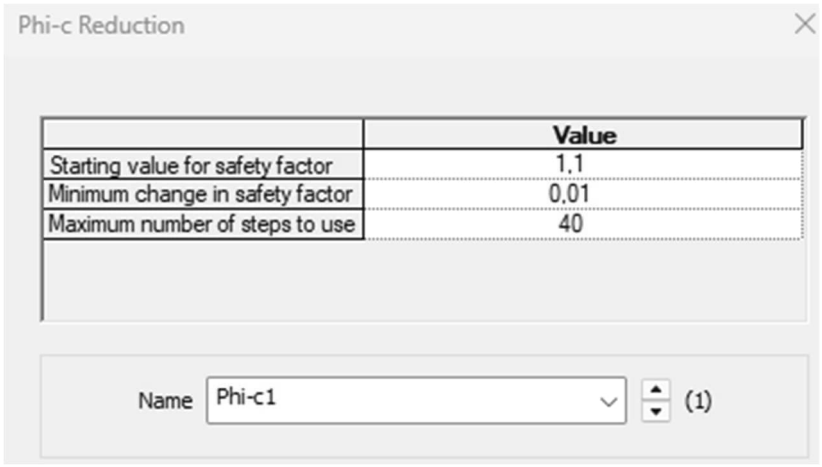
Stage #	LC name	Control	Branch	Incrementation
1	Before excavation	Nonlinear	-	Automatic
2	Wall installation	Nonlinear	-	Automatic
3	Excavation:1	Nonlinear	-	Automatic
4	Install anchor:1	Nonlinear	-	Automatic
5	Excavation:2	Nonlinear	-	Automatic
”	-”-	-”-	Branch 1	Automatic
6	Construct tunnel	Nonlinear	-	Automatic
7	Filling at top slab	Nonlinear	-	Automatic
”	-”-	Nonlinear	Branch 2	Automatic
”	-”-	Nonlinear	Branch 3	Automatic
”	-”-	Linear	Branch 4	-
”	-”-	Linear	Branch 5	-

Incrementation as chosen to be performed *Automatic* with chosen parameters in dialogue box.



2.3 SAFETY FACTOR ANALYSIS

A nonlinear safety factor analysis is performed using function *Phi-c Reduction* with starting values seen below. This analysis is performed at stage 5 which is considered most dangerous.



2.4 SKETCH SYSTEM ANALYSIS

To describe geometry first POINTS are defined.

Beam elements are defined by applying attributes to LINES.

Shell elements are defined by applying attributes to SURFACES.

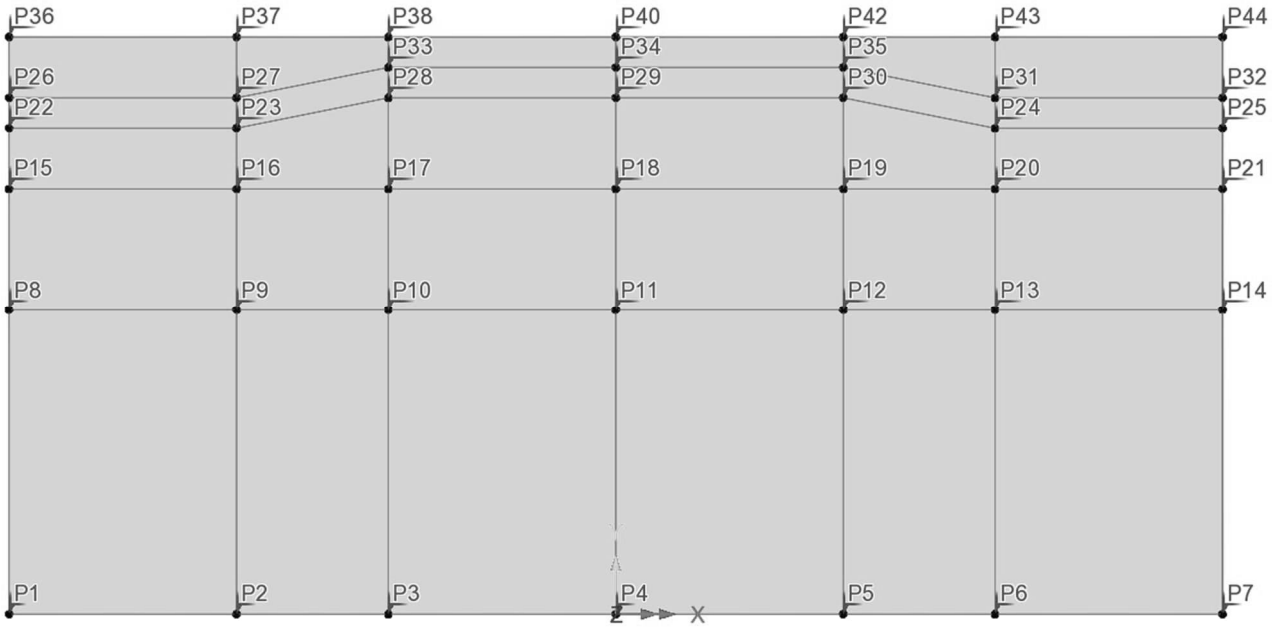
All coordinates needed to describe POINTS are found in attachment 1.

All POINTS needed to describe LINES are found in attachment 1.

All LINES need to describe SURFACE are found in attachment 1.

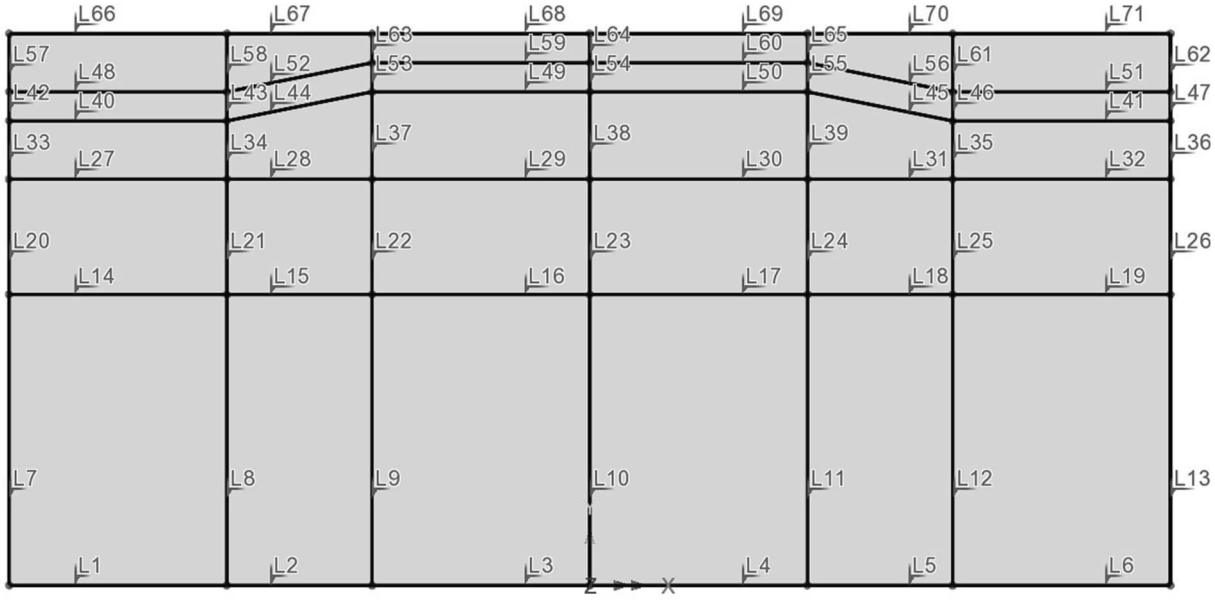
Sketches are generated by using POINTS, LINES and SURFACES.

2.4.1 Geometry: Points



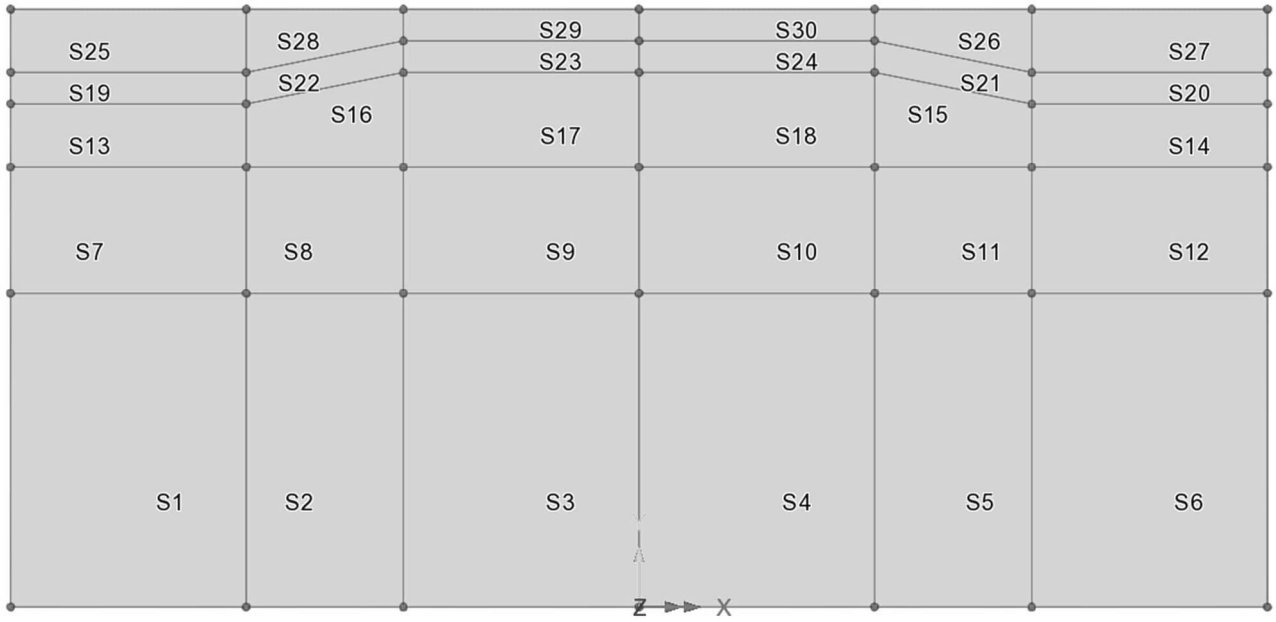
ELEVATION
Overall

2.4.2 Geometry: Lines



ELEVATION
Overall

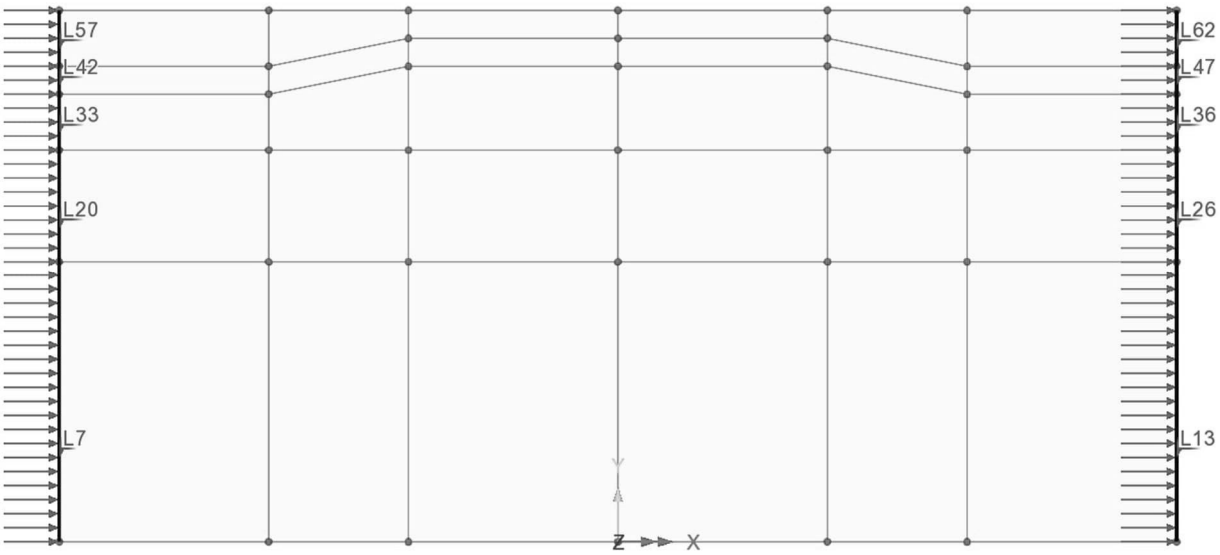
2.4.3 Geometry: Surfaces



ELEVATION
Overall

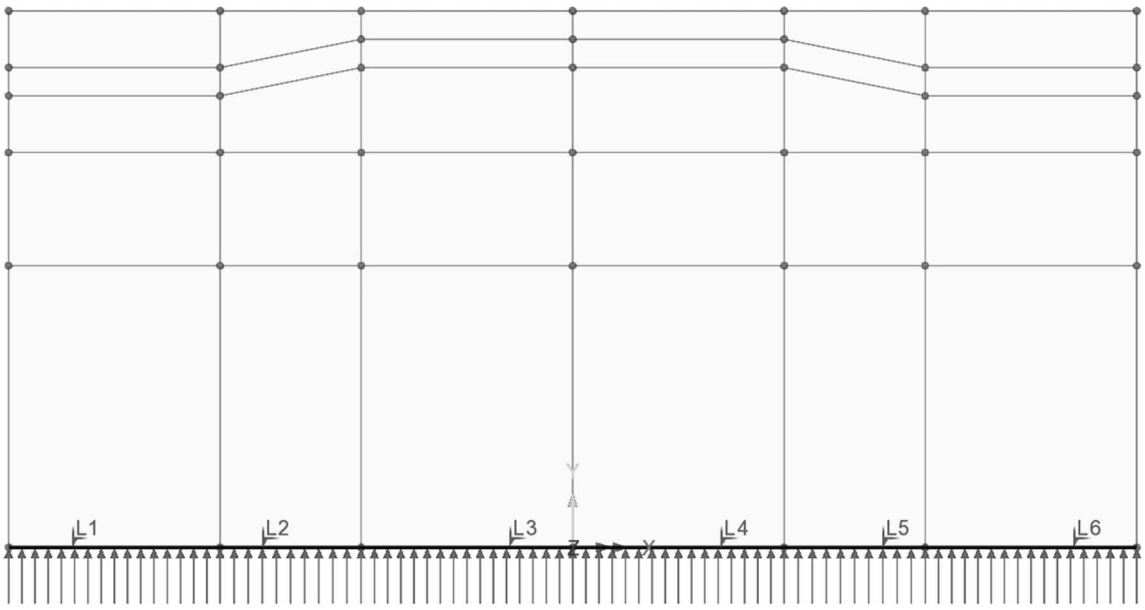
2.5 BOUNDARY CONDITIONS

2.5.1 Horizontal boundary soil: Fixed X



ELEVATION
Overall

2.5.2 Vertical boundary soil: Fixed Y



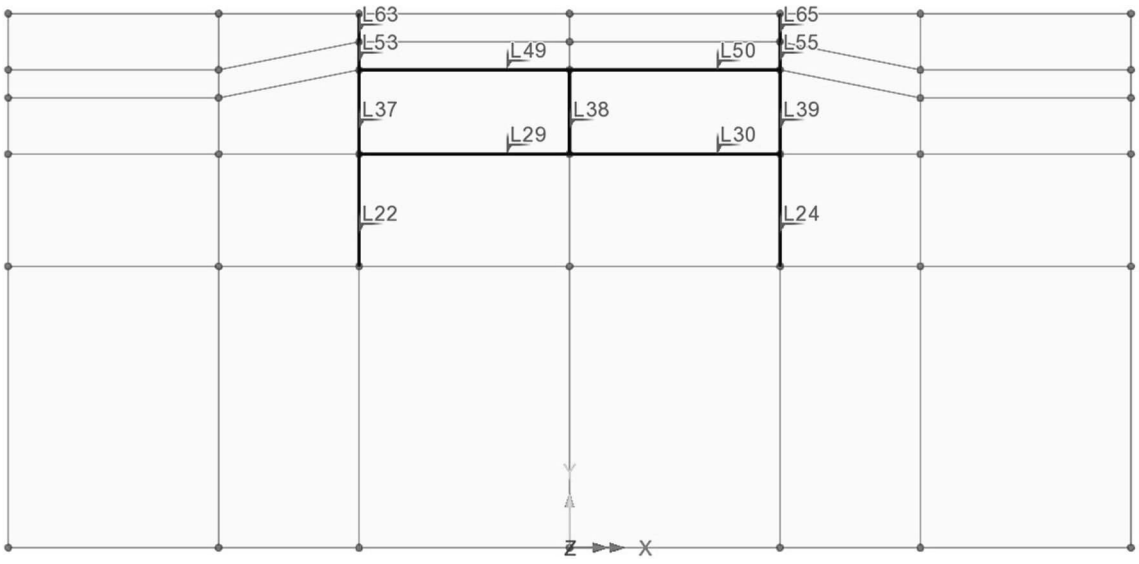
ELEVATION
Overall

2.6 MESH

2.6.1 Tunnel: Thick beam (BMI3)

Diaphragms seen below with two dimensional long structures retaining walls for which the plane strain assumption is appropriate.

Name	Element type	Element length	Order element
BMI3	Thick beam	2.0 m	Quadratic

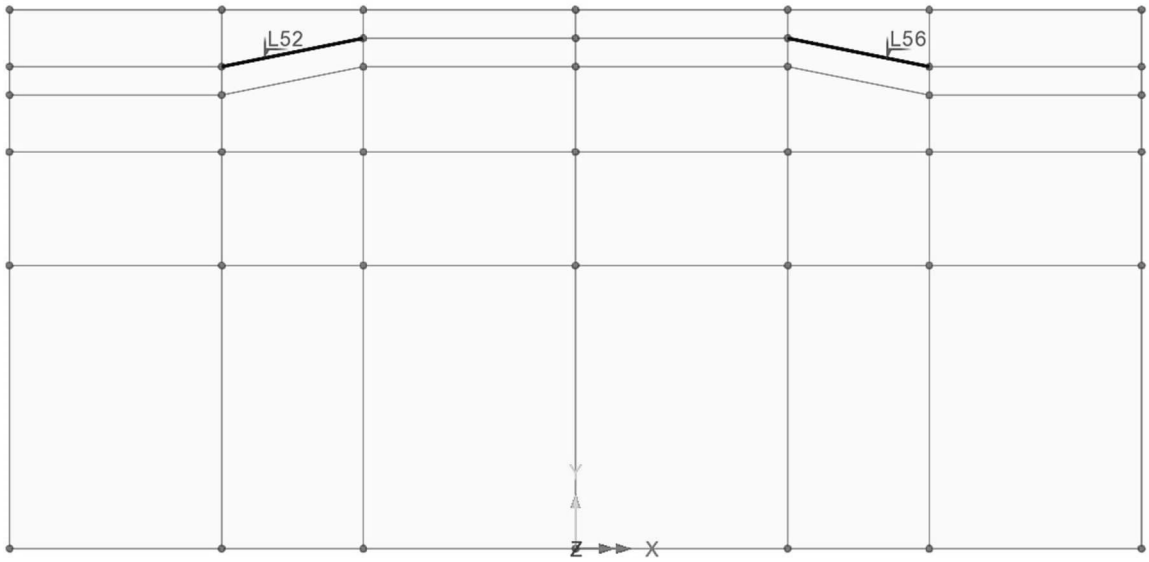


ELEVATION
Overall

2.6.2 Anchor rod: Bar element (BAR3)

Anchor rods are modelled as seen below. This element is connected to nodes in soil thus the rod is defined by same nodes as soil.

Name	Element type	Element length	Order element
BAR3	Bar	2.0 m	Quadratic



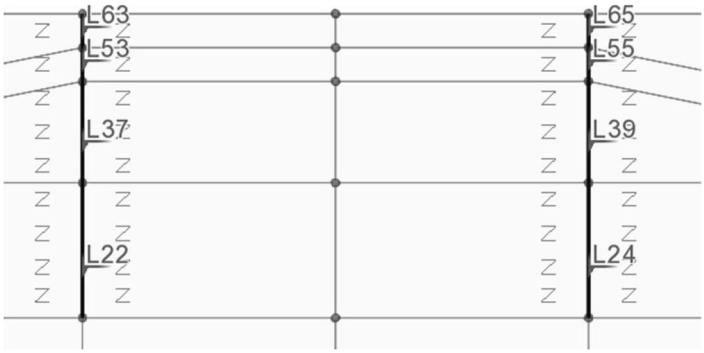
ELEVATION
Overall

2.6.3 Interface element between tunnel and soil: Interface plain strain (IPN6)

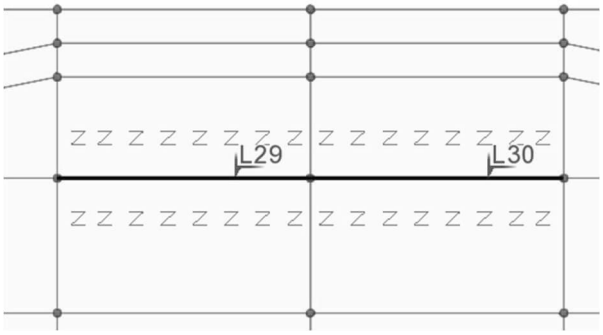
The interface between soil and wall is modelled as seen below.

The element is used for modelling standard Mohr-Coulomb friction contact in soil/structure interactions.

Name	Element type	Element length	Assignment type	Order element
IPN6	Interface: vertical	2 m	Single feature (automatic)	Quadratic
IPN6	Interface: horizontal	2 m	Single feature (automatic)	Quadratic



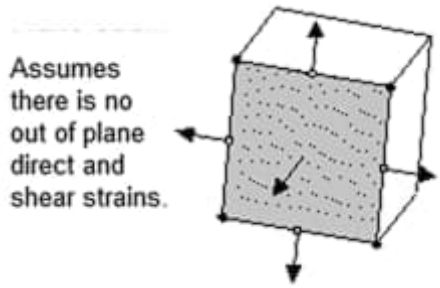
ELEVATION
Interface: vertical



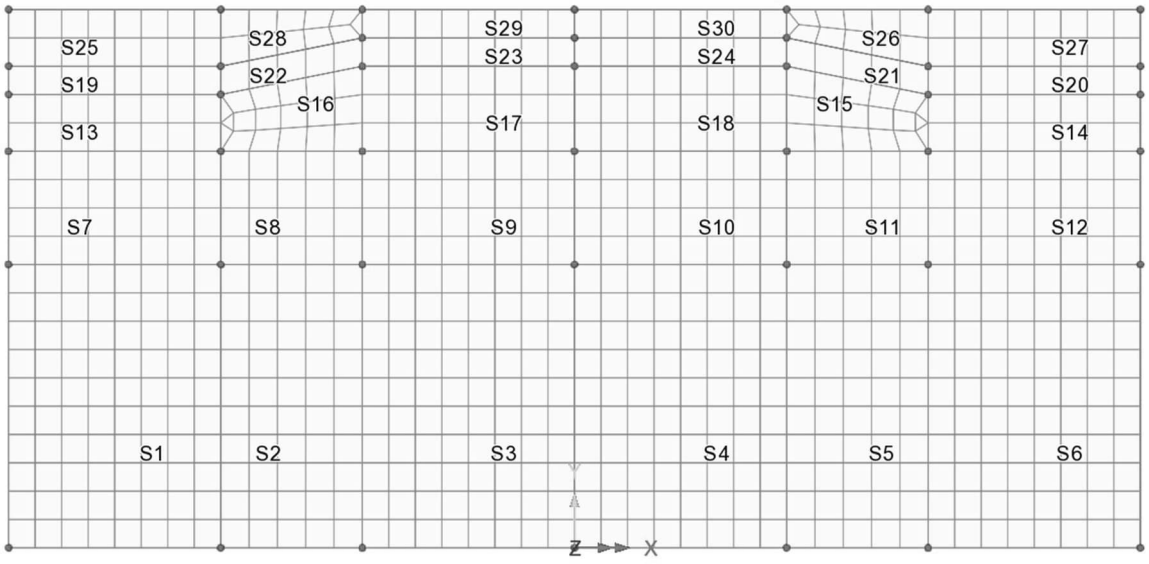
ELEVATION
Interface: horizontal

2.6.4 Soil: plain strain surface elements (QPN8)

Soil is modelled using surface elements as seen below. The element type plain strain.



Name	Element type	Element size	Order element	Mesh
QPN8	Plain strain surfacde	Automatic	Quadratic	Regular



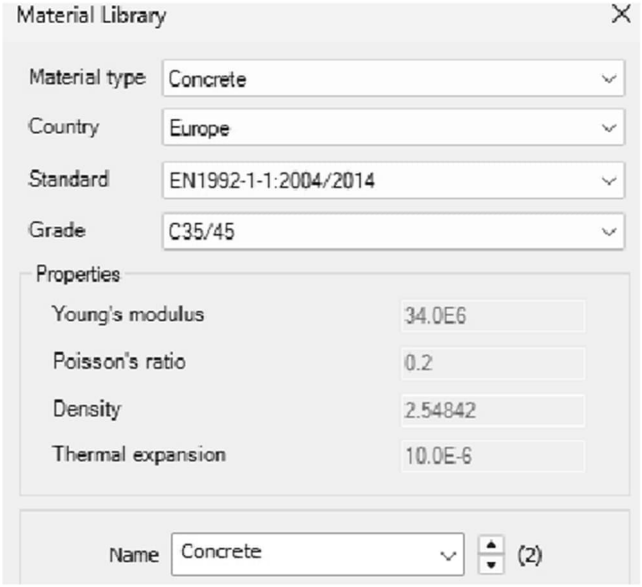
ELEVATION
Overall

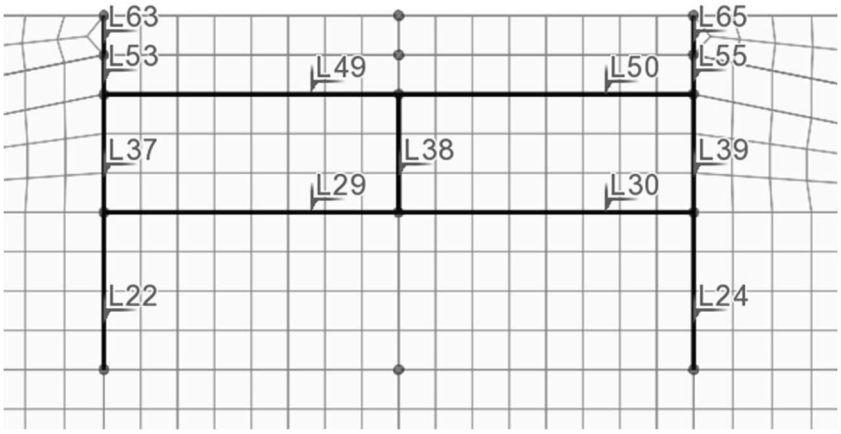
2.7 MATERIAL

2.7.1 Linear elastic material: tunnel & anchors

Tunnel:

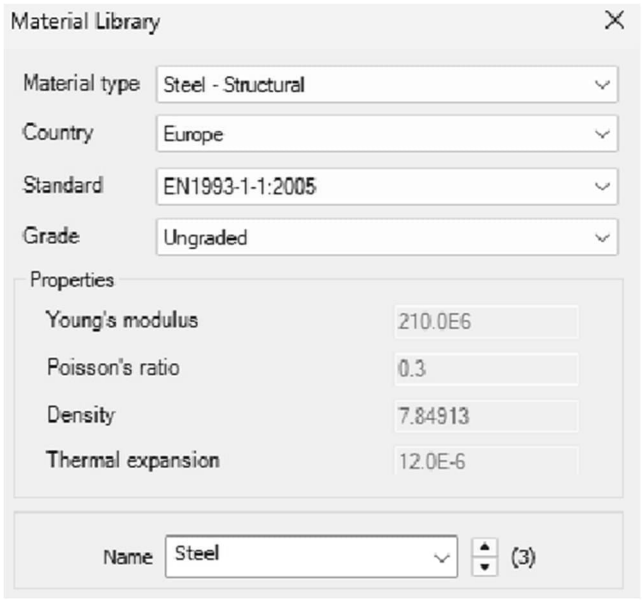
The retaining wall is assumed to be isotropic concrete C40/50.

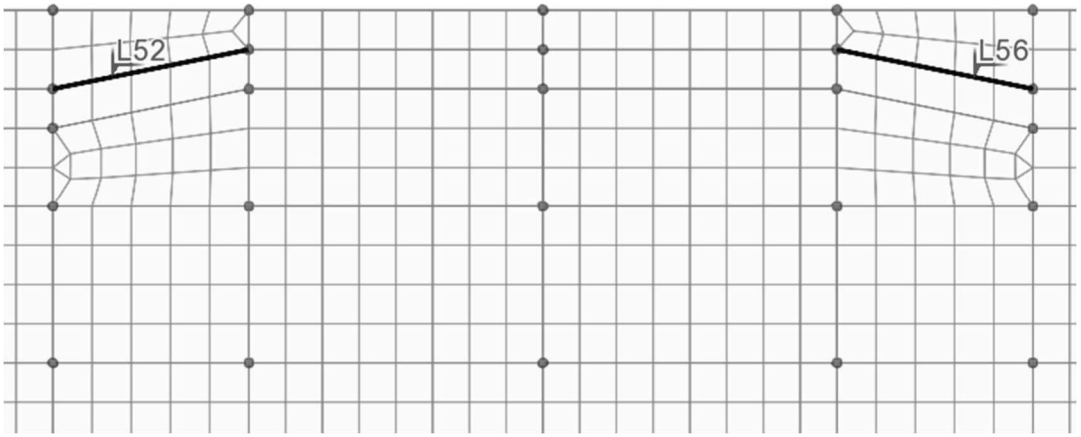




ELEVATION
Detail

Anchors:





ELEVATION
Detail

2.7.2 Nonlinear material: soil

Soil is modelled modified Mohr-Coulomb (called modell 65).

The above mentioned material assumes:

- Perfectly plastic after the failure criterion is reached.
- Yielding is governed by the Mohr–Coulomb failure formula, which relates shear strength as seeen below.

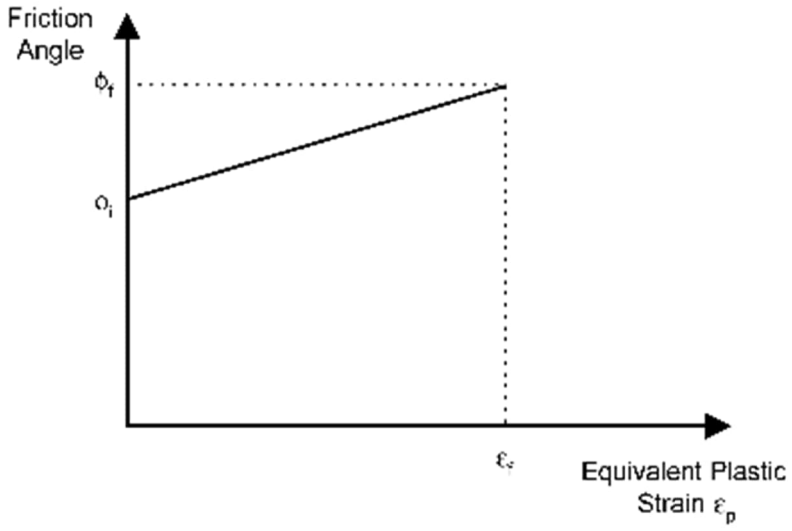
$$\tau_f = c + \sigma_n \tan\phi$$

$$\sigma_1 = \sigma_3 \frac{1+\sin\phi}{1-\sin\phi} + \frac{2c\cos\phi}{1-\sin\phi}$$

where:

σ_1 = major principal stress,

σ_3 = minor principal stress.



Definition	Parameter	Soil
Elastic	Young's Modulus	**8,000** kPa
Elastic	Poisson's ratio	**0.3**
Elastic	Mass density (Fully Saturated)	**2.0**
Plastic	Friction angle	**30.0°**
Plastic	Dilation angle	**0 °**
Plastic	Cohesion	**1.0** kPa
Plastic (Rankine)	Tensile cut-off stress	**0** kPa
Plastic (Rankine)	Compressive cut-off stress	**1E30** kPa
Plastic (Rankine)	Damping factor	**0**
Plastic (Rankine)	Coefficient of lateral earth pressure K_0	**0.5**

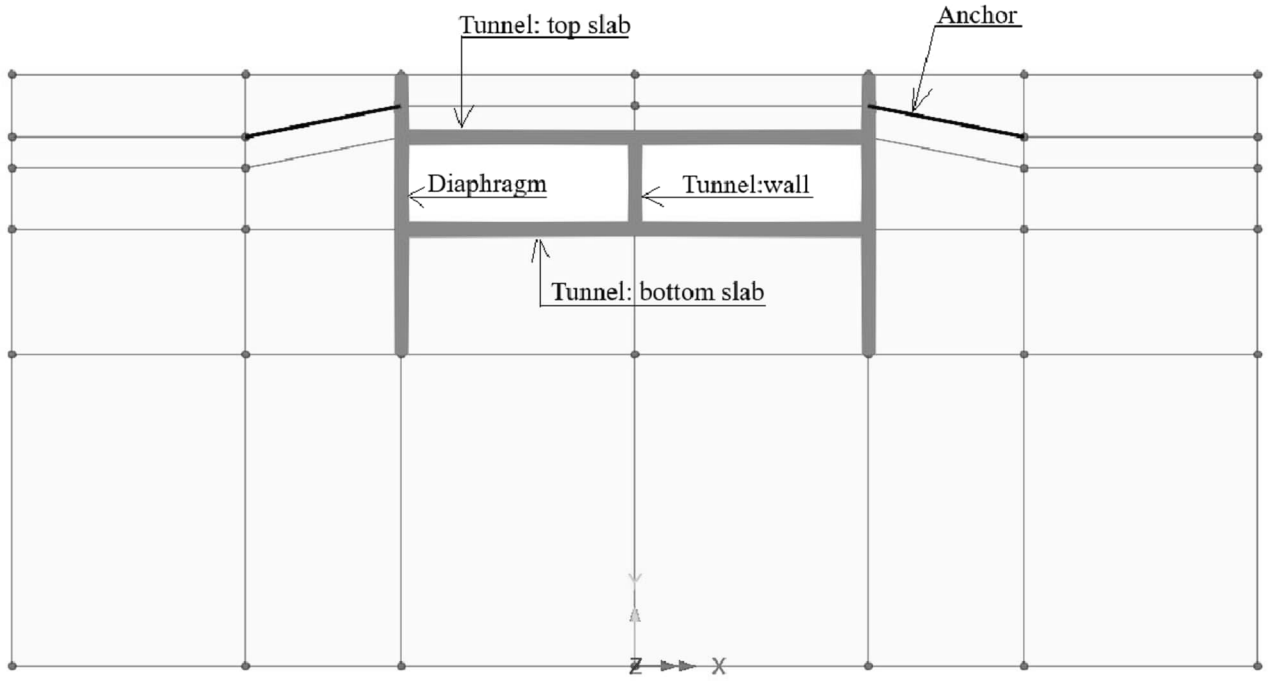
2.7.3 Nonlinear joint material between retaining tunnel and soil

The tangential slip surface is defined as seen below.

Defintion	Parameter	Tunnel/soil
Soil structure interface (tangential slip)	Angle of friction	**20°**
Soil structure interface (tangential slip)	Dilatency angle	0
Soil structure interface (tangential slip)	Cohesion	**0** kPa

2.8 CROSS SECTIONS

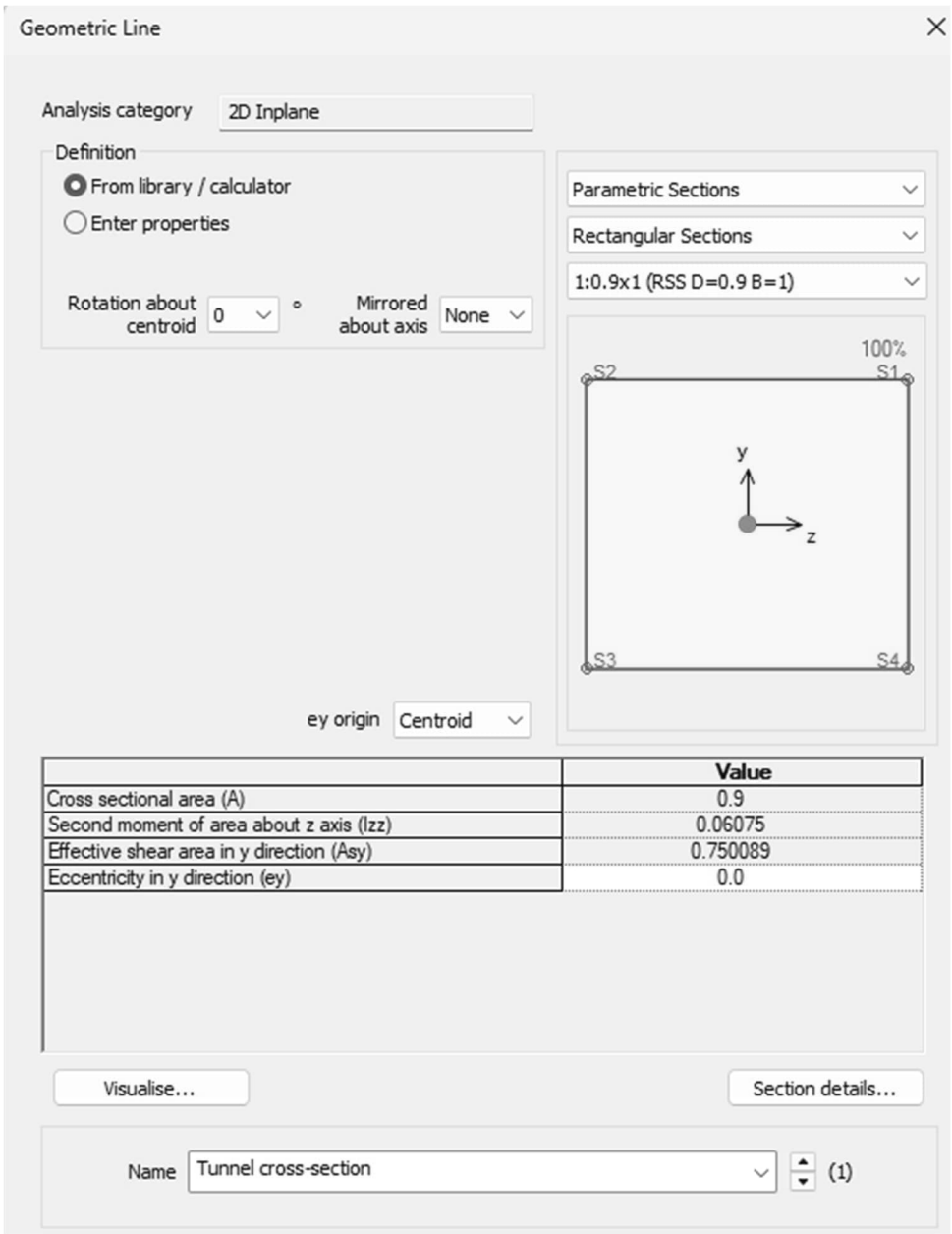
Defined cross section properties.



ELEVATION
Detail

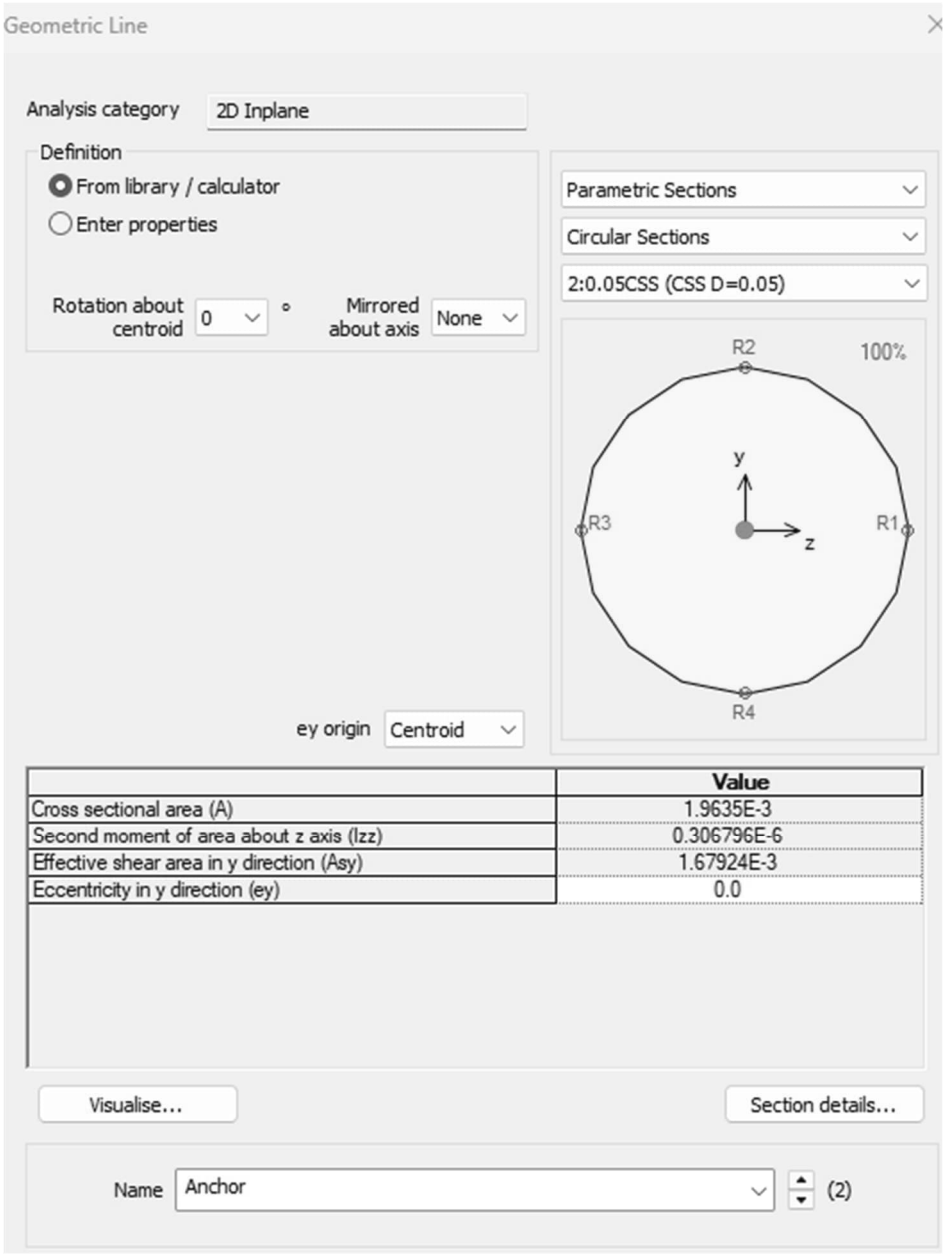
2.8.1 Tunnel

Same tunnel section is used for all parts including diaphragm.



2.8.2 Rod anchor

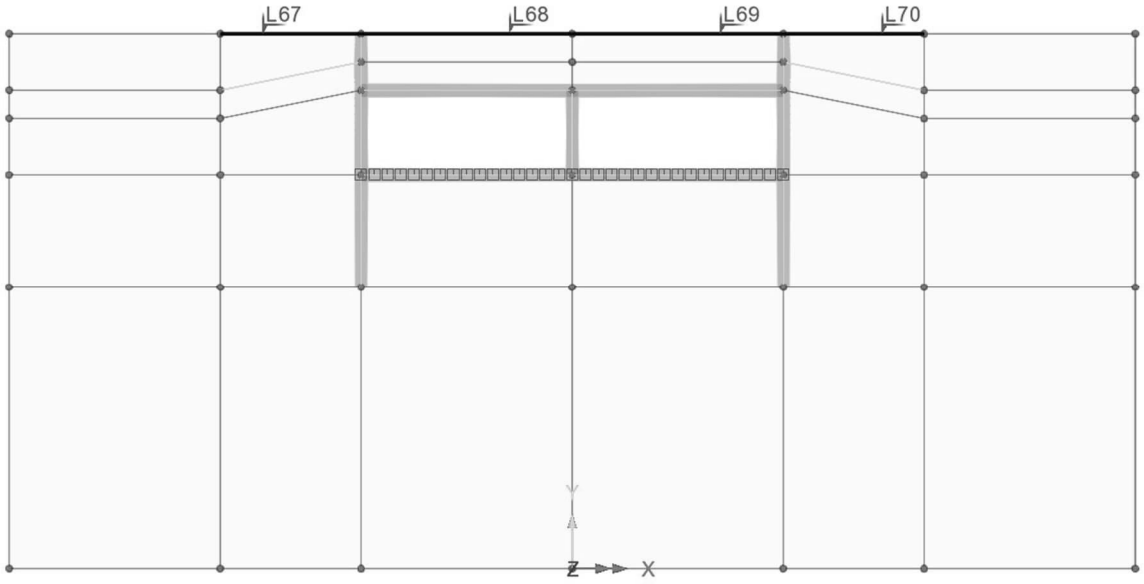
Rod area is adapted to c/c 2.5 m of anchor rods.



2.9 SEARCH AREA

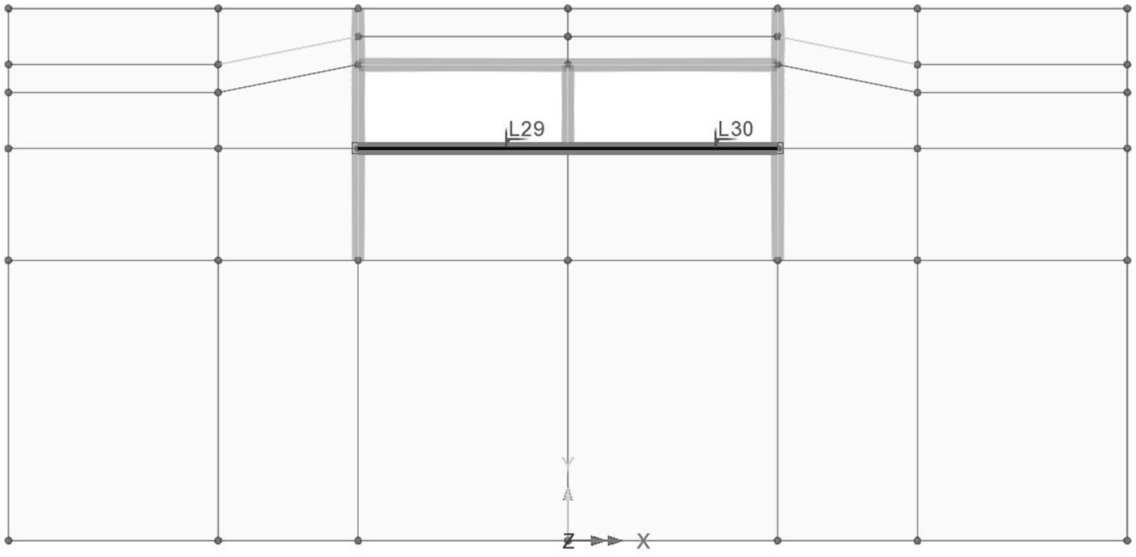
Discrete load can be applied to structure as geometrical load areas. The load areas are termed “Search Area”.

2.9.1 Search area: Fictive beam



ELEVATION

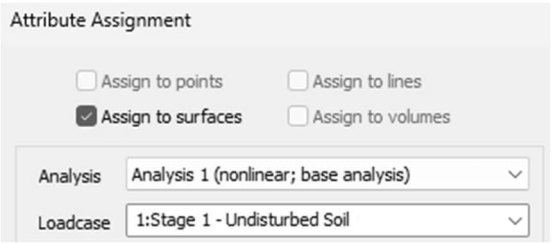
2.9.2 Search area: Bottom slab

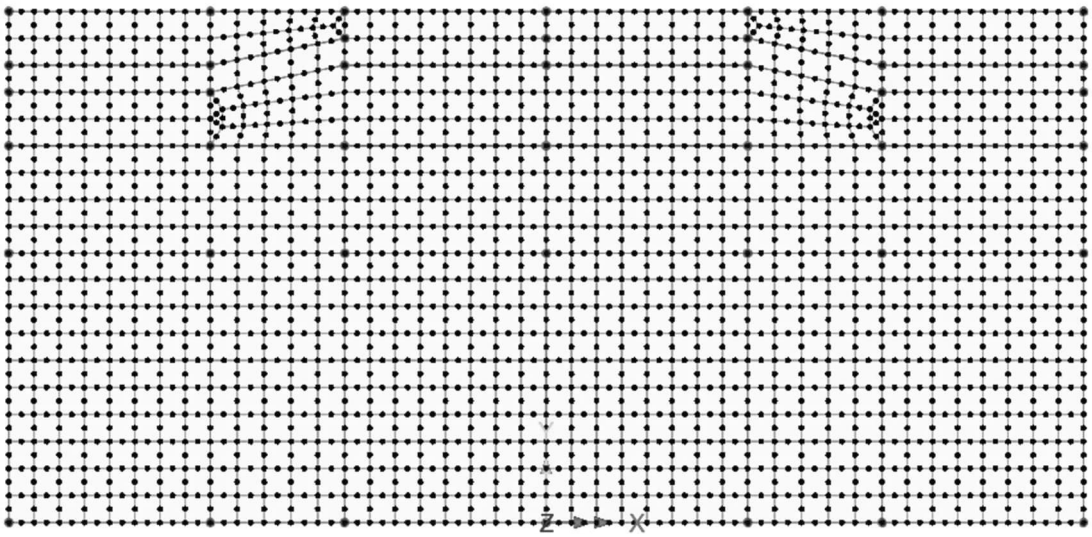


ELEVATION

2.10 RESET DEFORMATIONS

All node deformations at stage 1 are set to zero.



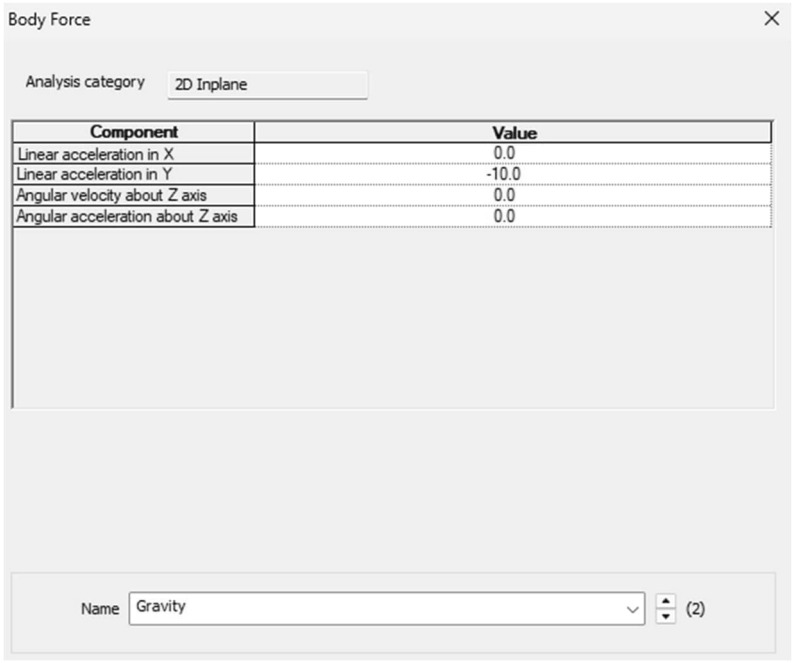


ELEVATION
Overall

3. LOADS

3.1 Soil weight (Gravity)

Soil weight is determined material density.



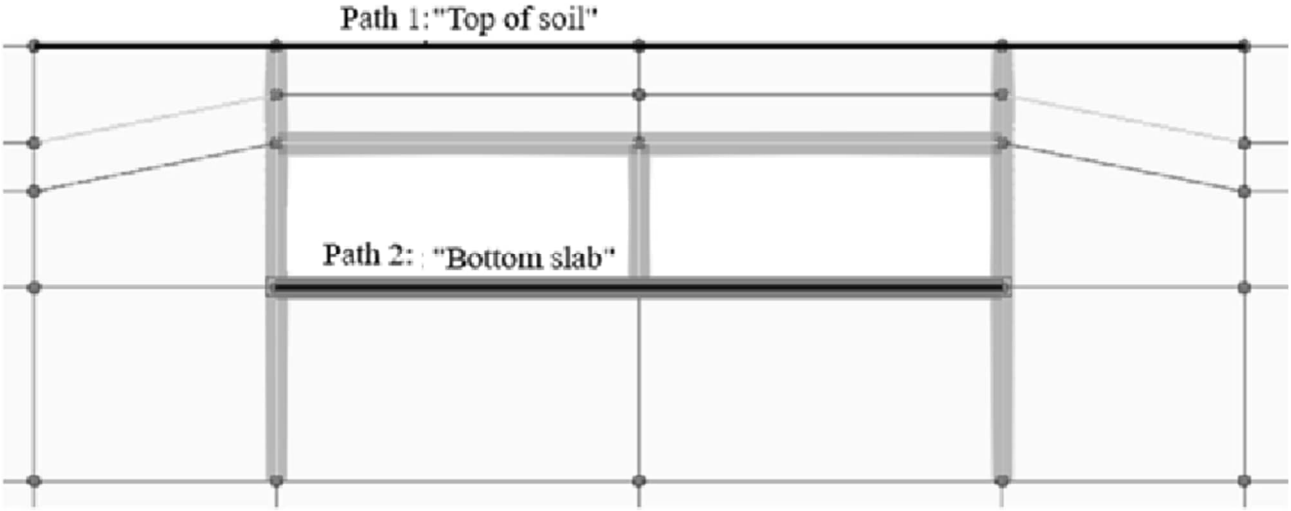
3.2 Traffic load – LM 1

Traffic i applied at two level, “top of soil” and “bottom slab”.

Since soil is nonlinear analysing moving traffic load is difficult. Another difficulty is principle of load superstition which does not apply.

To verify nonlinear traffic load a linear analysis is also conducted.

Branch #	Level at road	Soil	LC
2	"Top of soil"	Linear	Branch 2: LM 1
3	"Bottom slab"	Linear	Branch 3: LM 1
4	"Top of soil"	Nonlinear	Branch 4: LM 1
5	"Bottom slab"	Nonlinear	Branch 5: LM 1



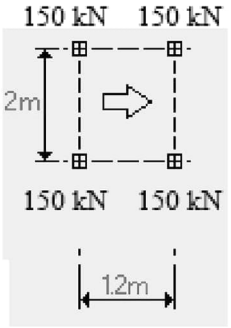
ELEVATION

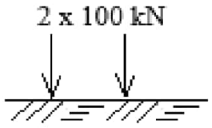
3.2.1 Road “Top of soil”

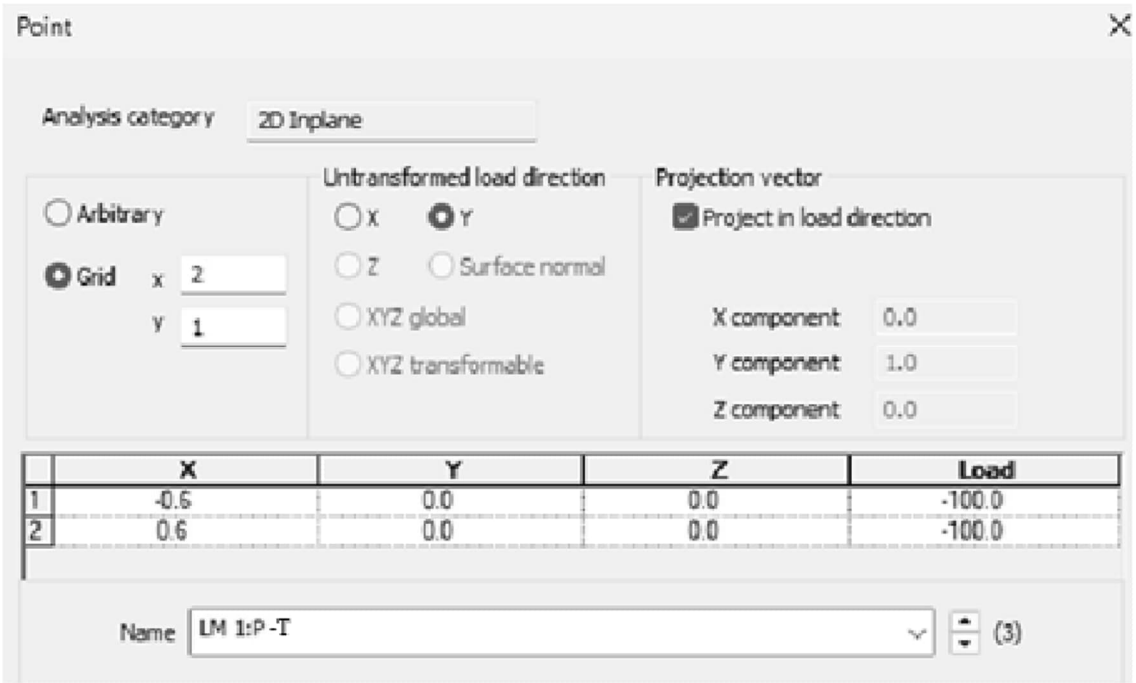
3.2.1.1 Traffic load

Axle load (LM 1:P-T):

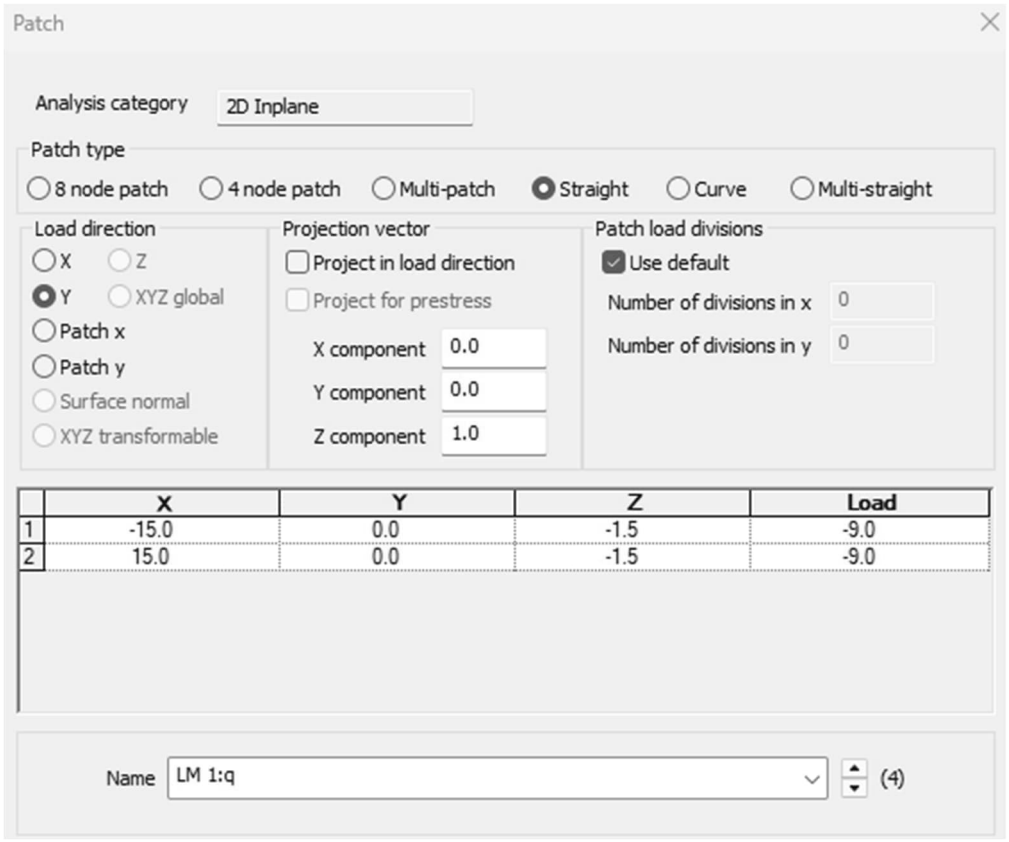
Distribution width 3.0 m I assumed in transversal traffic direction.



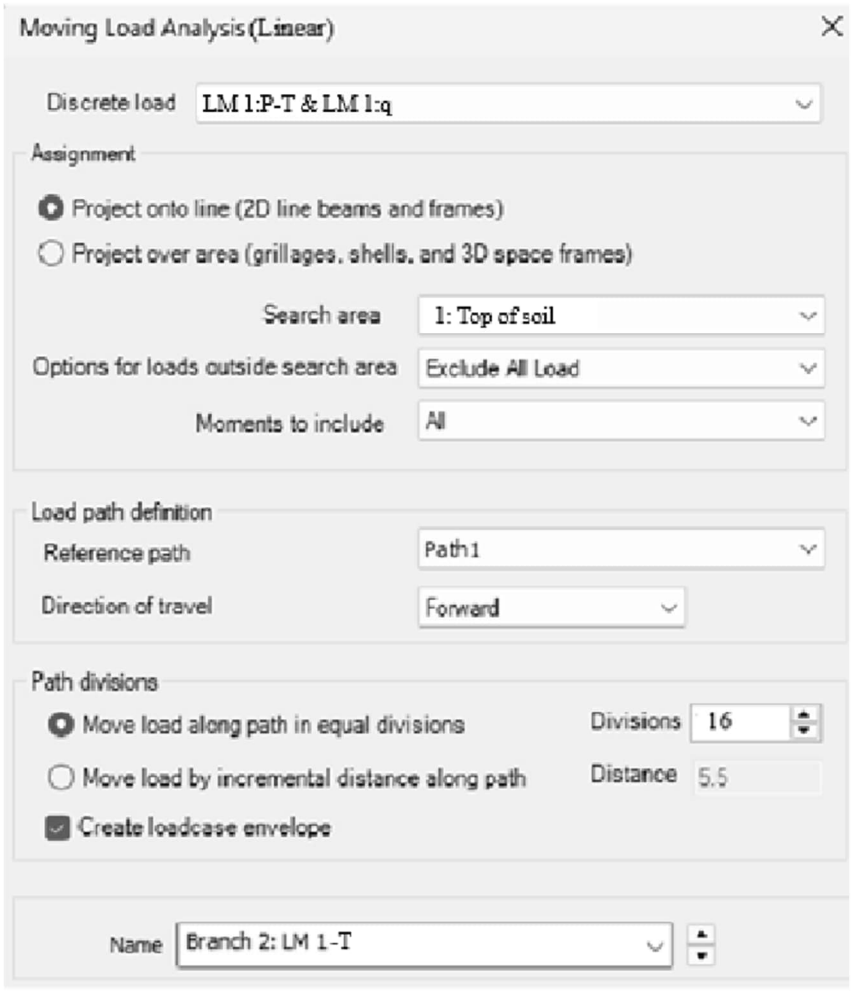




Surface load (LM 1:q):



3.2.1.2 Linear analysis



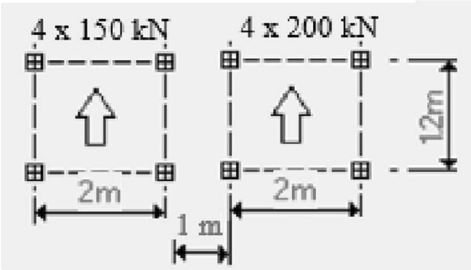
3.2.1.3 Nonlinear analysis

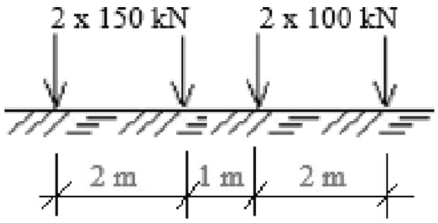
3.2.2 Road “Bottom slab”

3.2.2.1 Traffic load

Axle load (LM 1:P-B):

Distribution width 2.0 m I assumed in transversal traffic direction.





Point

Analysis category: 2D Inplane

Arbitrary
Grid x 4
y 1

Untransformed load direction
X Y
Z Surface normal
XYZ global
XYZ transformable

Projection vector
Project in load direction
X component 0.0
Y component 1.0
Z component 0.0

	X	Y	Z	Load
1	-2.5	0.0	0.0	-150.0
2	-0.5	0.0	0.0	-150.0
3	0.5	0.0	0.0	-100.0
4	2.5	0.0	0.0	-100.0

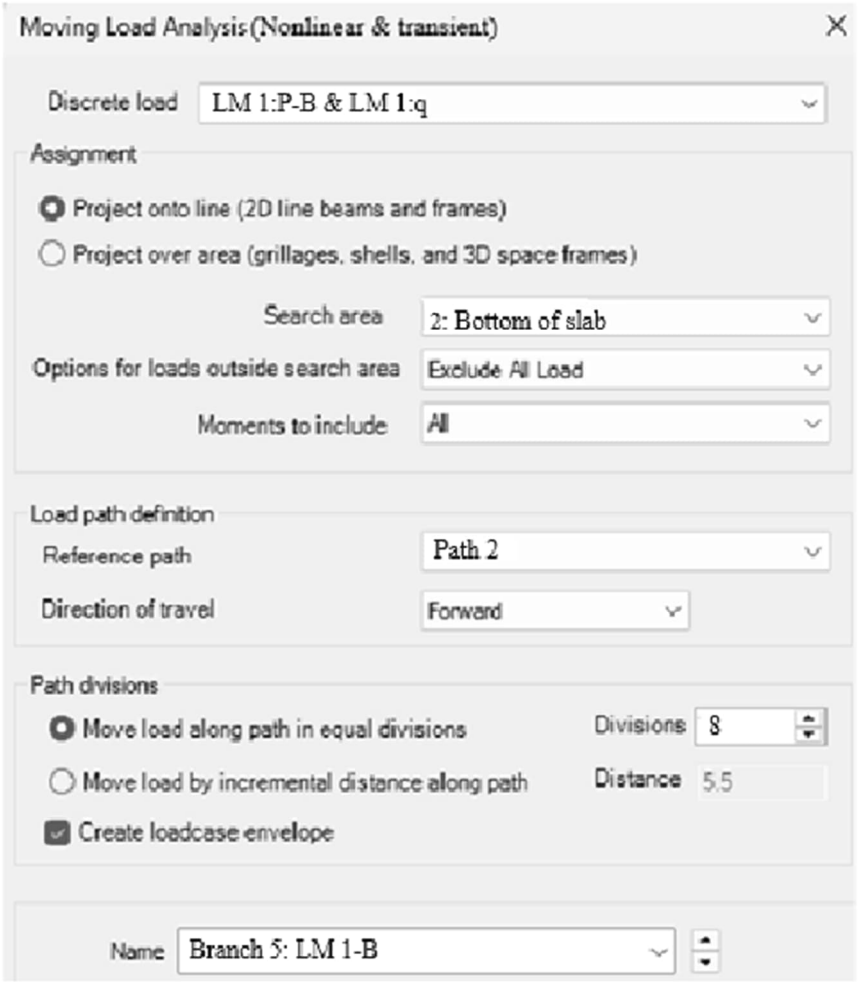
Name: LM 1:P-B (5)

Surface load (LM 1:q):

See page 37.

3.2.2.2 Linear analysis

3.2.2.3 Nonlinear analysis



4. RESULTS (FEM-program)

Summary soil stress (min SY):

Stage #	LC name	Min Sy	Branch	Type
1	Before excavation	-671	-	Nonlinear
2	Wall installation	-684	-	Nonlinear
3	Excavation:1	-672	-	Nonlinear
4	Install anchor:1	-671	-	Nonlinear
5	Excavation:2	-657	-	Nonlinear
6	Construct tunnel	-666	-	Nonlinear
7	Filling at top slab	-667	-	Nonlinear
"	Traffic & gravity	-684	Branch 2	Nonlinear
"	Traffic (linear)	-137	Branch 4	Nonlinear
"	Traffic (nonlinear)	-145	Branch 2	Smart combination
-	-	kPa	-	-

Geotechnical safety factor (SF):

Stage #	LC name	SF	Branch	Type
1	Before excavation	-	-	Nonlinear
2	Wall installation	-	-	Nonlinear
3	Excavation:1	-	-	Nonlinear
4	Install anchor:1	-	-	Nonlinear
5	Excavation:2	1.42	-	Nonlinear
6	Construct tunnel	-	-	Nonlinear
7	Filling at top slab	-	-	Nonlinear

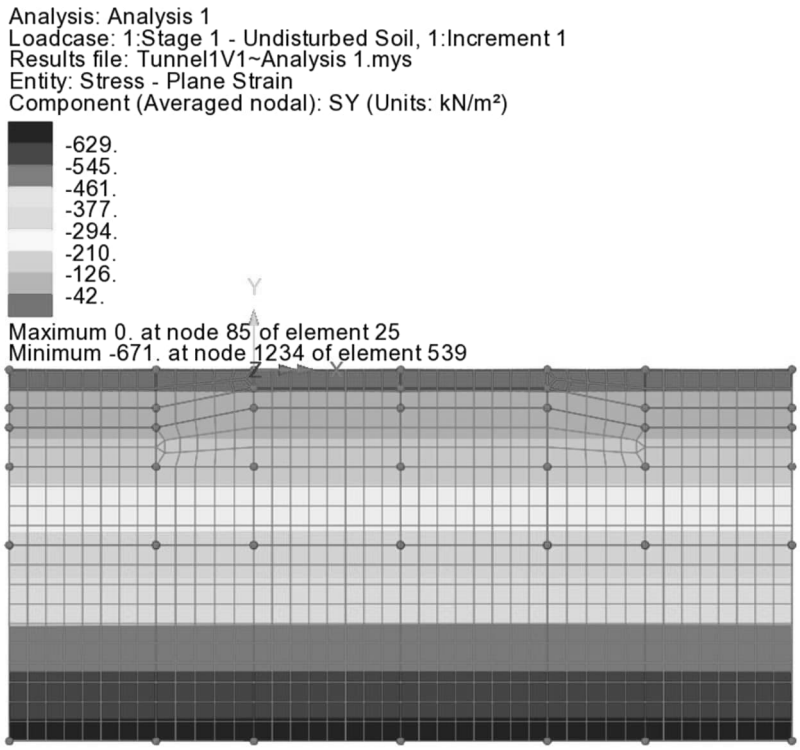
Summary deformations (max RSLT):

Stage #	LC name	max RSLT	Branch	Type
1	Before excavation	0	-	Nonlinear
2	Wall installation	0	-	Nonlinear
3	Excavation:1	14	-	Nonlinear
4	Install anchor:1	14	-	Nonlinear
5	Excavation:2	77	-	Nonlinear
6	Construct tunnel	61	-	Nonlinear
7	Filling at top slab	43	-	Nonlinear
"	Traffic (linear)	12	Branch 4	Nonlinear
"	Traffic (nonlinear)	69	Branch 2	Smart combination
-	-	mm	-	-

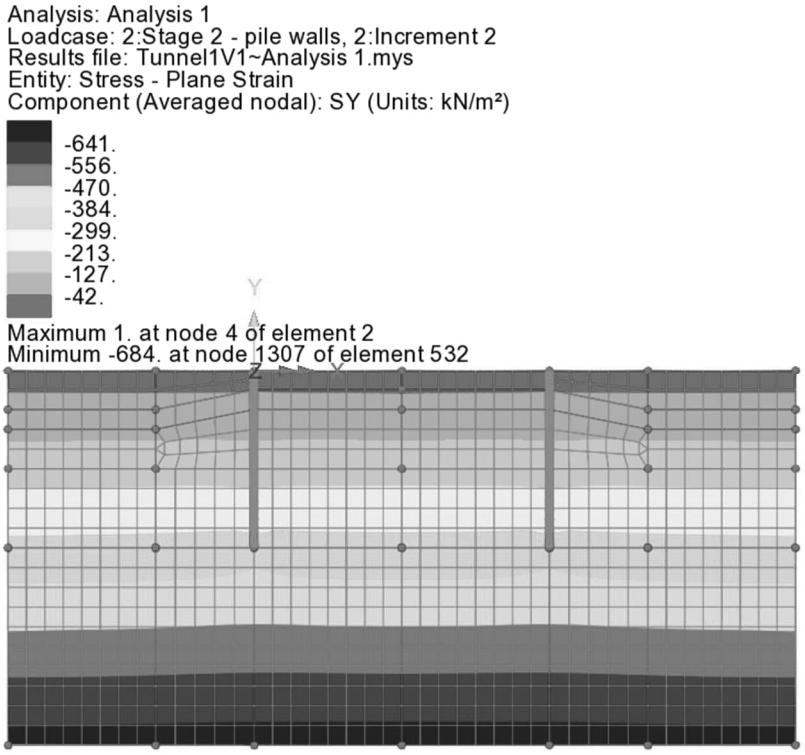
Summary forces tunnel (max/min My):

Stage #	LC name	Max My	Min My	Branch	Type
1	Before excavation	-	-	-	Nonlinear
2	Wall installation	0	0	-	Nonlinear
3	Excavation:1	42	-46	-	Nonlinear
4	Install anchor:1	42	-46	-	Nonlinear
5	Excavation:2	245	-366	-	Nonlinear
6	Construct tunnel	628	-686	-	Nonlinear
7	Filling at top slab	1953	-2125	-	Nonlinear
"	Traffic & gravity	2219	-2620	Branch 2	Nonlinear
"	Traffic (linear)	261	-258	Branch 4	Nonlinear
"	Traffic (nonlinear)	266	-495	Branch 2	Smart combination
-	-	kNm/m	kNm/m	-	-

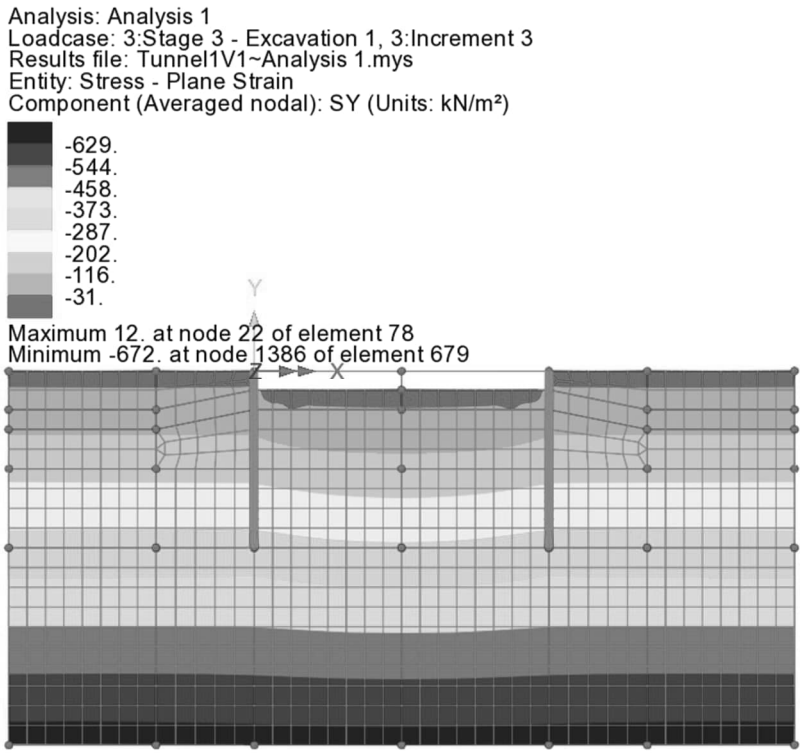
4.1 SOIL STRESS GLOBAY Y-DIRECTION (SY)



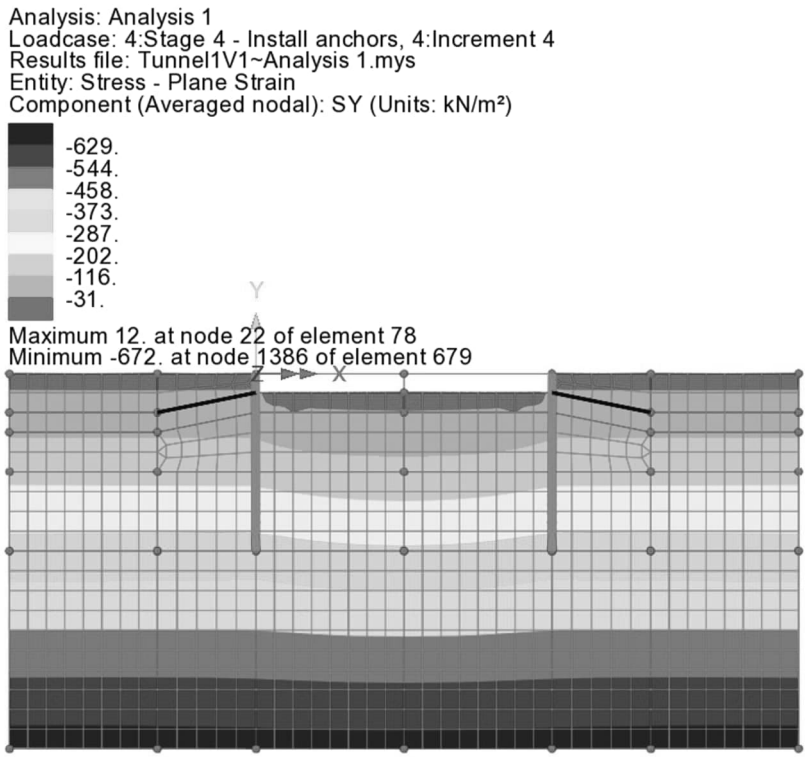
→ min Sy = -671 kPa



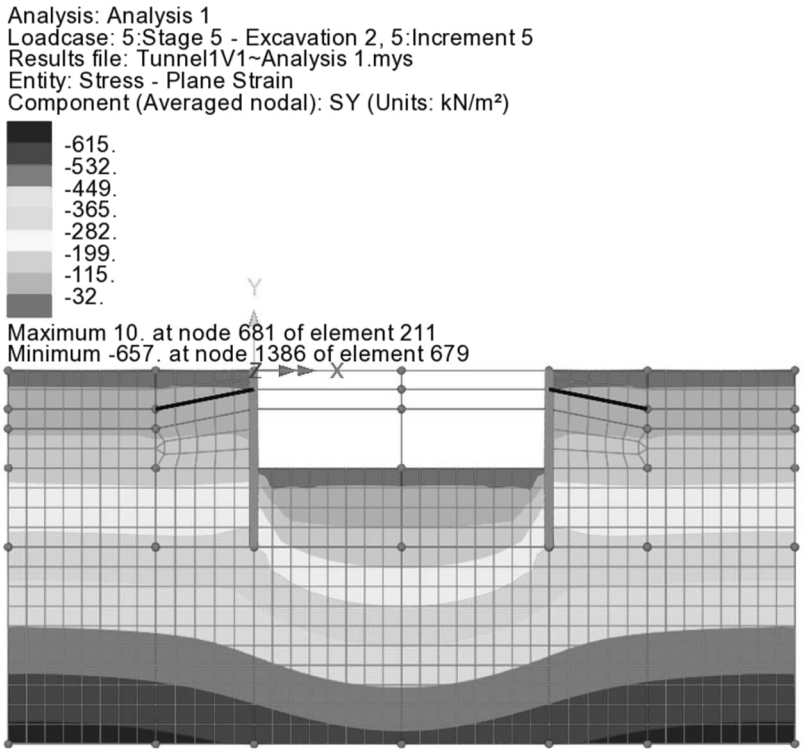
→ min Sy = -684 kPa



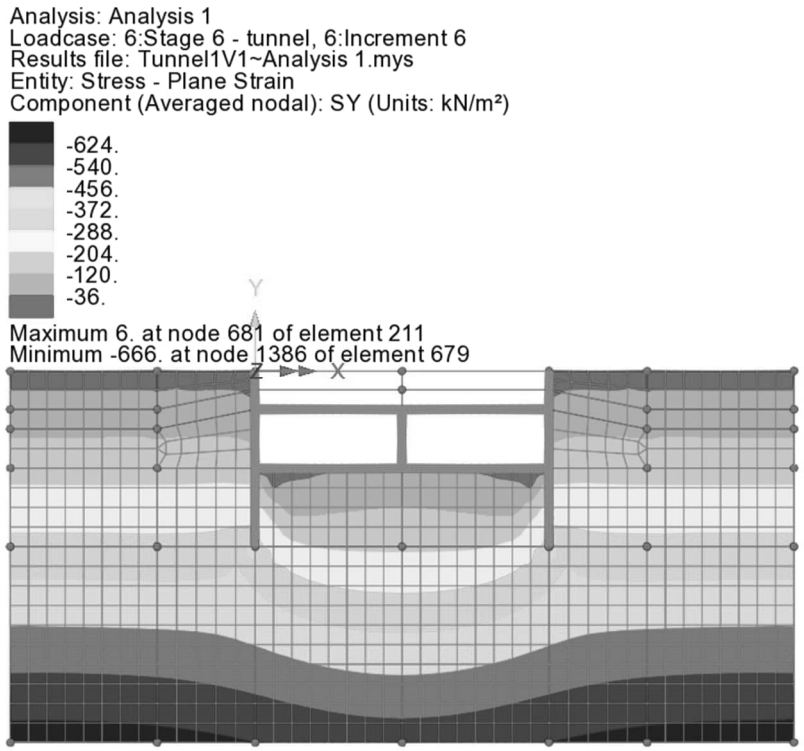
→ min Sy = -672 kPa



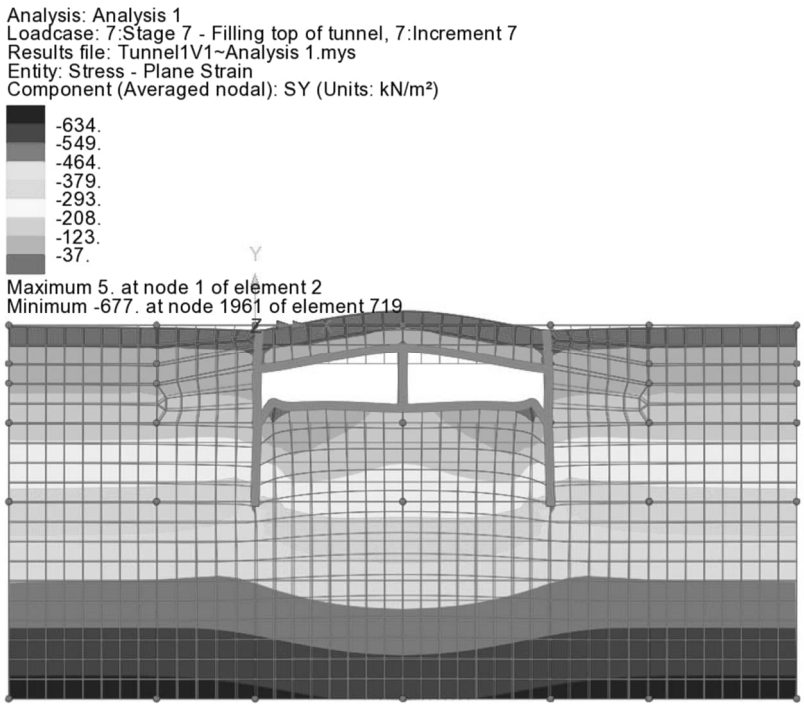
→ min Sy = -671 kPa



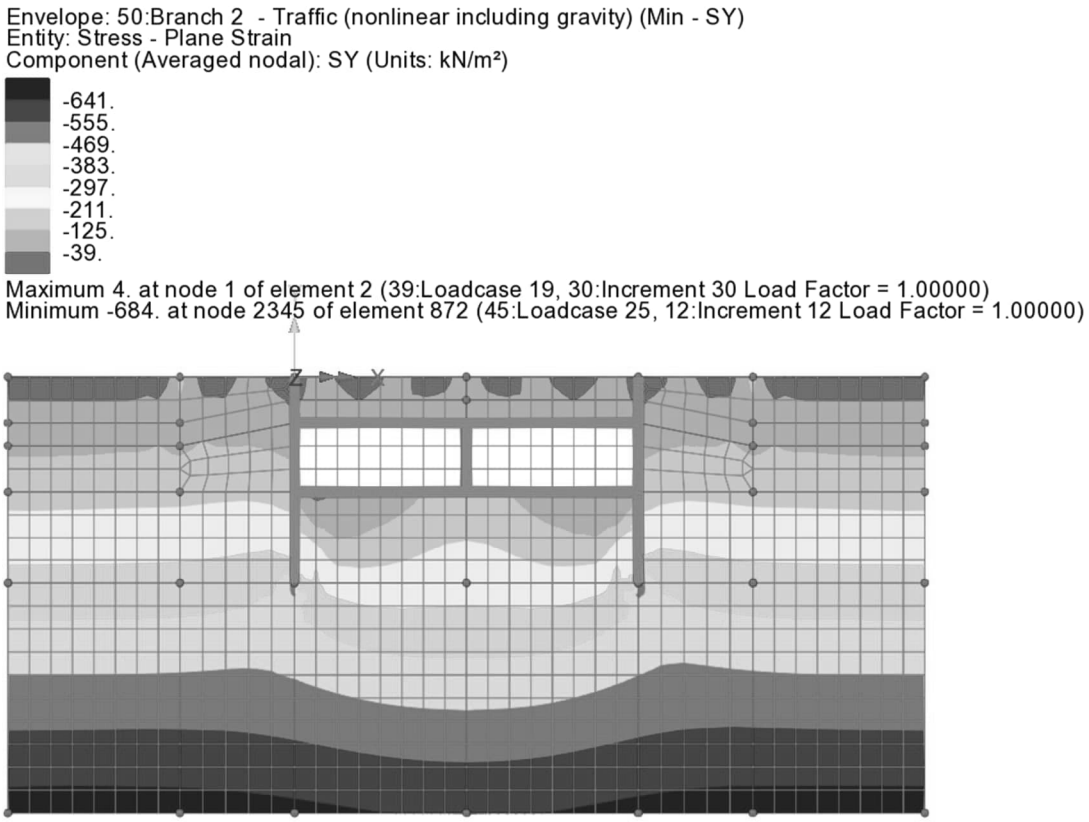
→ min Sy = -657 kPa



→ min Sy = -666 kPa



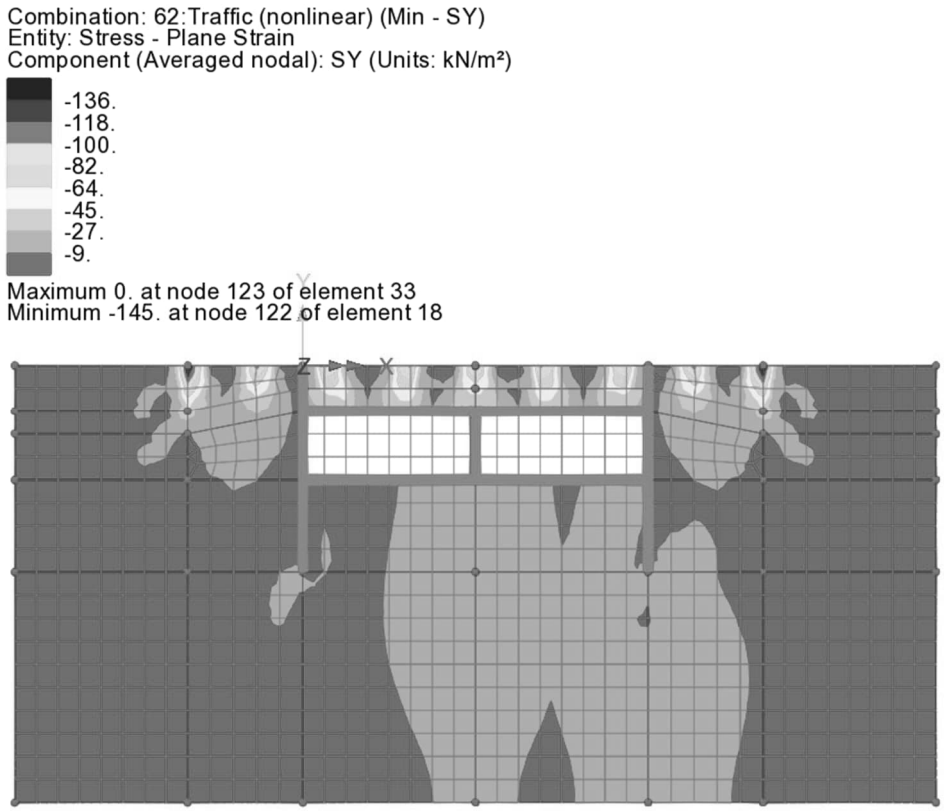
→ min Sy = -667 kPa



→ min Sy = -684 kPa

Remark

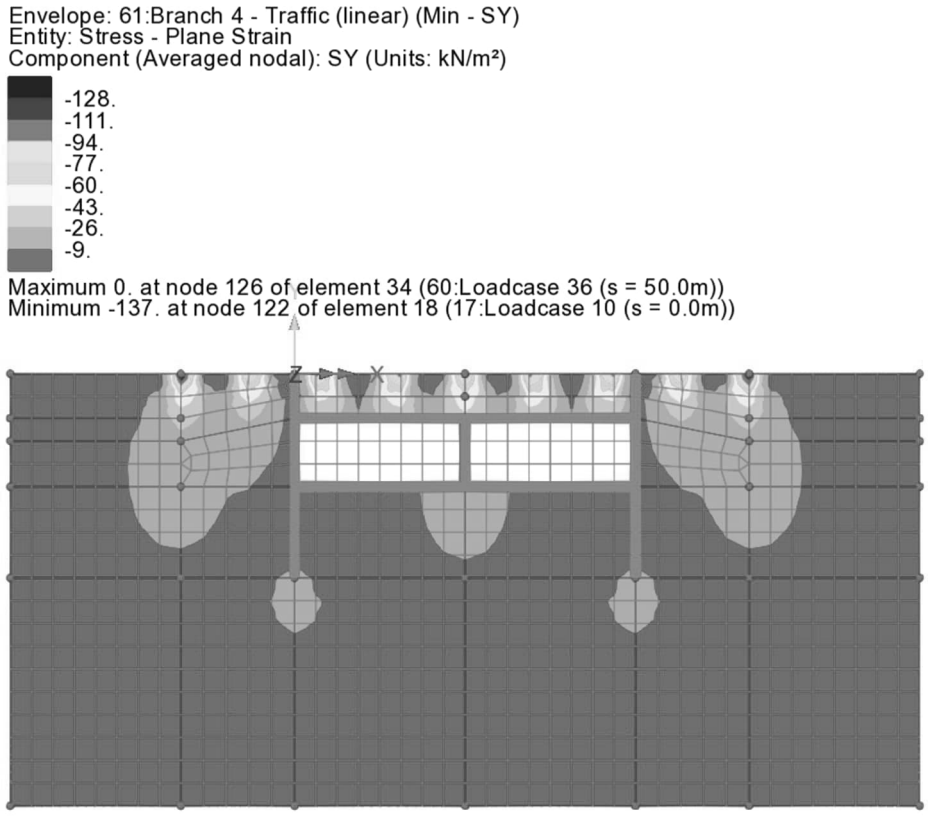
Envelope above contain traffic load (nonlinear) including gravity (soil + tunnel).



→ min Sy = -145 kPa

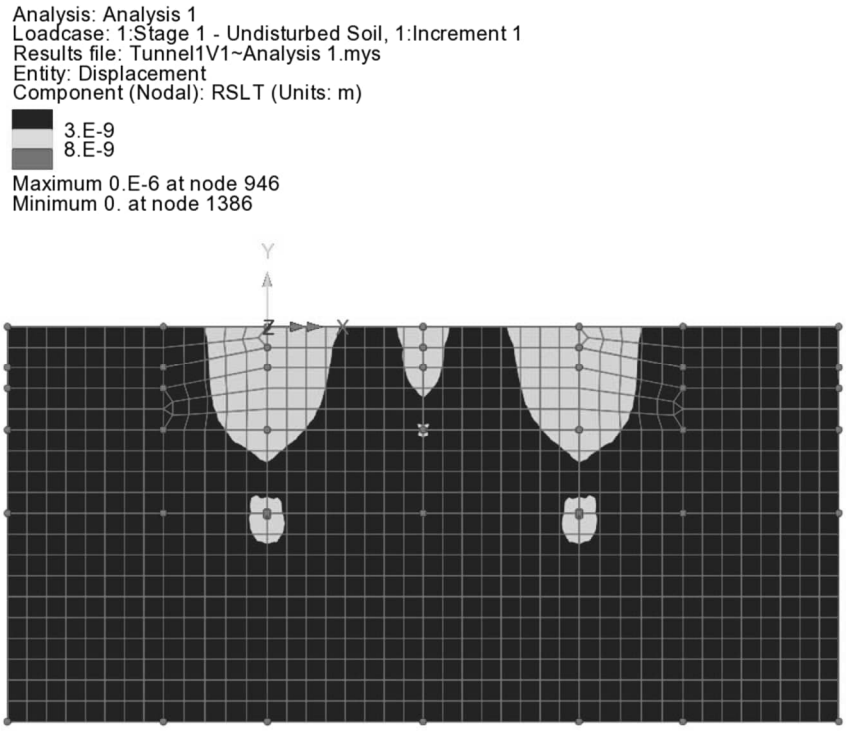
Remark

Envelope above contain traffic load (nonlinear) excluding gravity. Achieved by subtracting LC 7 from envelope 50.

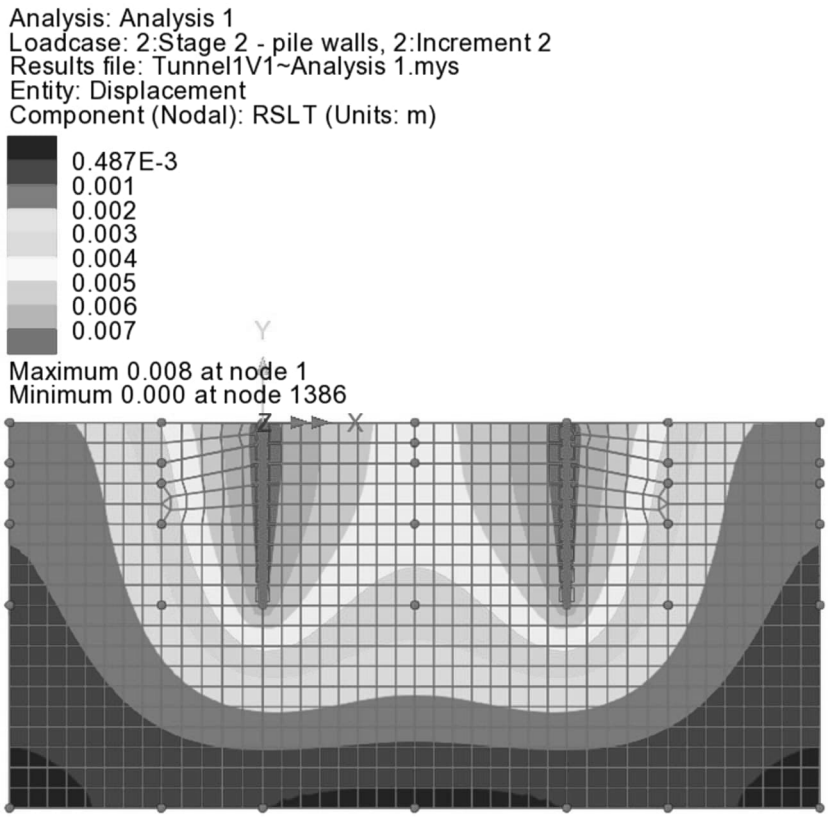


→ min Sy = -137 kPa

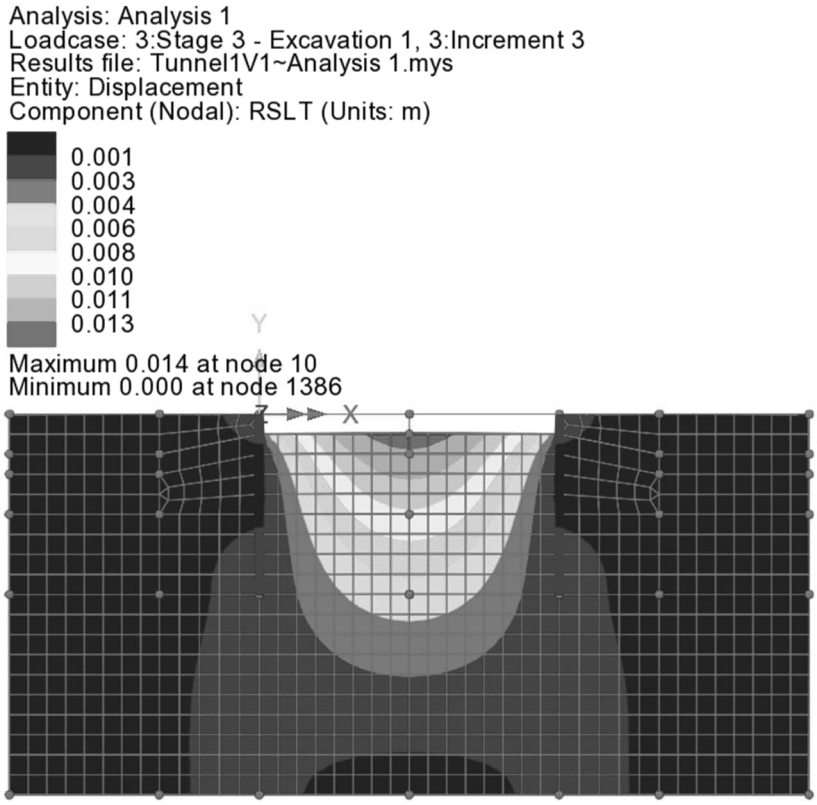
4.2 SOIL DEFORMATIONS



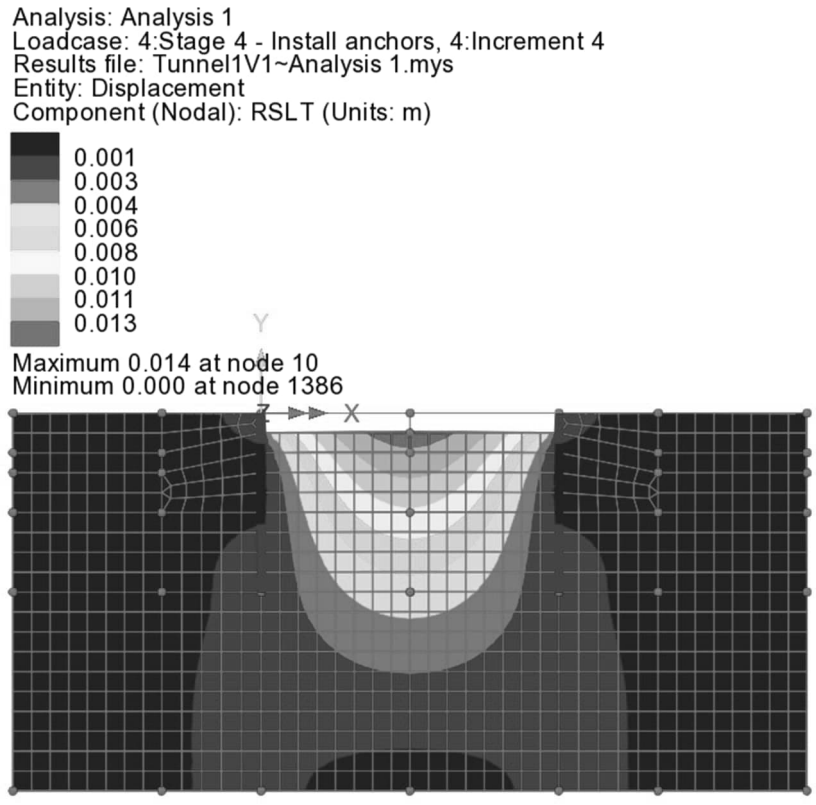
→ max RSLT = 0 mm



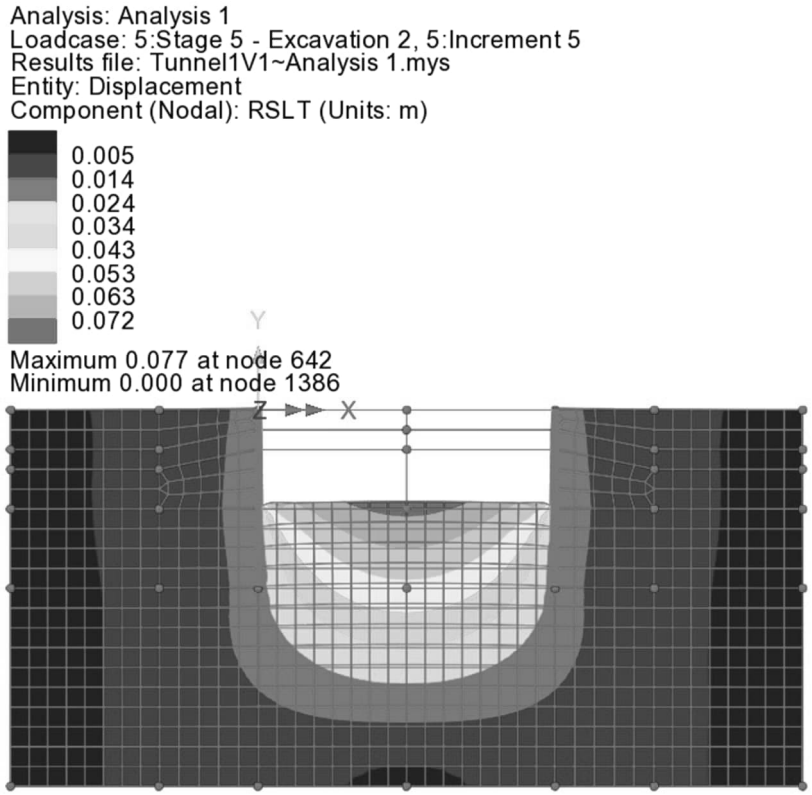
→ max RSLT = 0 mm



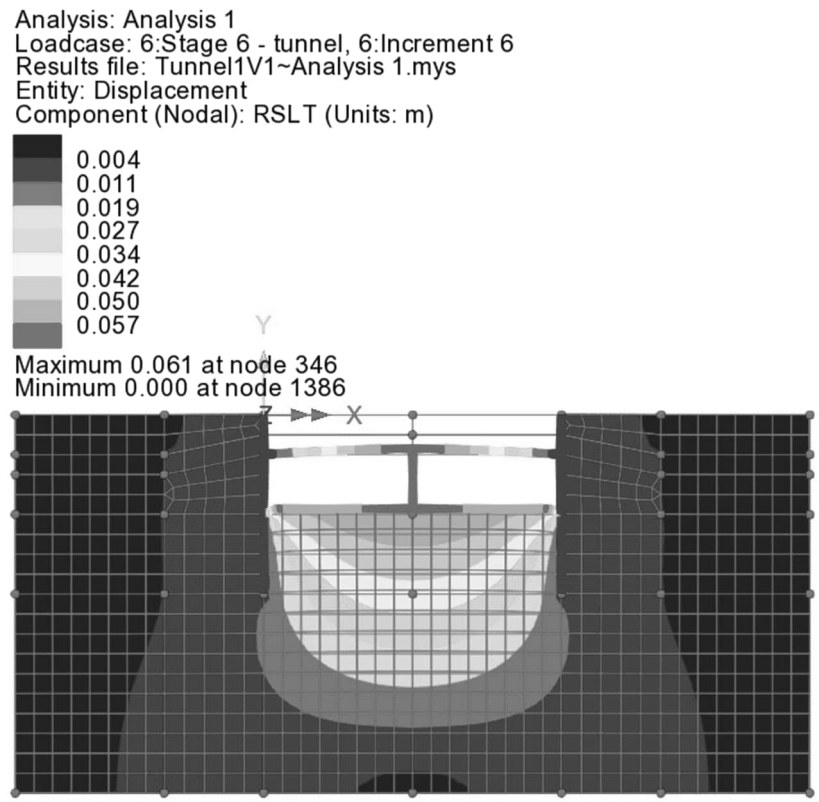
→ max RSLT = 14 mm



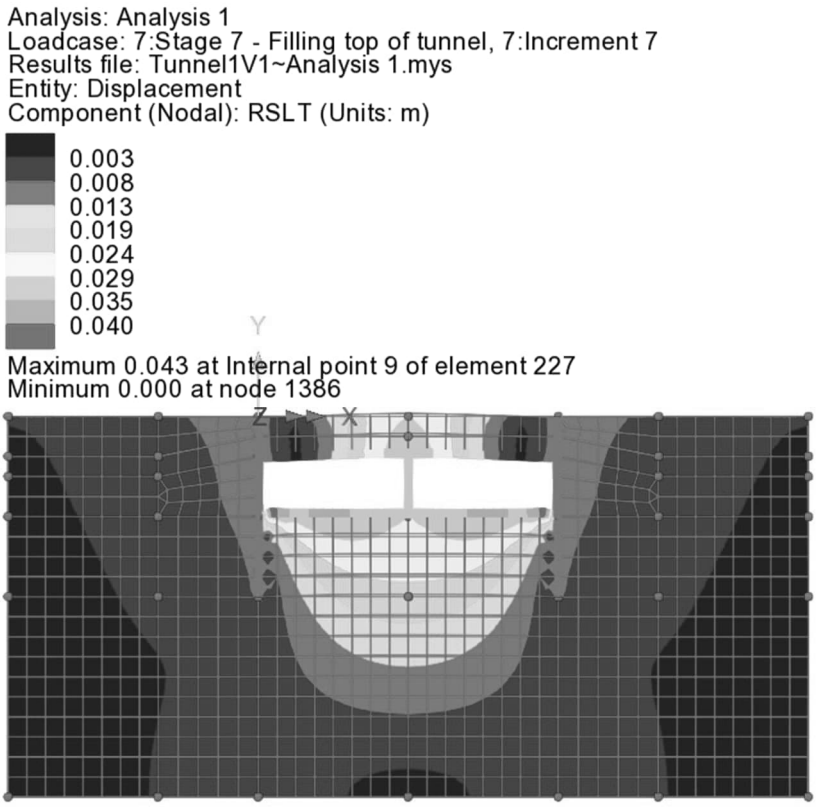
→ max RSLT = 14 mm



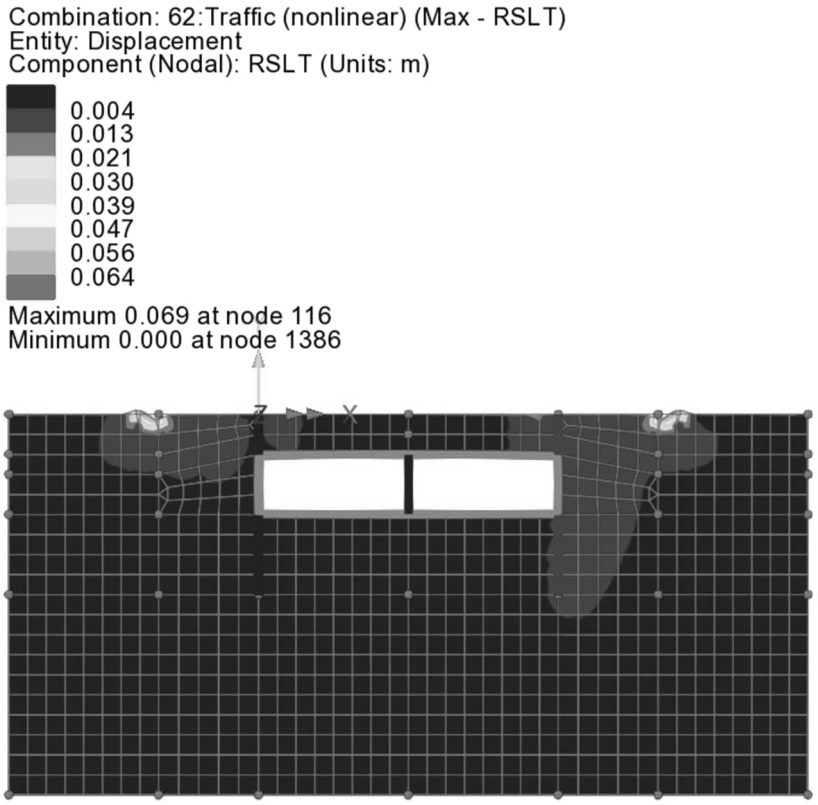
→ max RSLT = 77 mm



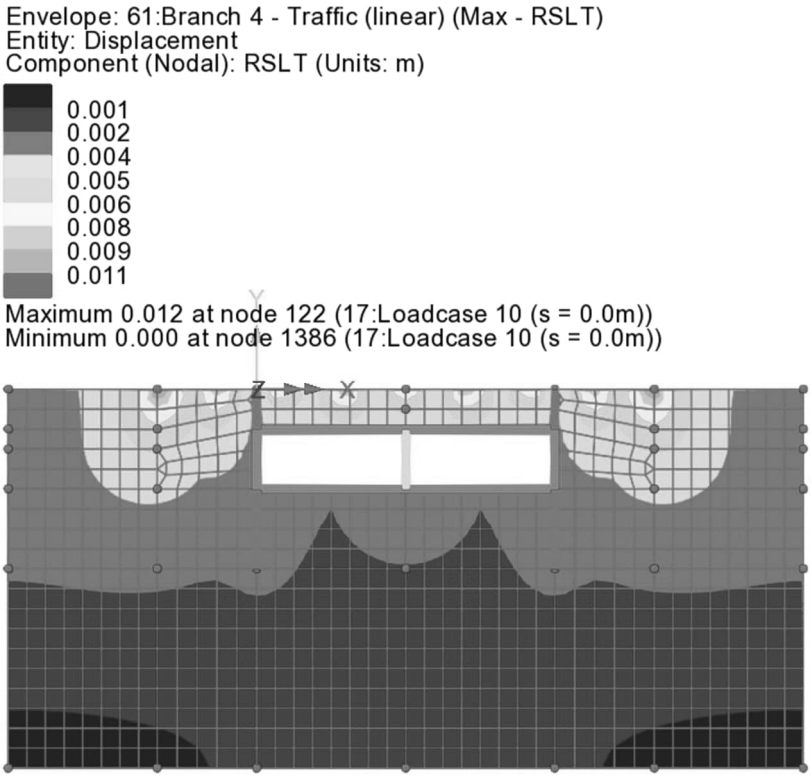
→ max RSLT = 61 mm



→ max RSLT = 43 mm

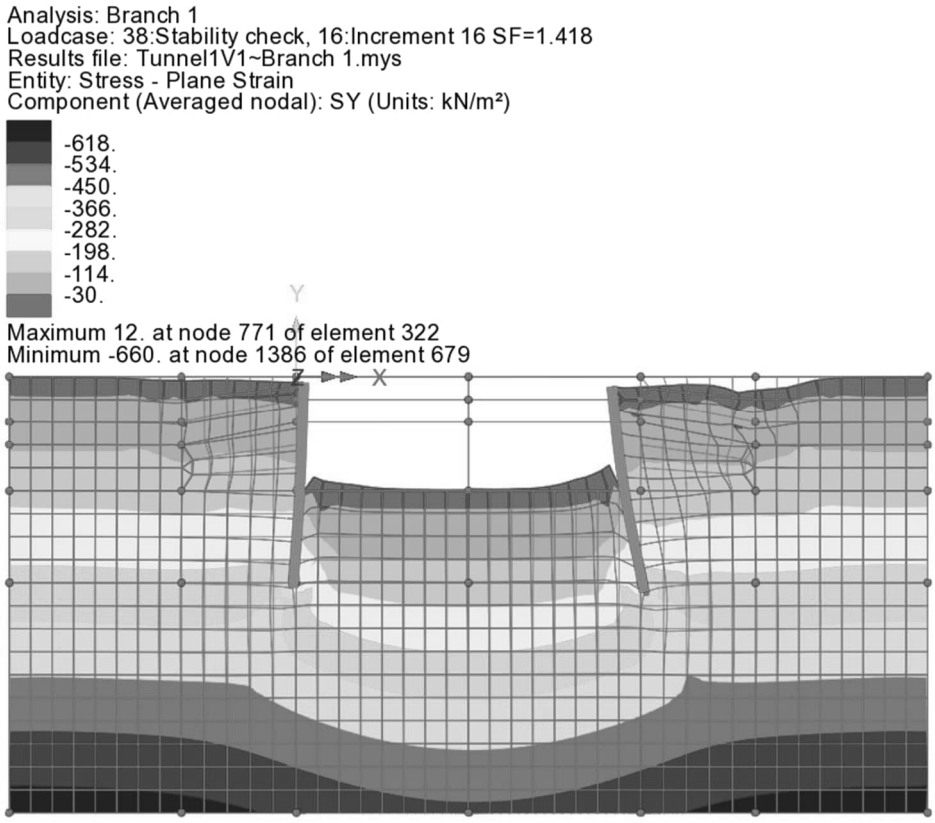


→ max RSLT = 69 mm



→ max RSLT = 12 mm

4.3 SAFETY FACTOR SOIL STABILITY (SF)

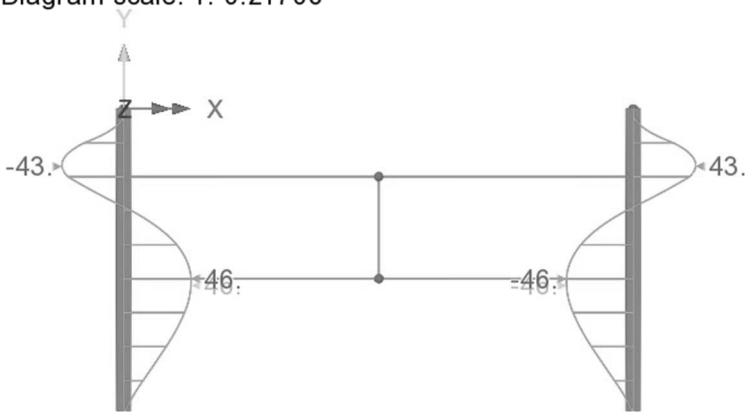


4.4 FORCES TUNNEL

4.4.1 Moment (Mz)

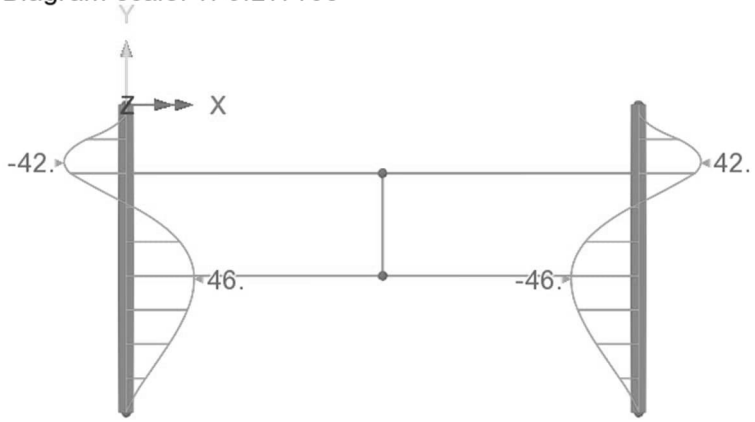
Scale: 1: 200.032
Zoom: 50.6631
Eye: (-9.00435E-3, 4.50227E-3, 0.999949)
Nonlinear analysis
Analysis: Analysis 1
Loadcase: 3:Stage 3 - Excavation 1, 3:Increment 3
Results file: Tunnel1V1~Analysis 1.mys

Diagram entity: Force/Moment - Thick 2D Beam
Diagram component: Mz (Units: kN.m)
Diagram maximum 46.0702 at node 650 of element 237
Diagram minimum -46.0702 at node 698 of element 264
Diagram scale: 1: 0.21706



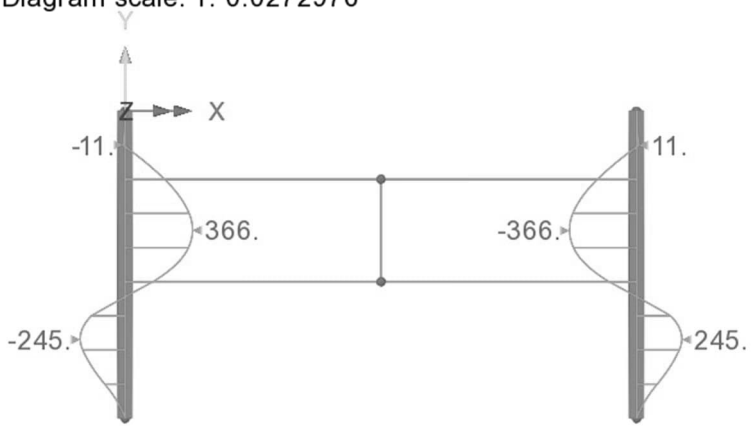
Scale: 1: 200.032
Zoom: 50.6631
Eye: (-9.00435E-3, 4.50227E-3, 0.999949)
Nonlinear analysis
Analysis: Analysis 1
Loadcase: 4:Stage 4 - Install anchors, 4:Increment 4
Results file: Tunnel1V1~Analysis 1.mys

Diagram entity: Force/Moment - Thick 2D Beam
Diagram component: Mz (Units: kN.m)
Diagram maximum 46.0474 at Internal point 10 of element 237
Diagram minimum -46.0474 at Internal point 10 of element 264
Diagram scale: 1: 0.217168



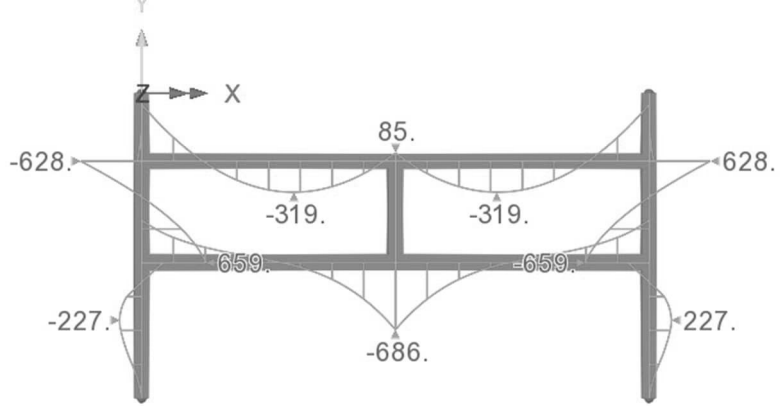
Scale: 1: 200.032
Zoom: 50.6631
Eye: (-9.00435E-3, 4.50227E-3, 0.999949)
Nonlinear analysis
Analysis: Analysis 1
Loadcase: 5:Stage 5 - Excavation 2, 5:Increment 5
Results file: Tunnel1V1~Analysis 1.mys

Diagram entity: Force/Moment - Thick 2D Beam
Diagram component: Mz (Units: kN.m)
Diagram maximum 366.333 at Internal point 6 of element 236
Diagram minimum -366.333 at Internal point 6 of element 263
Diagram scale: 1: 0.0272976



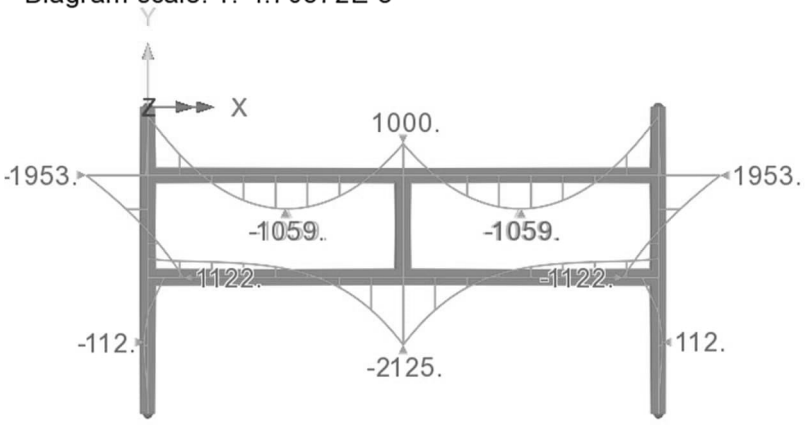
Scale: 1: 200.032
Zoom: 50.6631
Eye: (-9.00435E-3, 4.50227E-3, 0.999949)
Nonlinear analysis
Analysis: Analysis 1
Loadcase: 6:Stage 6 - tunnel, 6:Increment 6
Results file: Tunnel1V1~Analysis 1.mys

Diagram entity: Force/Moment - Thick 2D Beam
Diagram component: Mz (Units: kN.m)
Diagram maximum 659.226 at node 650 of element 237
Diagram minimum -686.013 at node 642 of element 234
Diagram scale: 1: 0.014577



Scale: 1: 200.032
Zoom: 50.6631
Eye: (-9.00435E-3, 4.50227E-3, 0.999949)
Nonlinear analysis
Analysis: Analysis 1
Loadcase: 7:Stage 7 - Filling top of tunnel, 7:Increment 7
Results file: Tunnel1V1~Analysis 1.mys

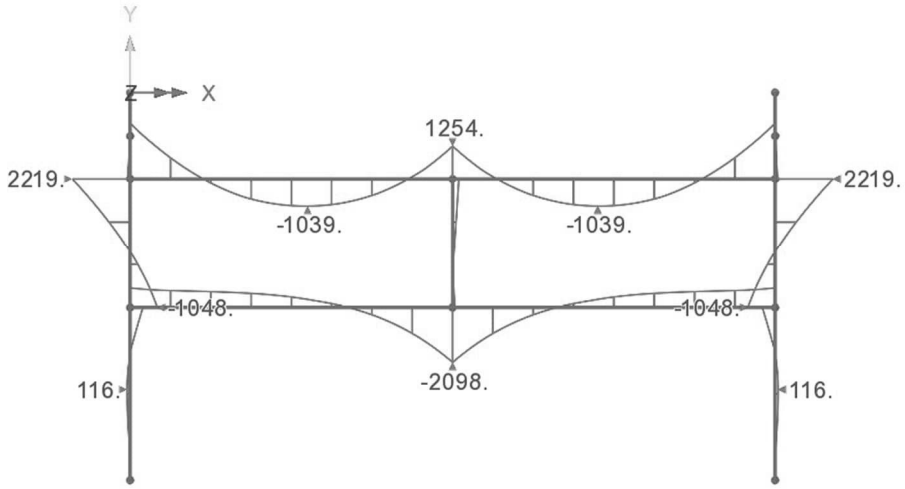
Diagram entity: Force/Moment - Thick 2D Beam
Diagram component: Mz (Units: kN.m)
Diagram maximum 1.95292E3 at node 402 of element 262
Diagram minimum -2.12507E3 at node 642 of element 234
Diagram scale: 1: 4.70572E-3



Nonlinear traffic (incl. gravity soil & tunnel) max/min Mz:

Scale: 1: 149.493
Zoom: 55.6272
Eye: (-9.00435E-3, 4.50227E-3, 0.999949)
Envelope: 50:Branch 2 - Traffic (nonlinear including gravity) (Max - All)

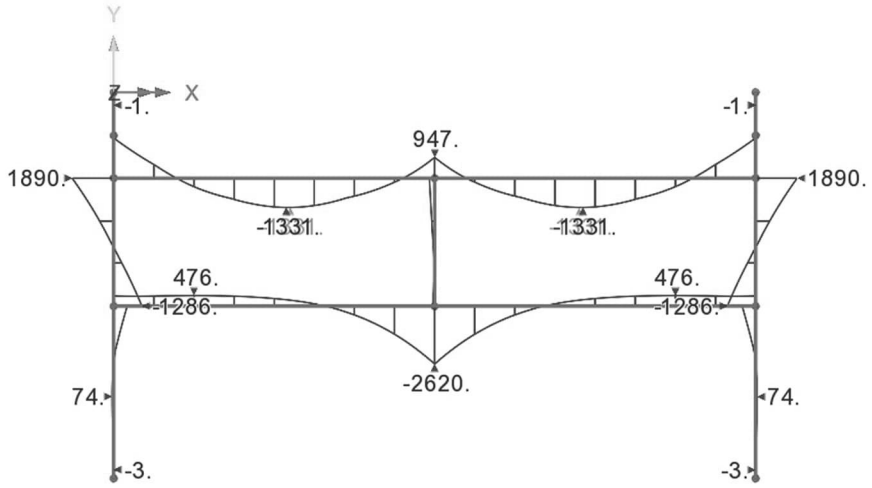
Diagram entity: Force/Moment - Thick 2D Beam
Diagram component: Mz (Units: kN.m)
Diagram maximum 2.21868E3 at node 354 of element 145 (42:Loadcase 22, 12:Increment 12 Load Factor = 1.00000)
Diagram minimum -2.09757E3 at node 642 of element 234 (40:Loadcase 20, 12:Increment 12 Load Factor = 1.00000)
Diagram scale: 1: 4.50719E-3



→ Max Mz = +2219 kNm/m

Scale: 1: 149.493
Zoom: 55.6272
Eye: (-9.00435E-3, 4.50227E-3, 0.999949)
Envelope: 50:Branch 2 - Traffic (nonlinear including gravity) (Min - All)

Diagram entity: Force/Moment - Thick 2D Beam
Diagram component: Mz (Units: kN.m)
Diagram maximum 1.89013E3 at node 354 of element 145 (40:Loadcase 20, 12:Increment 12 Load Factor = 1.00000)
Diagram minimum -2.62047E3 at node 642 of element 234 (43:Loadcase 23, 12:Increment 12 Load Factor = 1.00000)
Diagram scale: 1: 3.81611E-3

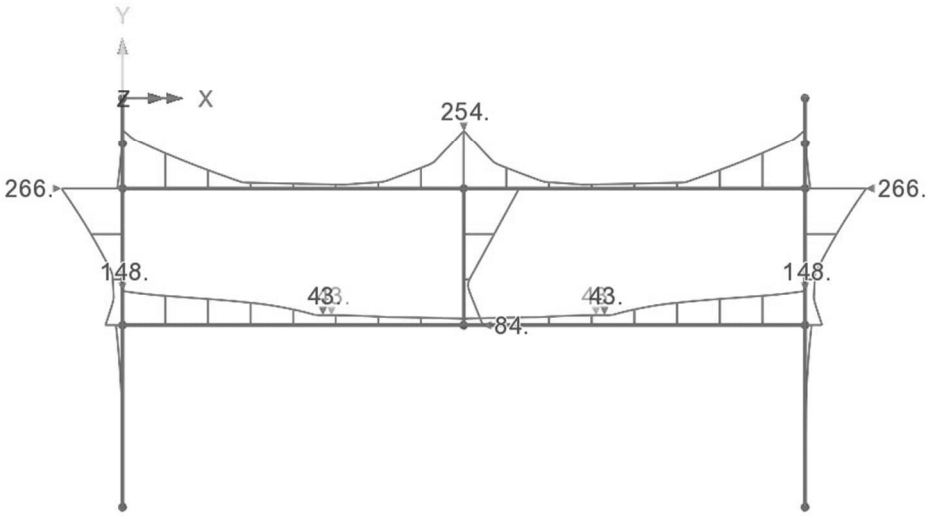


→ Min Mz = -2620 kNm/m

Nonlinear traffic max/min Mz:

Scale: 1: 149.493
Zoom: 55.6272
Eye: (-9.00435E-3, 4.50227E-3, 0.999949)
Combination: 62:Traffic (nonlinear) (Max - All)

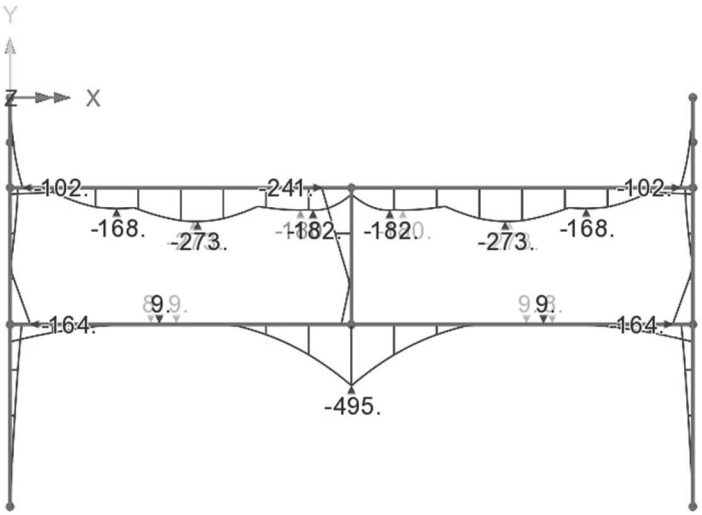
Diagram entity: Force/Moment - Thick 2D Beam
Diagram component: Mz (Units: kN.m)
Diagram maximum 265.752 at node 354 of element 145
Diagram scale: 1: 0.0376291



→ Max Mz = +266 kNm/m

Scale: 1: 149.493
Zoom: 55.6272
Eye: (-9.00435E-3, 4.50227E-3, 0.999949)
Combination: 62:Traffic (nonlinear) (Min - All)

Diagram entity: Force/Moment - Thick 2D Beam
Diagram component: Mz (Units: kN.m)
Diagram maximum 8.52754 at Internal point 5 of element 230
Diagram minimum -495.399 at node 642 of element 234
Diagram scale: 1: 0.0201858

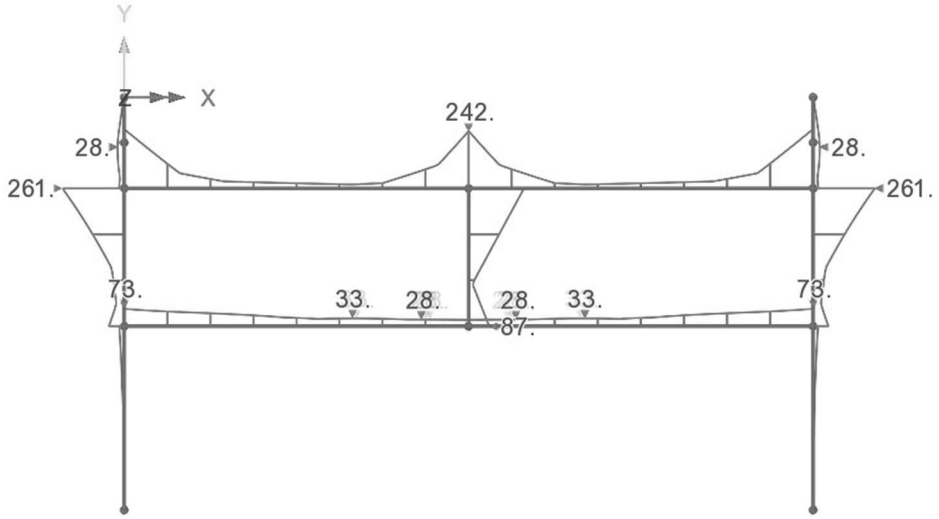


→ Min Mz = -495 kNm/m

Linear traffic max/min Mz:

Scale: 1: 149.493
Zoom: 55.6272
Eye: (-9.00435E-3, 4.50227E-3, 0.999949)
Envelope: 61:Branch 4 - Traffic (linear) (Max - All)

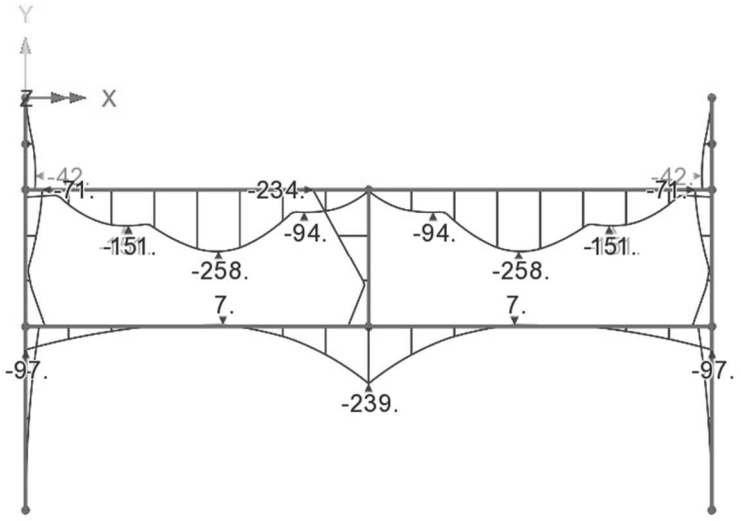
Diagram entity: Force/Moment - Thick 2D Beam
Diagram component: Mz (Units: kN.m)
Diagram maximum 260.848 at node 354 of element 145 (55:Loadcase 31 (s = 18.75m))
Diagram scale: 1: 0.0383366



→ Max Mz = +261 kNm/m

Scale: 1: 149.493
Zoom: 55.6272
Eye: (-9.00435E-3, 4.50227E-3, 0.999949)
Envelope: 61:Branch 4 - Traffic (linear) (Min - All)

Diagram entity: Force/Moment - Thick 2D Beam
Diagram component: Mz (Units: kN.m)
Diagram maximum 7.06972 at Internal point 6 of element 231 (60:Loadcase 36 (s = 50.0m))
Diagram minimum -258.329 at Internal point 5 of element 111 (55:Loadcase 31 (s = 18.75m))
Diagram scale: 1: 0.0387104



→ Min Mz = -258 kNm/m