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

Advanced nonlinear tunnel and geotechnical FEA features:

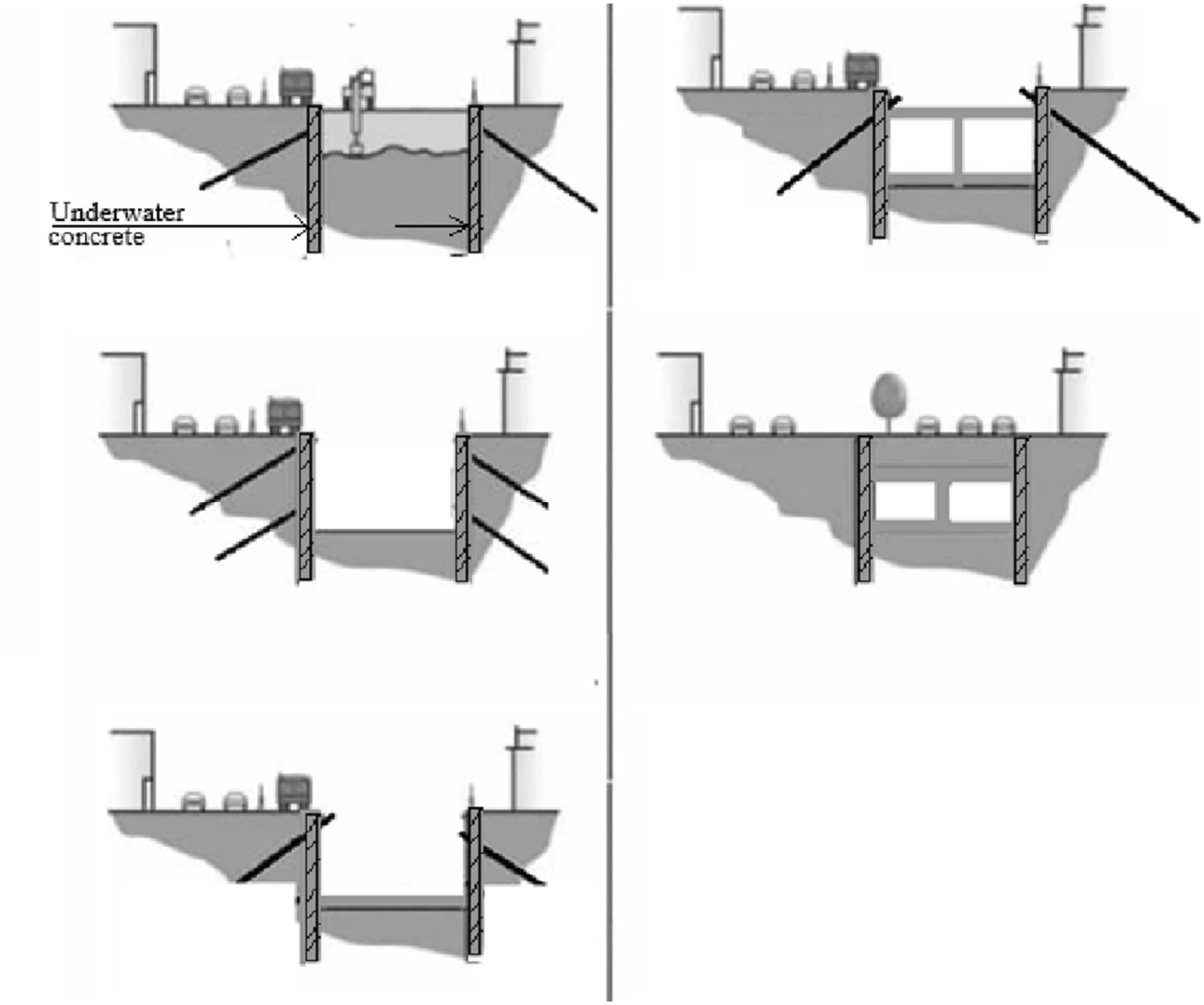
- *Moving traffic load analysis under nonlinear conditions (linear is also performed).*
- *Geotechnical stability utlitmates state (”Jordbrott).*
- *Staged construction analysis for excavation, tunnel and anchors.*
- *Mohr–Coulomb nonlinear soil model is used for nonlinear conditions.*
- *Initial horsiontal 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.*
- *Multiple soil layers.*
- *Prestrained anchors.*
- *Lowering av waterpressure.*

Table of content

Appendix

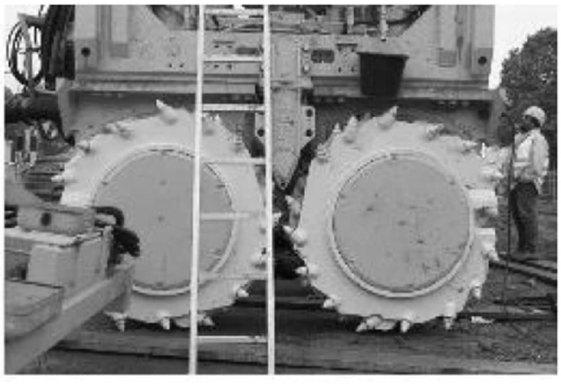
1. Input receipt (FEM-program)

0. PREFACE



Principal sketch
Overview

Excavation
Fine grained soil



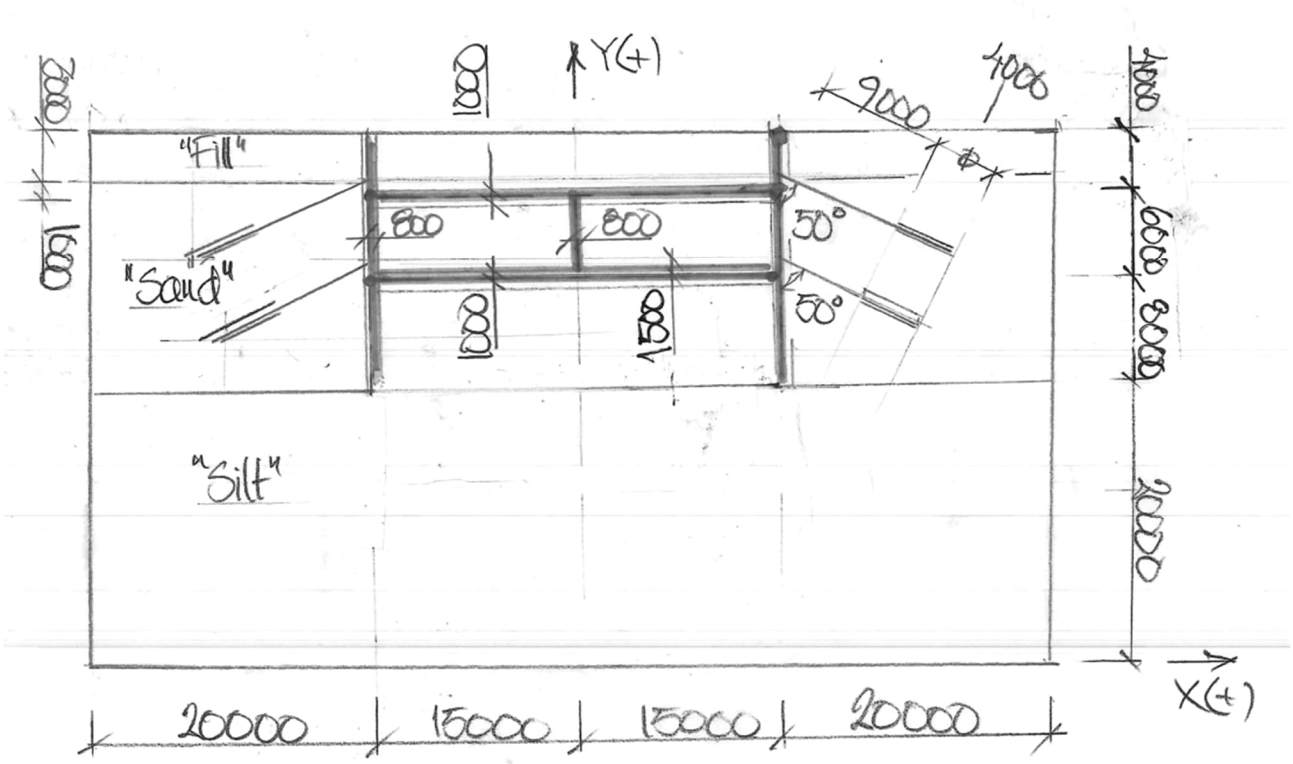
Excavation
Bouldery soil

1. GENERAL

Below is a description of varying stages of design.

1.1 GEOMETRY

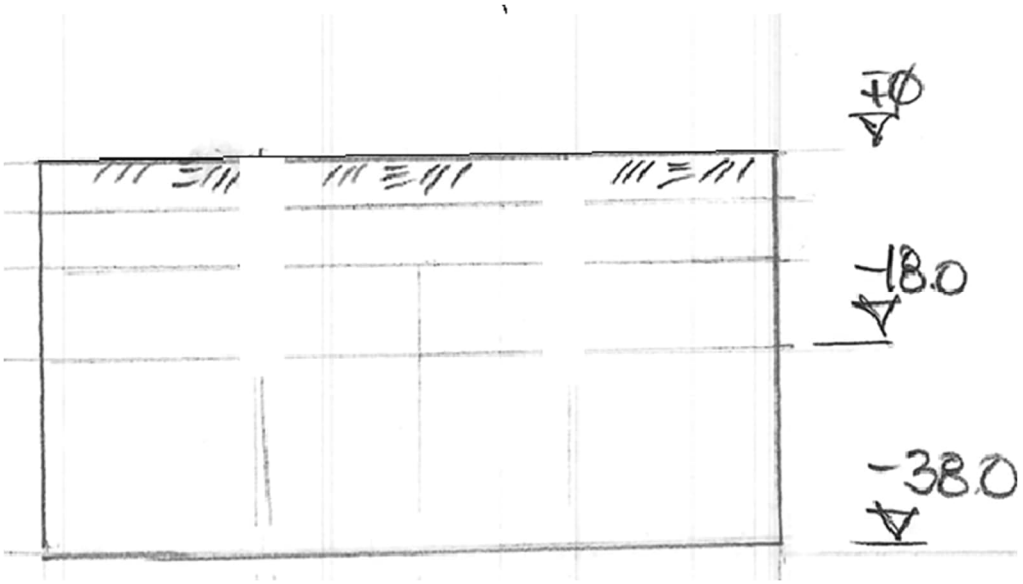
Below are geometries associated to constuction and operational stage.



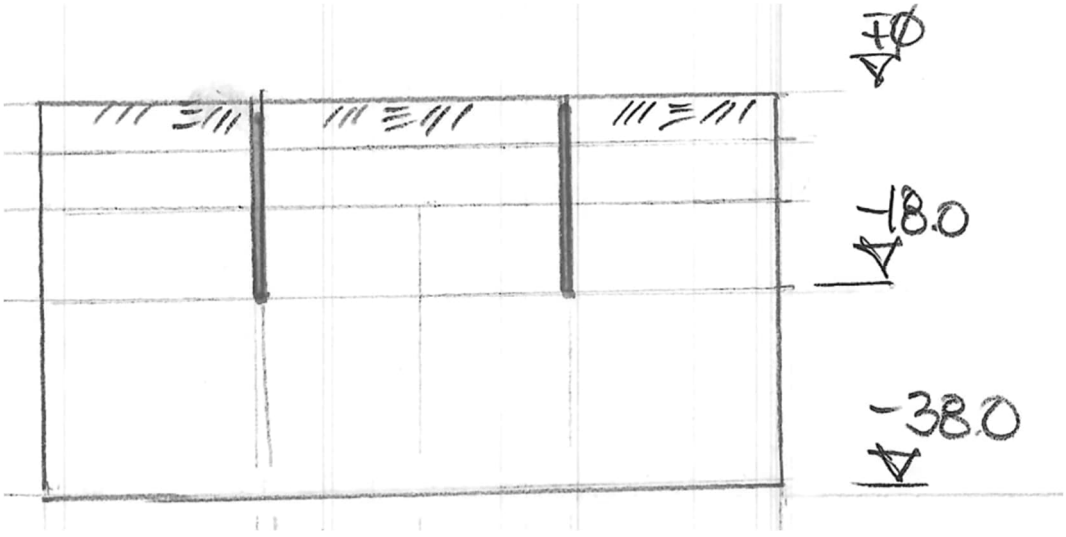
ELEVATION
Overall

1.2 CONSTRUCTION STAGES

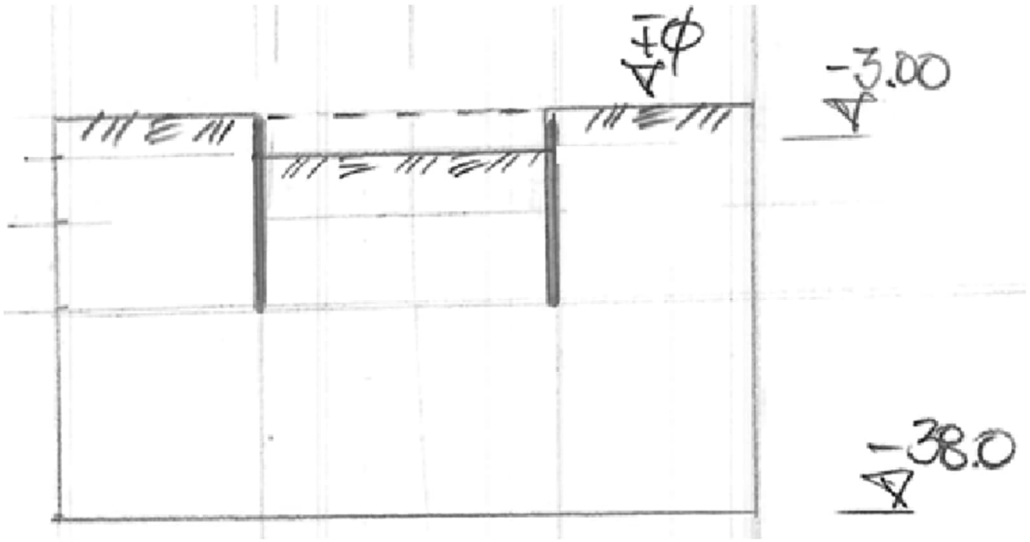
There are a total of 9 construction stages as seen on sketches below.



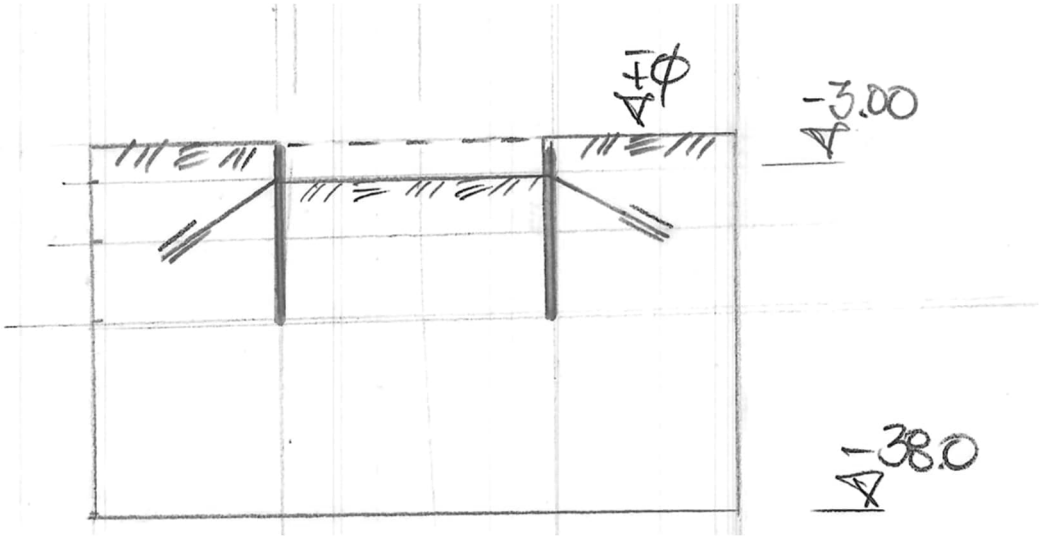
ELEVATION
Stage 1: Initial conditions.



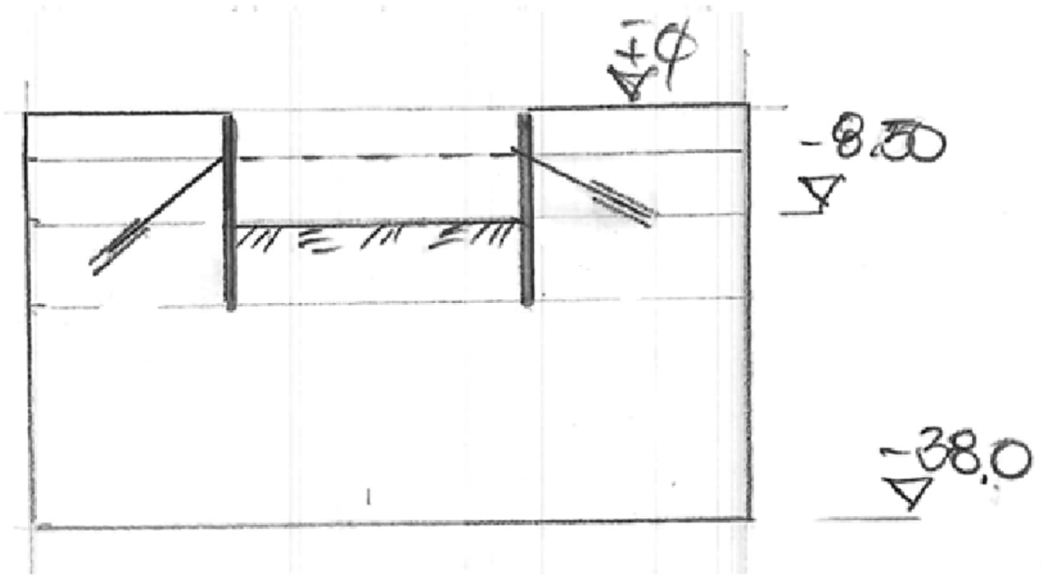
ELEVATION
Stage 2: Installation diaphragm-walls.



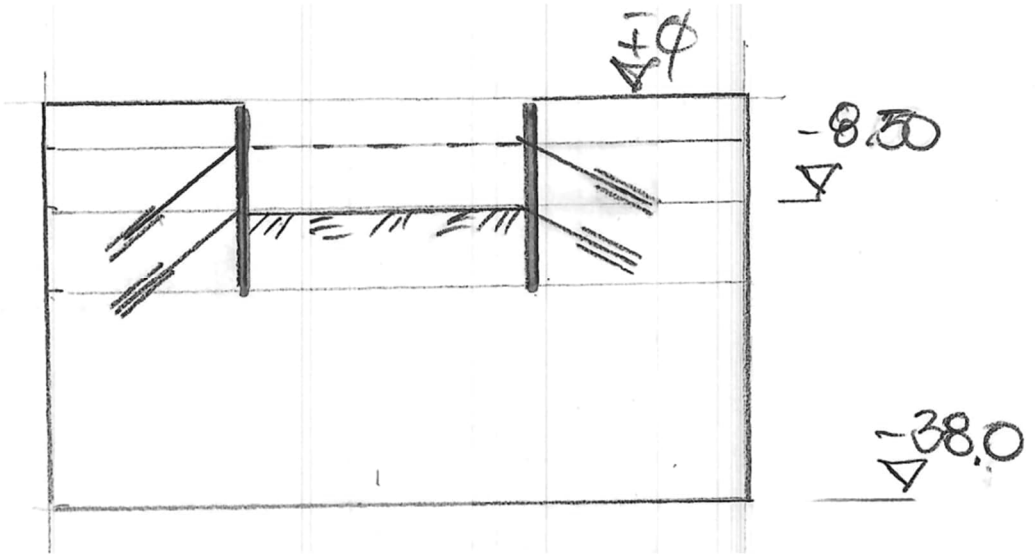
ELEVATION
Stage 3: Excavation 1.



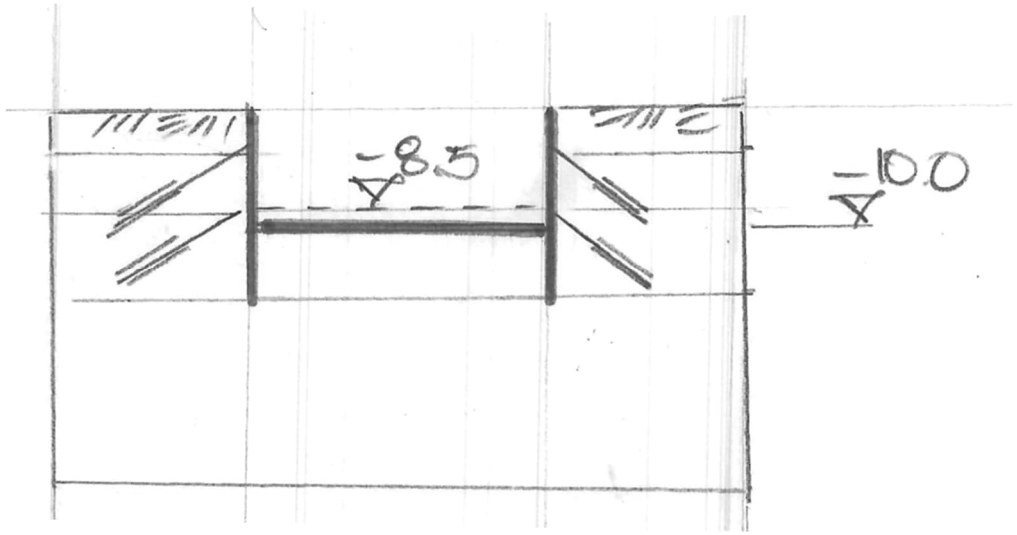
ELEVATION
Stage 4: Installation of anchors at level 1.



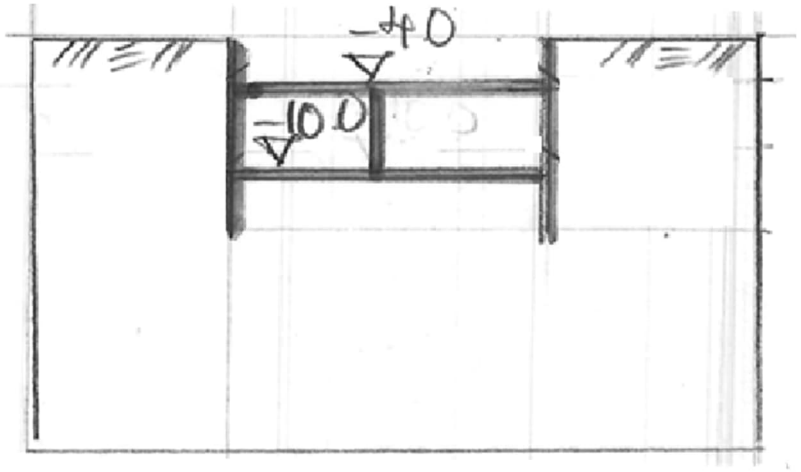
ELEVATION
Stage 5: Excavation 2.



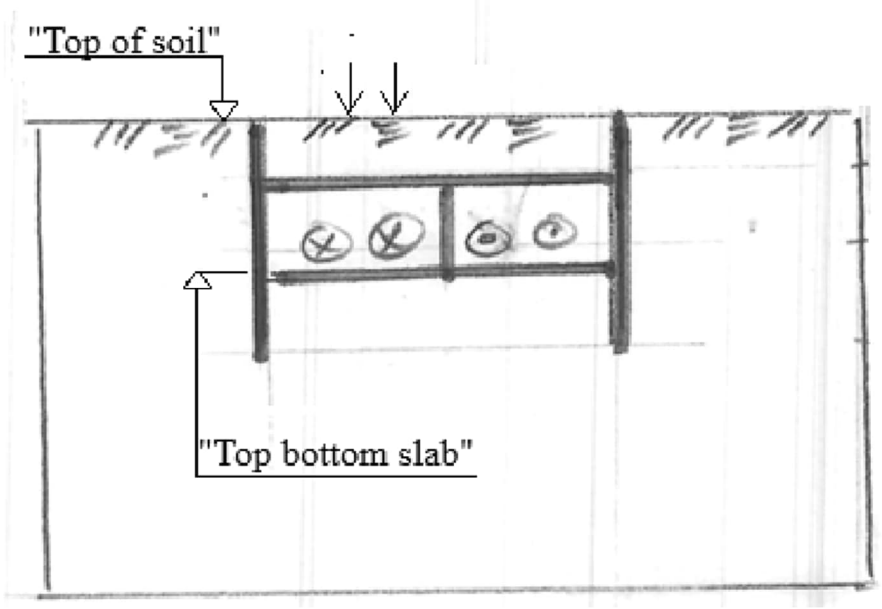
ELEVATION
LC 6: Installation of anchors at level 2.



ELEVATION
Stage 7: Excavation 3



ELEVATION
Stage 8: Construction tunnel



ELEVATION
Stage 9: Filling on top of tunnel

1.3 SOIL PROPROPETIES

1.3.1 Ground water

Ground water level is assumed lower than level ± 0.

1.3.2 Soil material

Geotechnical parameters:

Material	Level	ρ	ρ´	ϕ_k	E_k
”Fill”	± 0→ -4.0	20	11	30	8
”Sand”	-4.0 → -18.0	20	11	34	30
”Silt”	-18.0 → -38.0	19	11	29	20
”Rock”	± 0	-	-	-	-
-	m	kN/m³	kN/m³	deg	MPa

2. SYSTEM ANALYSIS

2.1 GENERAL

There are 9 construction stages (∴ Stage 1-9) 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.

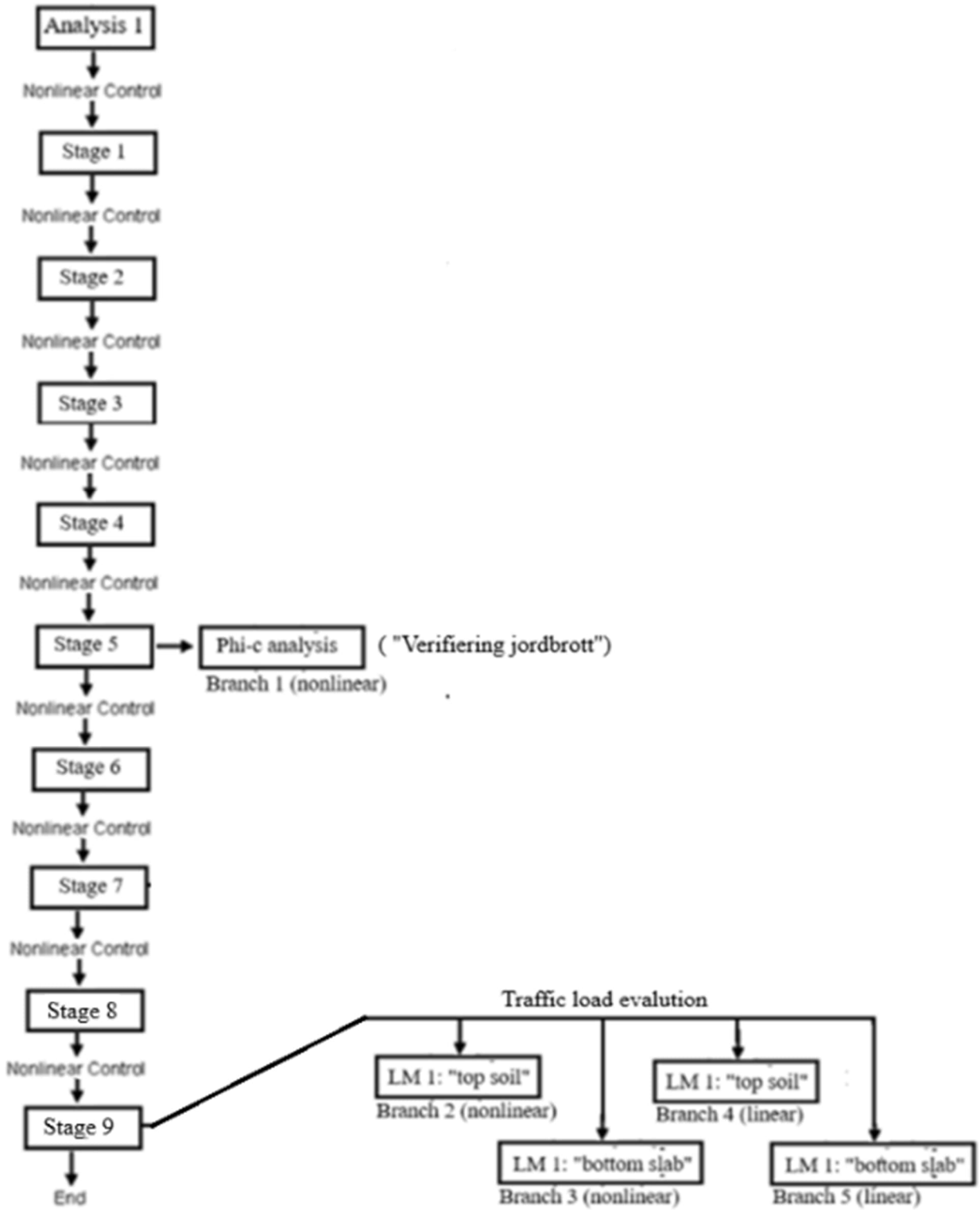
Soil is modelled using plain strain surface elements (QNP8).

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 #	LC 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	Install anchor:2	After excavation 2	Anchor load:2	-	Anchor:2
7	Excavation:3	After excavation 3	-	Excavation:3	-
8	Construct tunnel	After excavation 2	Gravity tunnel	Anchors	Tunnel
9	Filling top tunnel	After filling top slab	Filling top tunnel	-	Soil top slab

* = Reset deformation is applied to remove historic deformations.

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

2.2 NONLINEAR ANALYSIS

Nonlinear analysis is performed using increments using Newton_Raphson numerial procedure.

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

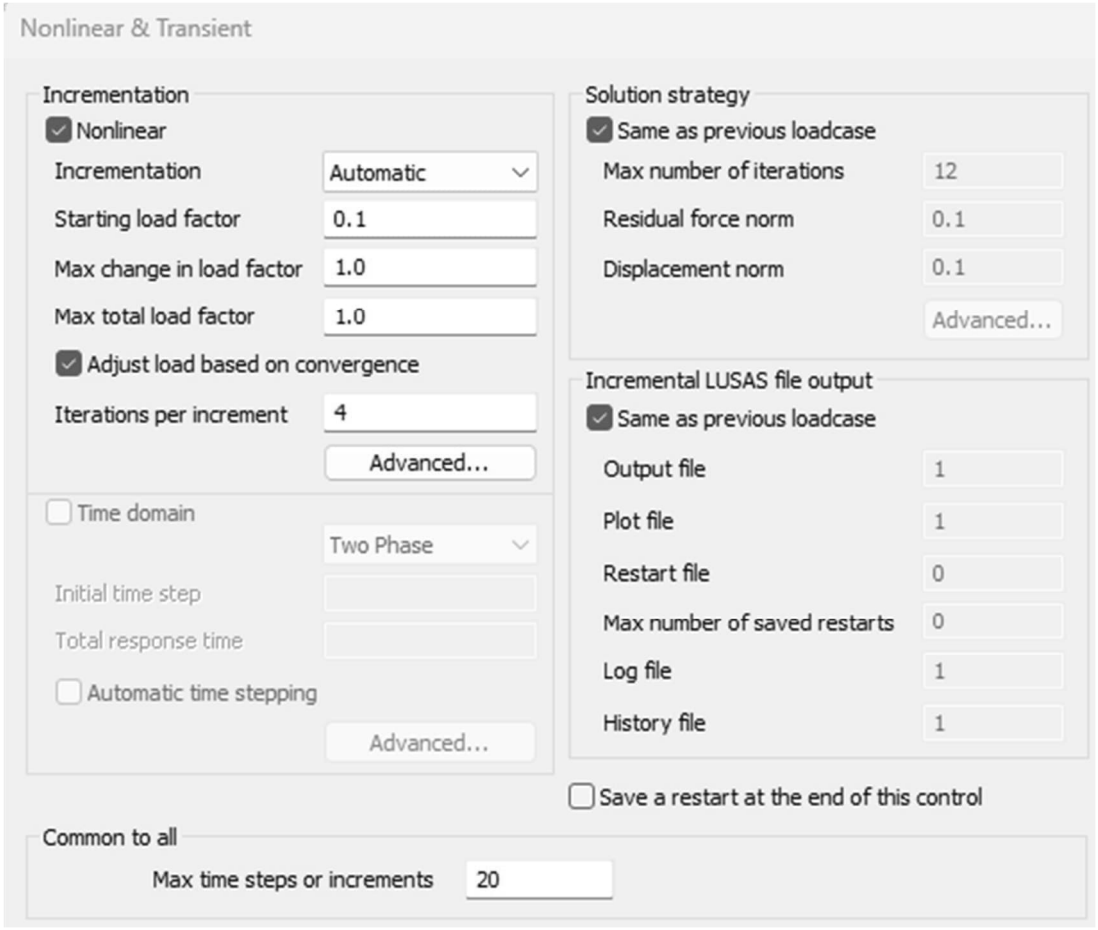
Residual force norm:
The limit for the sum of the squares of all residual forces as a percentage of the sum of the squares of all external forces, including reactions (rdnrm). By default only translation degrees of freedom are considered. So for a value of 0.1 the convergence of the solution at each 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	Install anchor:2	Nonlinear	-	Automatic
7	Excavation:3	Nonlinear	-	Automatic
8	Construct tunnel	Nonlinear	-	Automatic
9	Filling top tunnel	Nonlinear	-	Automatic
”	-”-	Nonlinear	Branch 2	Automatic
”	-”-	Nonlinear	Branch 3	Automatic
”	-”-	Linear	Branch 4	-
”	-”-	Linear	Branch 5	-

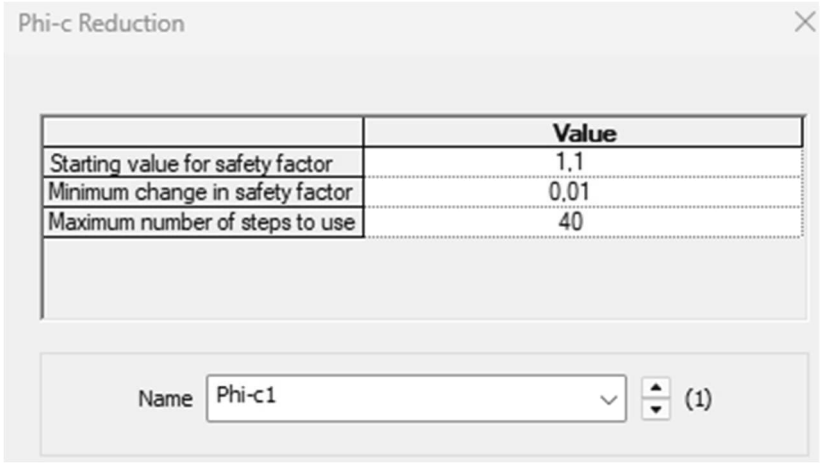
Incrementation as chosen to be performed *Automatic* with chosen parameters in dialogue box.

The only load is horizontal anchor load that is increased by load factors 1, 2,…. 9 & 10.



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.

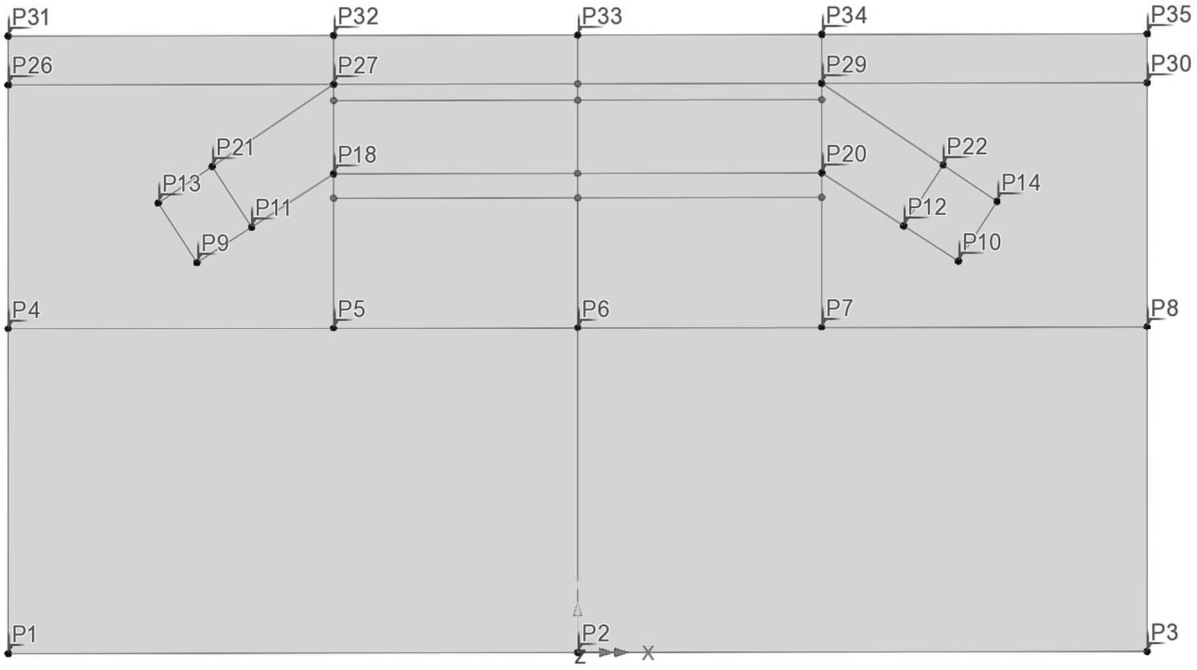
All coordinates needed to describe POINTS are found in attachment 1.

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

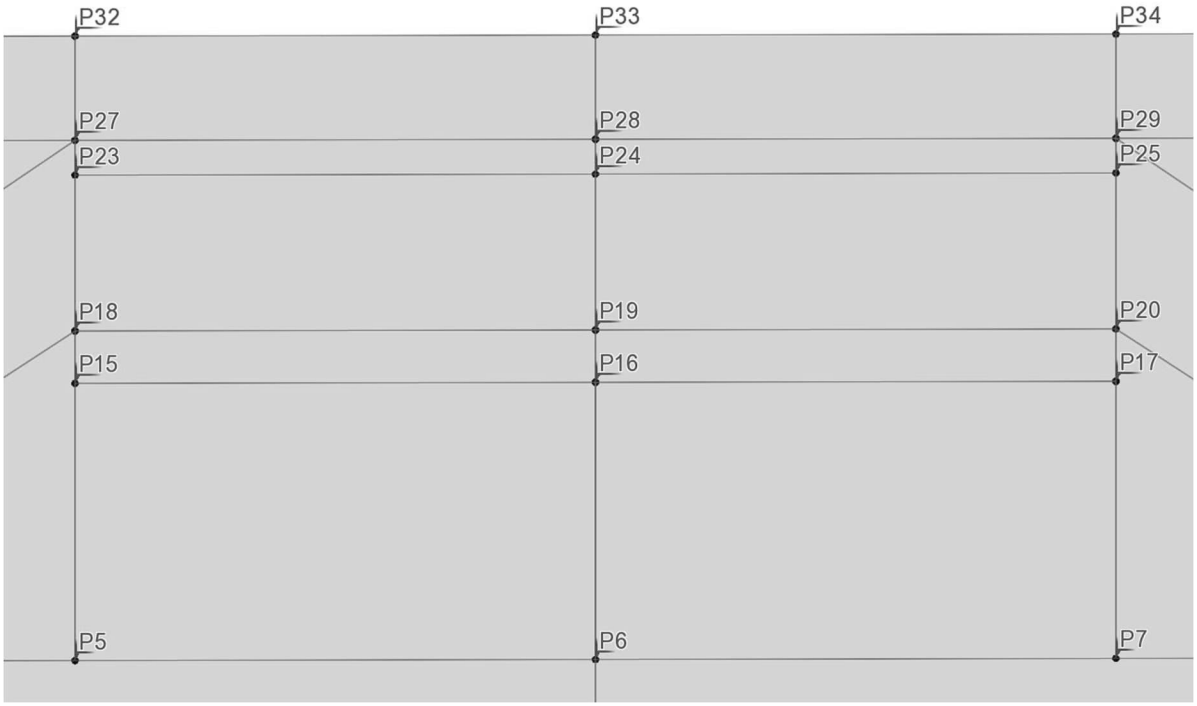
All LINES need to describe SURFACE are found in attachment 1.

Sketches are generated by using POINTS, LINES and SURFACES.

2.4.1 Geometry: Points

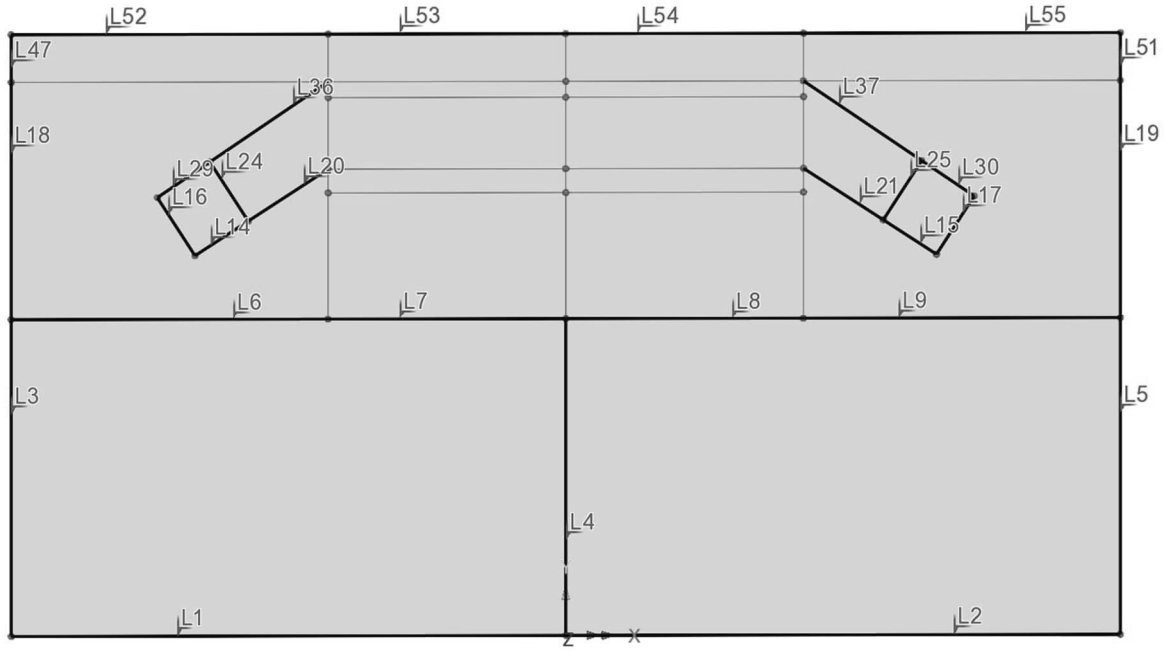


ELEVATION
Overall

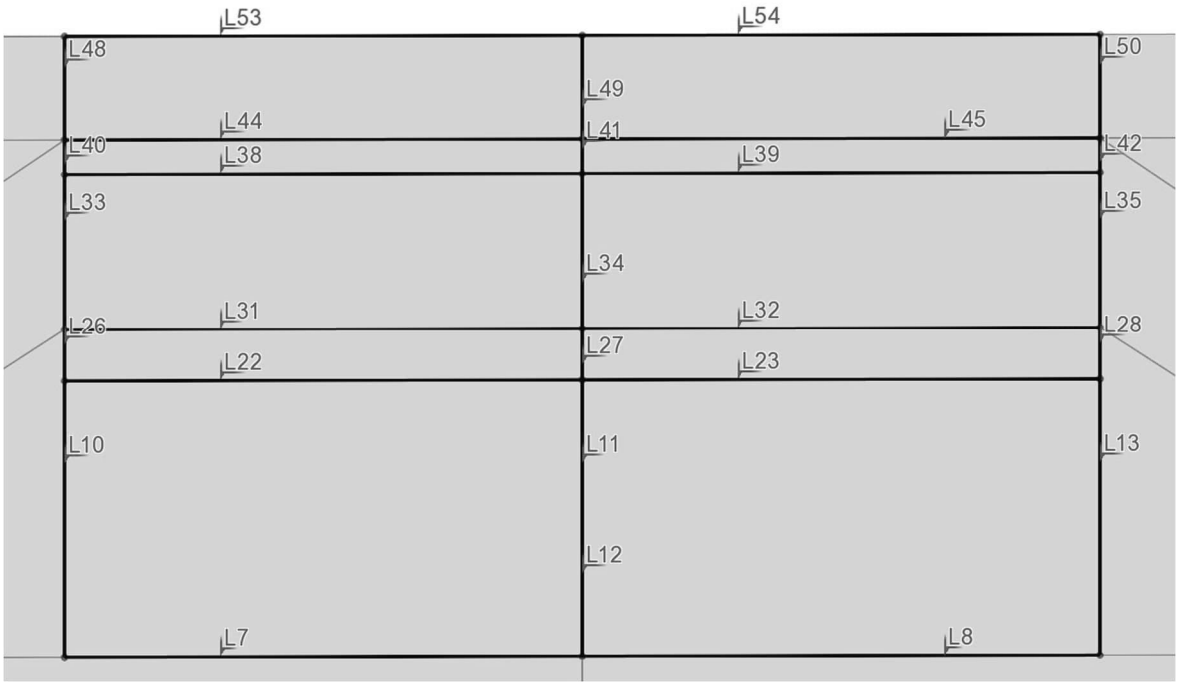


ELEVATION
Detail

2.4.2 Geometry: Lines

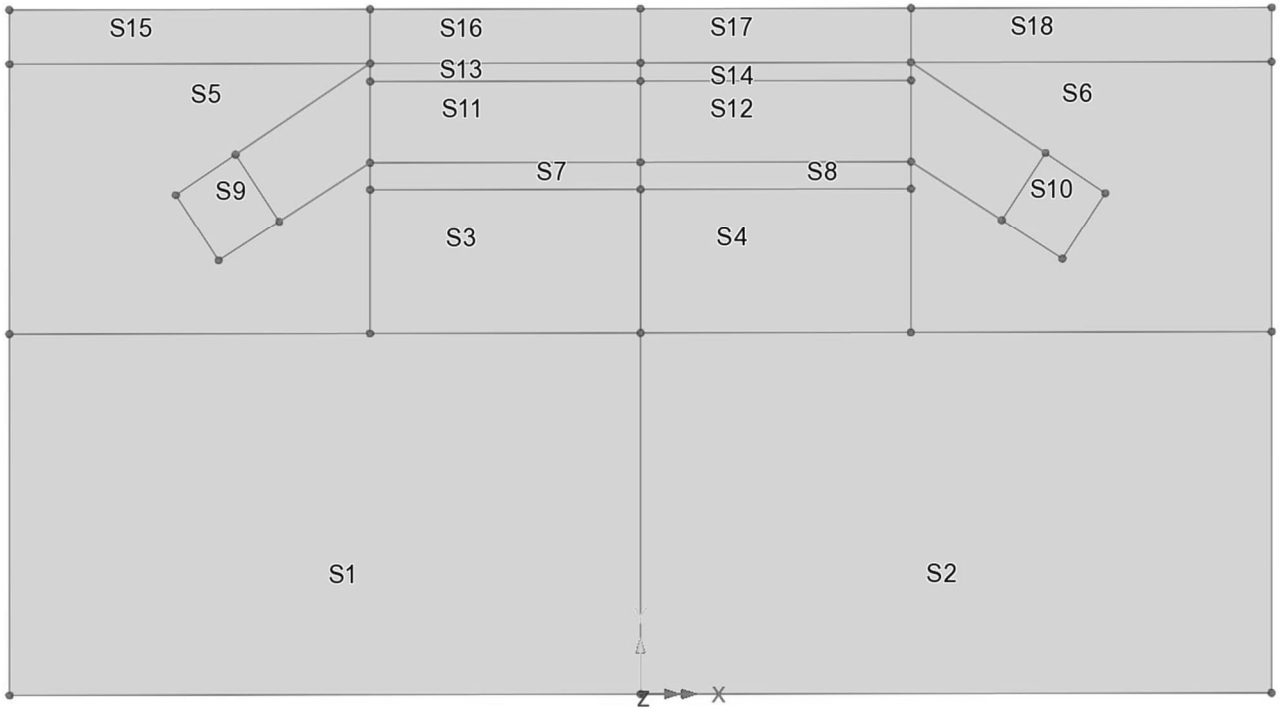


ELEVATION
Overall



ELEVATION
Detail

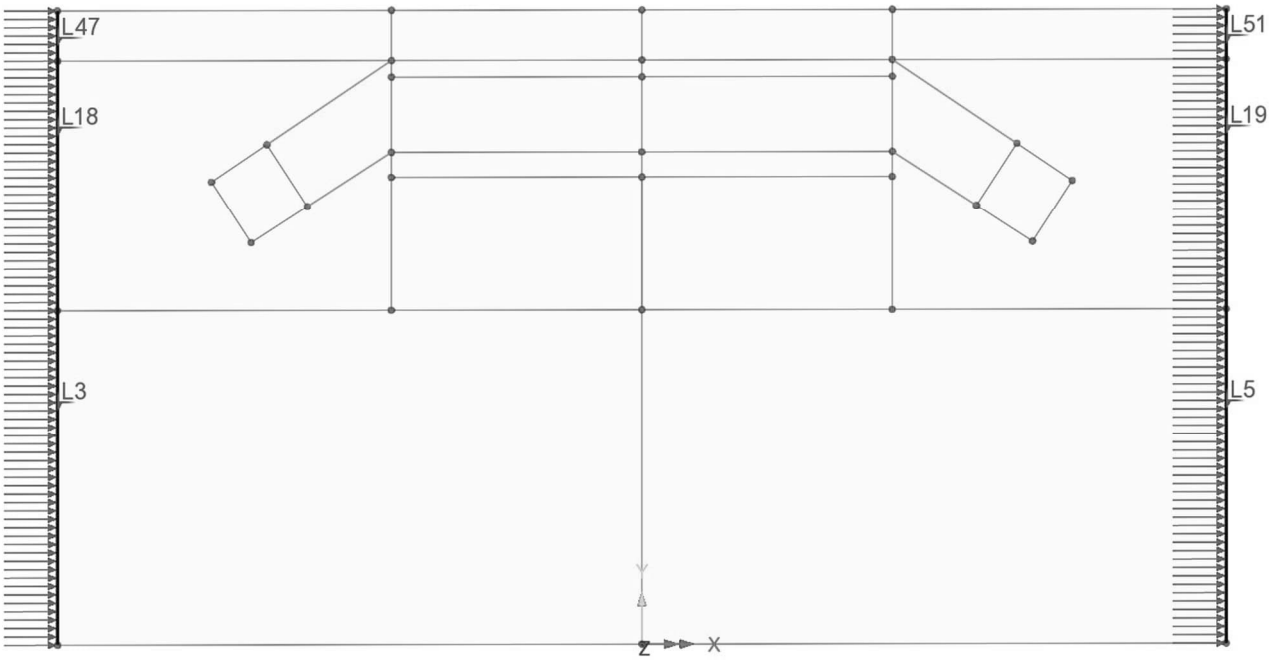
2.4.3 Geometry: Surfaces



ELEVATION
Overall

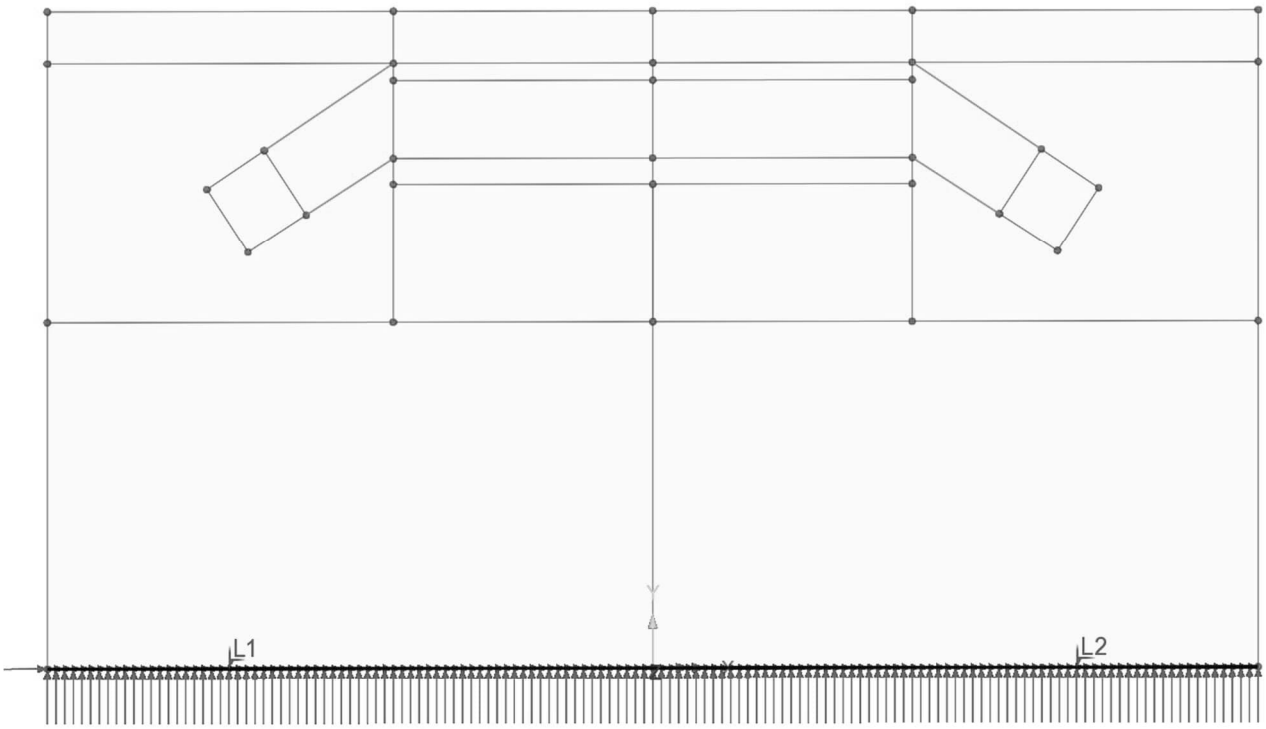
2.5 BOUNDARY CONDITIONS

2.5.1 Horizontal boundary soil: Fixed X



ELEVATION
Overall

2.5.2 Vertical boundary soil: Fixed XY



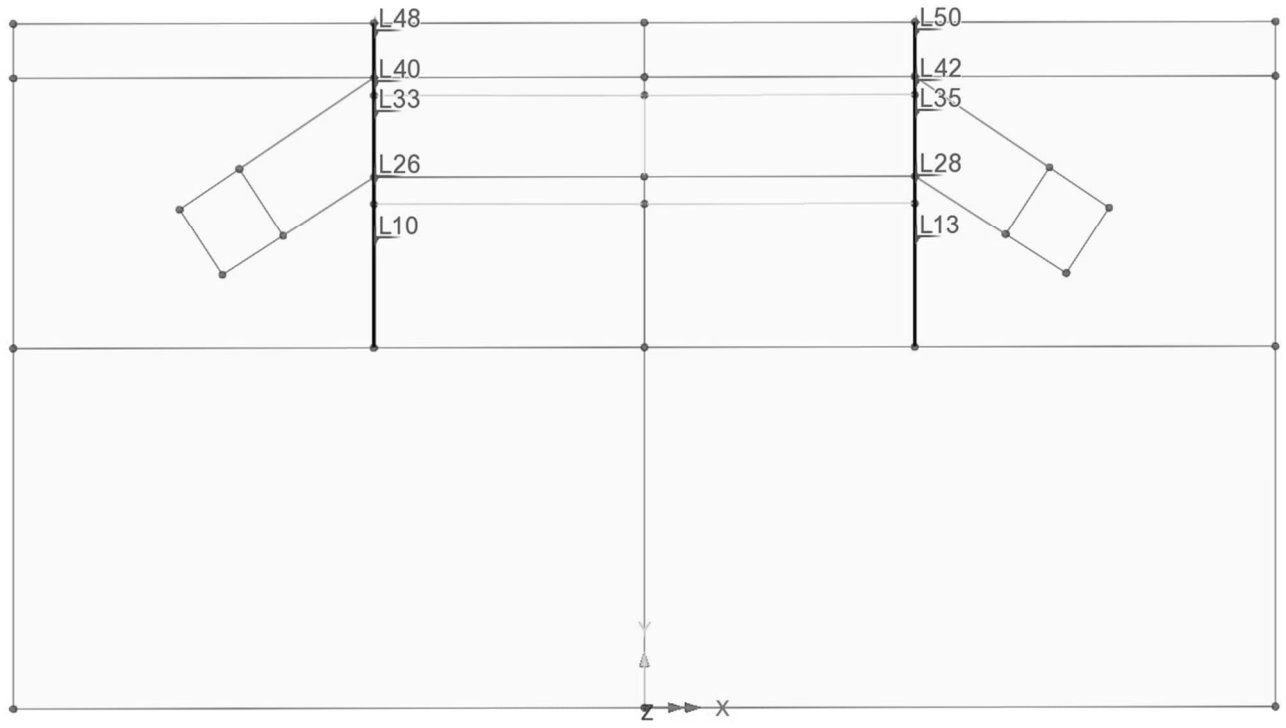
ELEVATION
Overall

2.6 MESH

2.6.1 Diaphragm: Plain strain beam element (BMI3N)

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
BMI3N	Plain strain beam	1.0	Quadratic

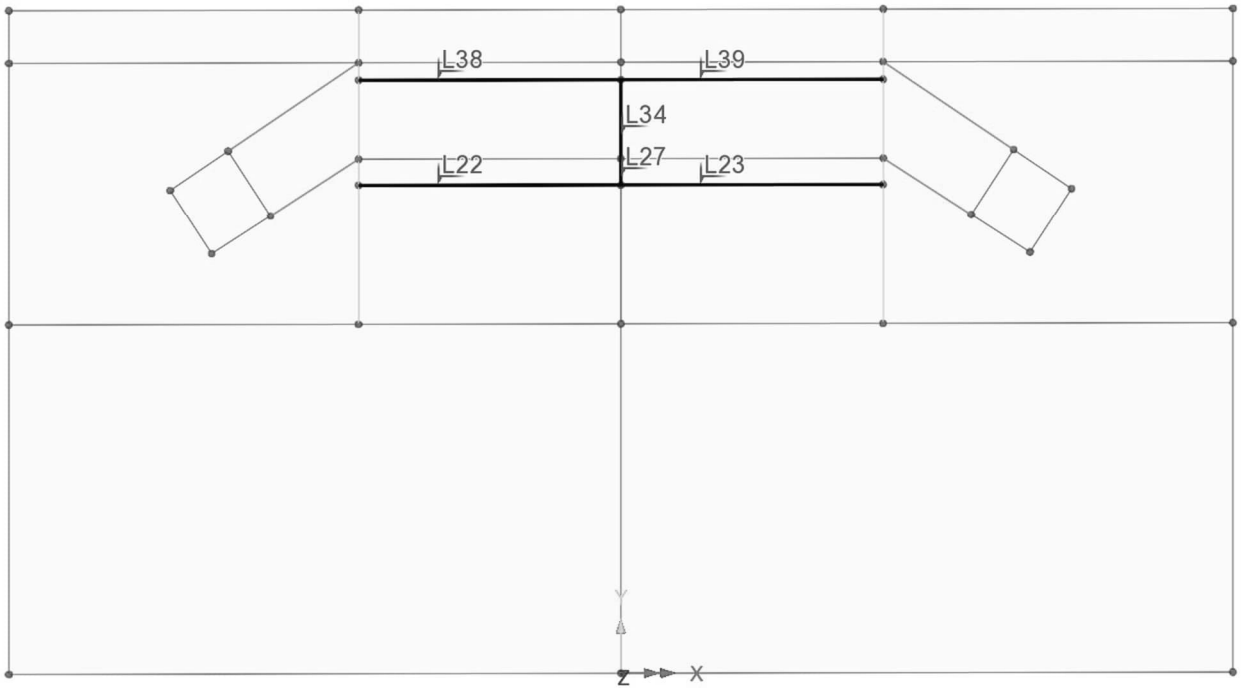


ELEVATION
Overall

2.6.2 Tunnel: Plain strain beam element (BMI3N)

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
BMI3N	Plain strain beam	1.0	Quadratic

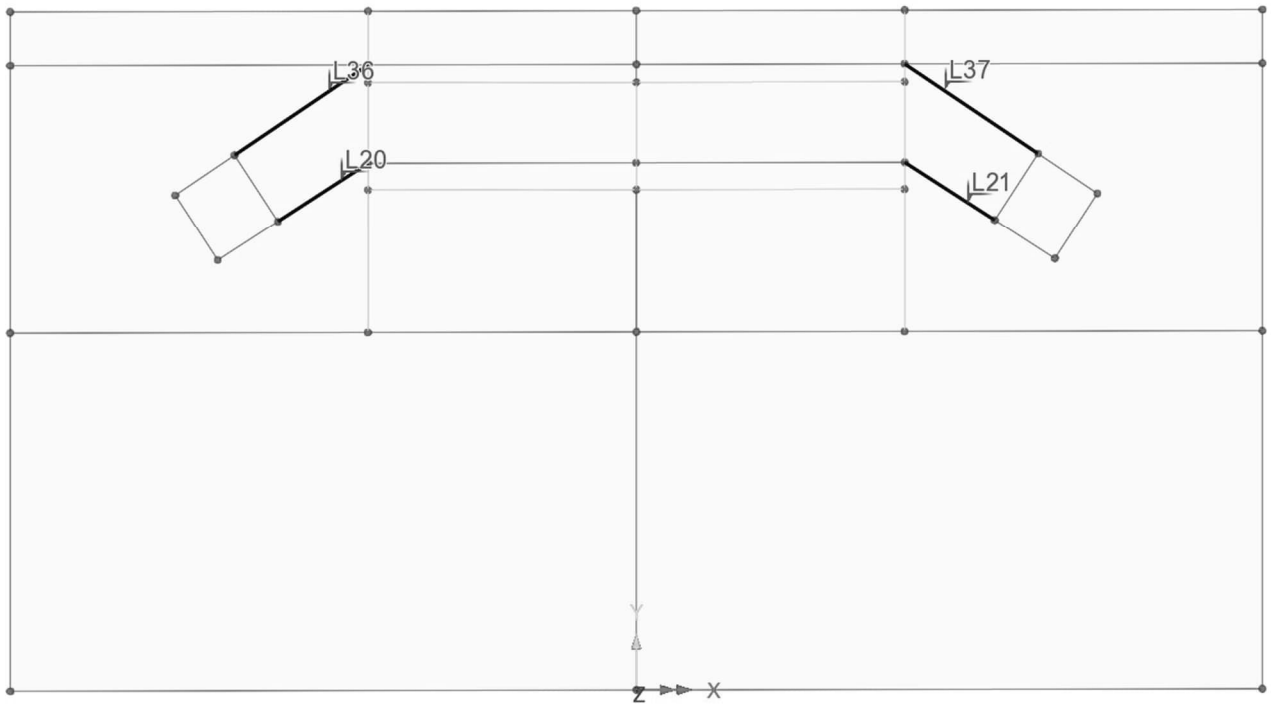


ELEVATION
Overall

2.6.3 Anchor rod: Bar element (BAR2)

Anchor rods are modelled as seen below. This element is not connected to nodes in soil thus the rod is defined by only one element. More elements than one would create a failure due mechanism.

Name	Element type	Number of divisions	Order element
BAR2	Bar	1	Linear

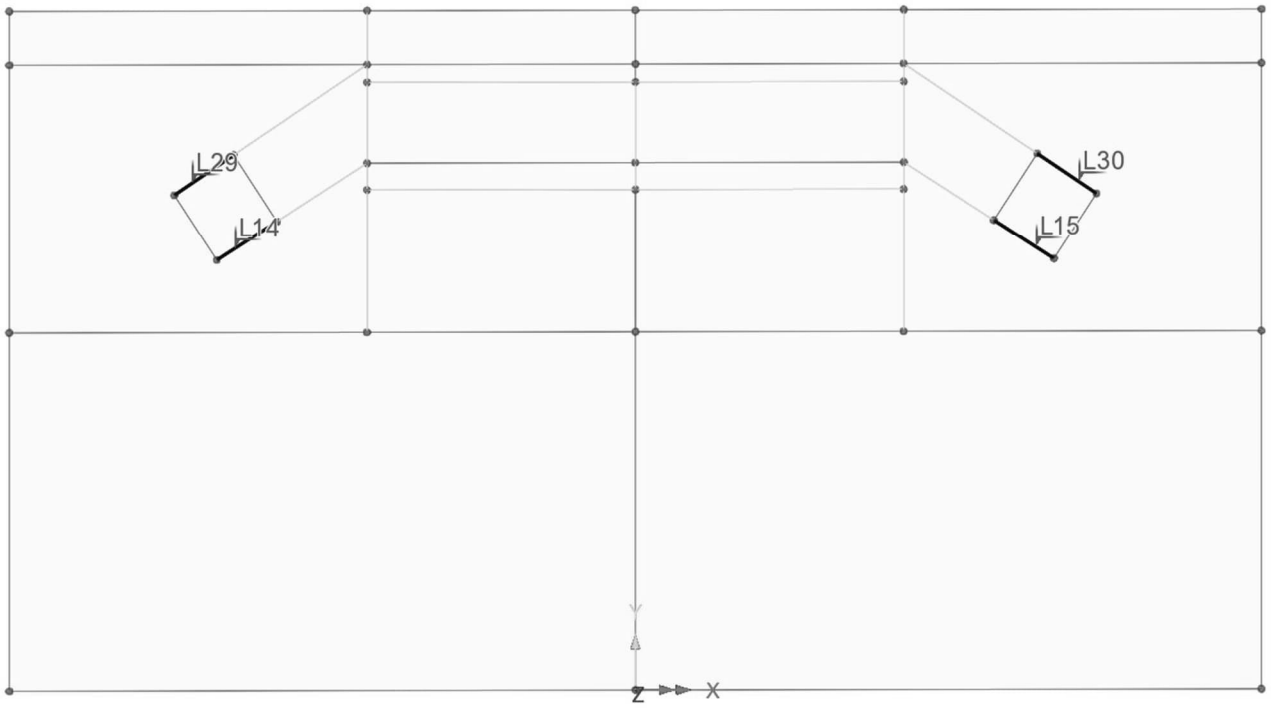


ELEVATION
Overall

2.6.4 Anchor grout : Bar element (BAR3)

Anchor grouts are modelled as seen below. These elements are connected to nodes in soil.

Name	Element type	Element length	Order element
BAR3	Bar	1	Quadratic



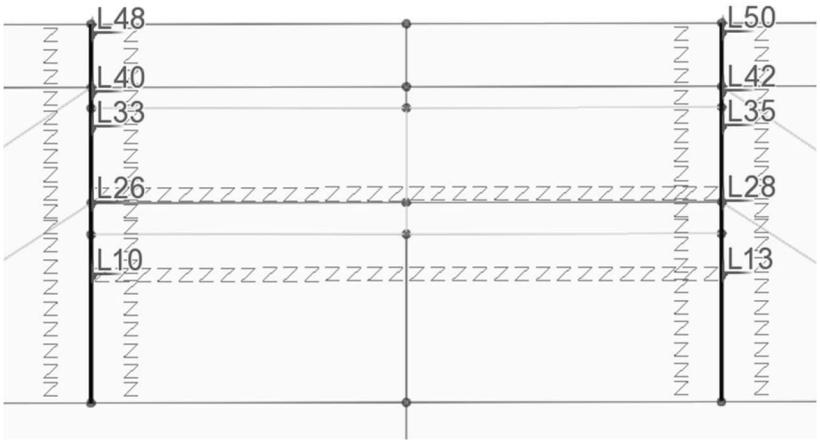
ELEVATION
Overall

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

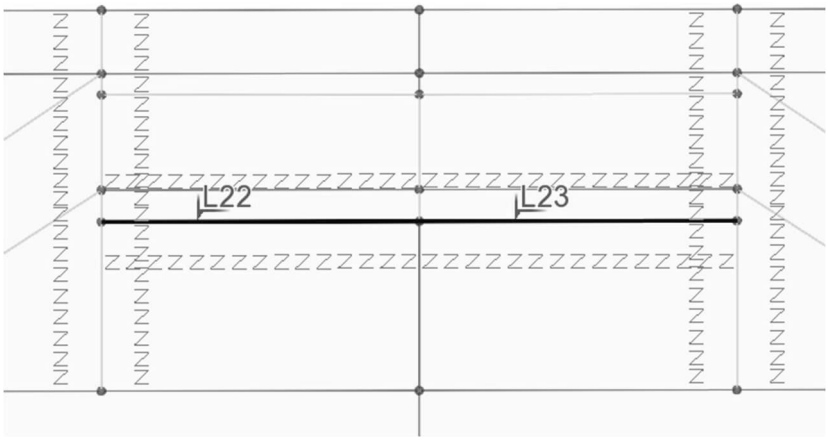
The interface between soil and wall is modelled as seen below.

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	1 m	Single feature (automatic)	Quadratic
IPN6	Interface: horizontal	1 m	Single feature (automatic)	Quadratic



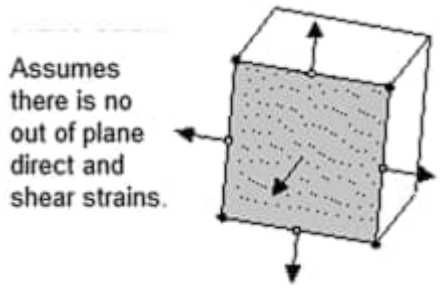
ELEVATION
Interface: vertical



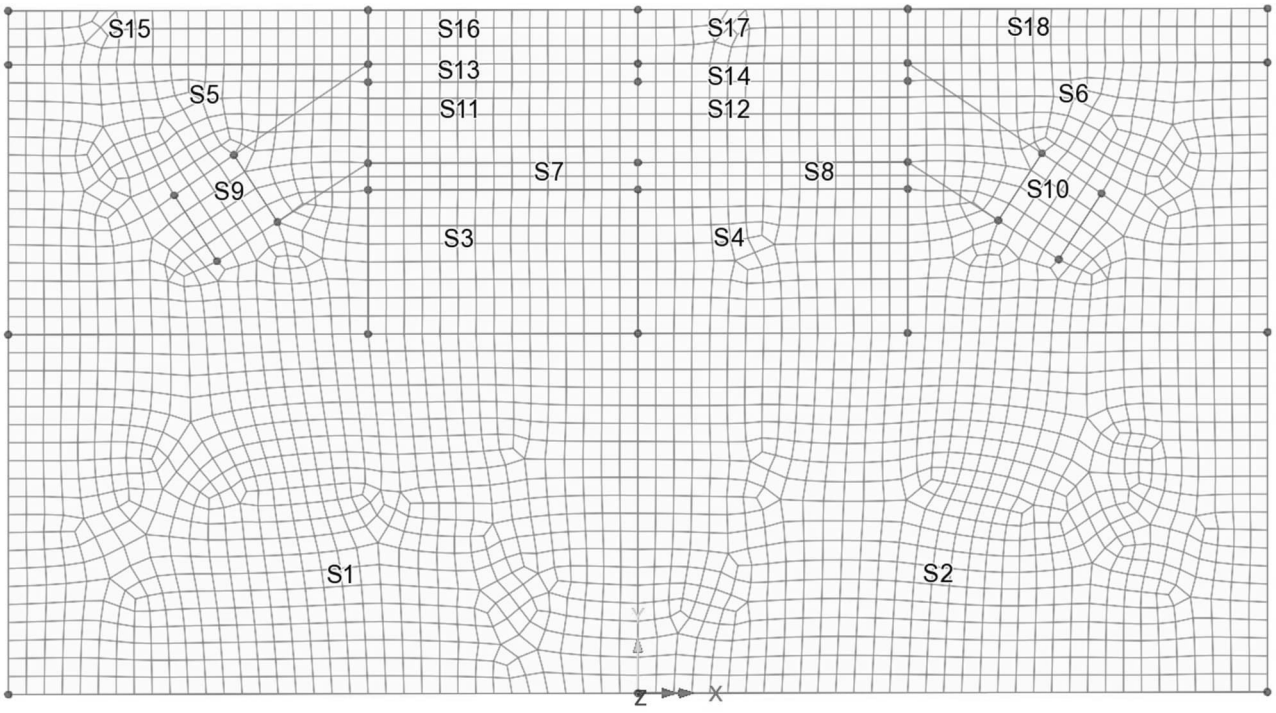
ELEVATION
Interface: horizontal

2.6.6 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 two phase	1 m	Quadratic	Irregular



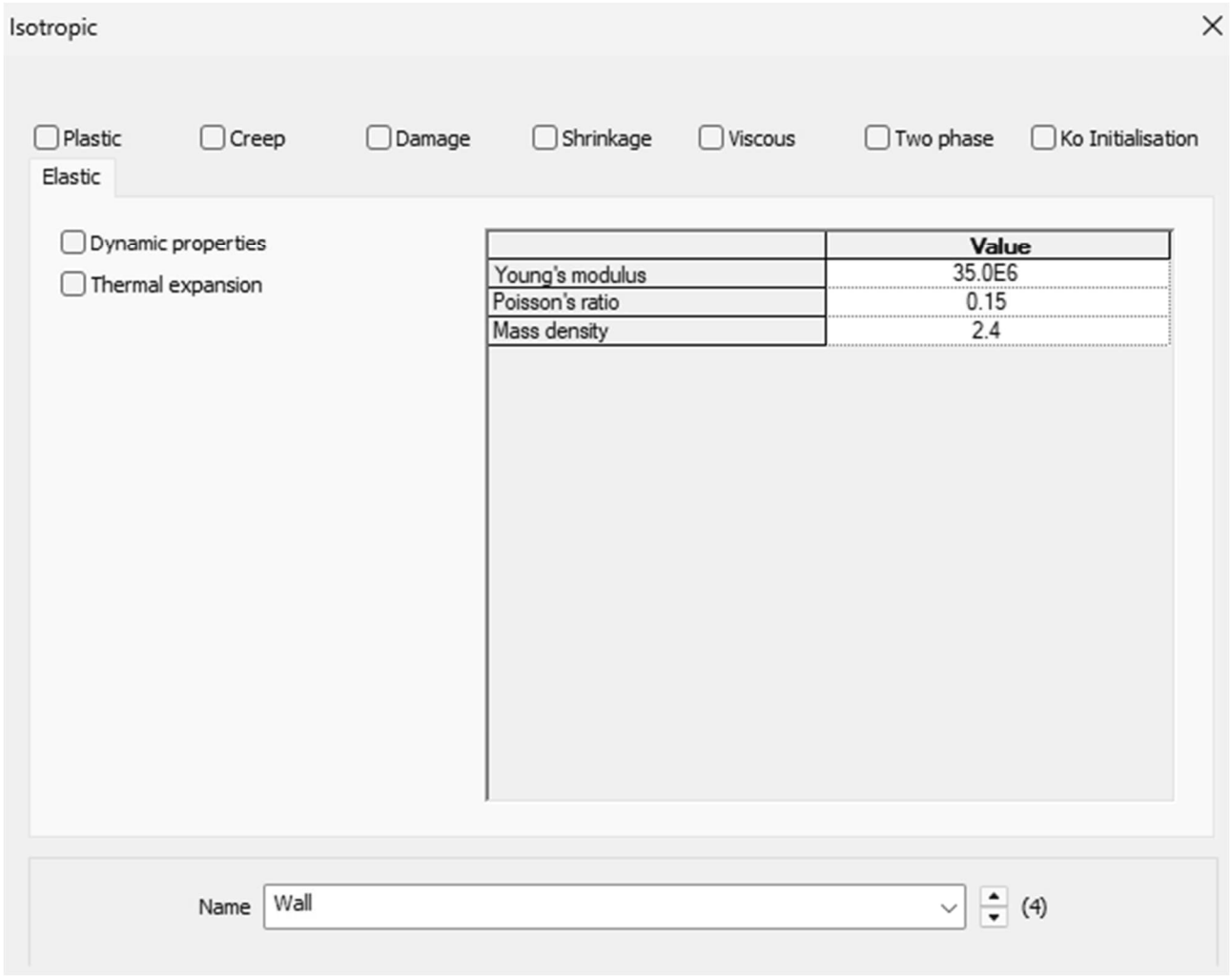
ELEVATION
Overall

2.7 MATERIAL

2.7.1 Linear elastic material: retaining wall, anchors rods & grouting

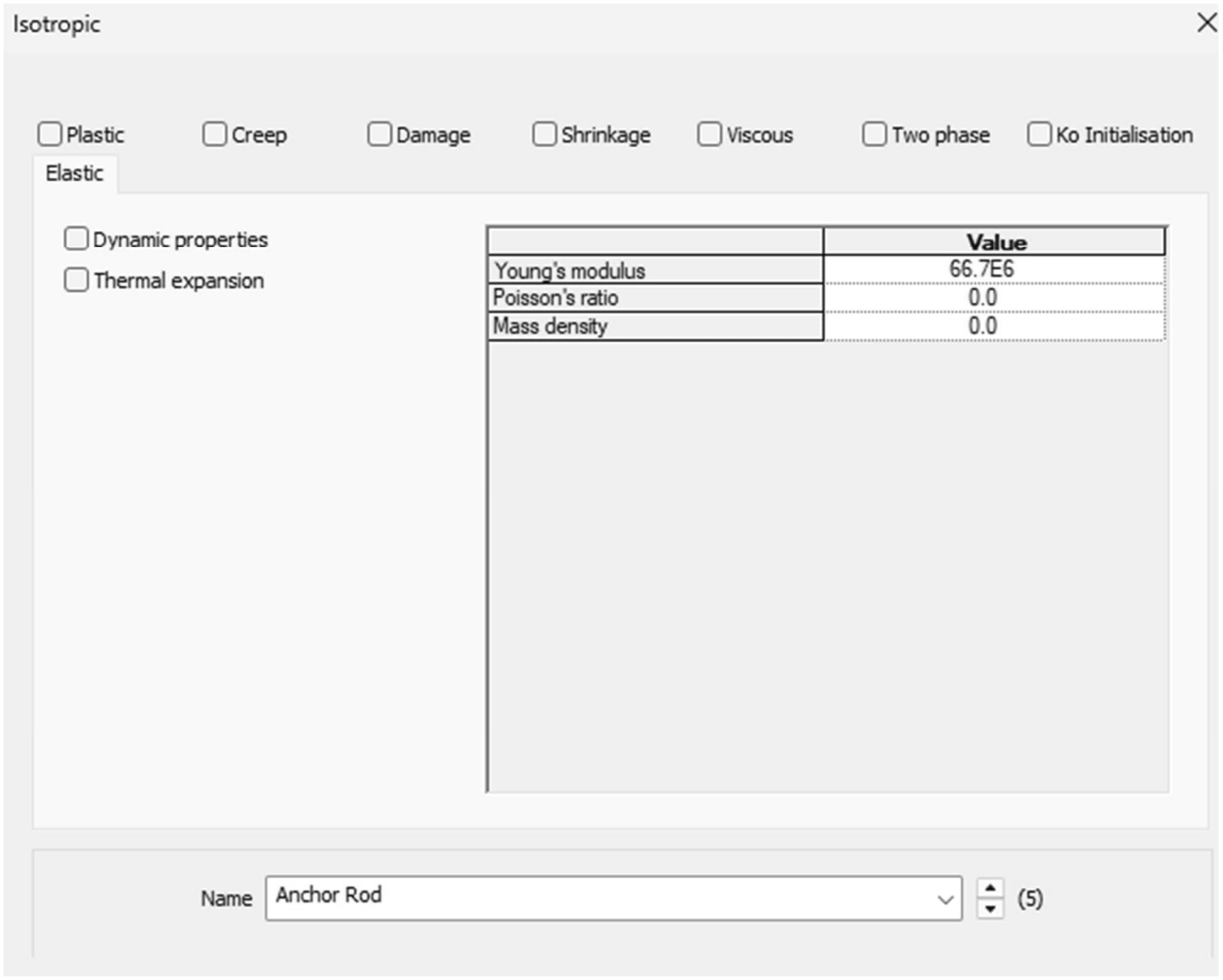
Retaining wall:

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



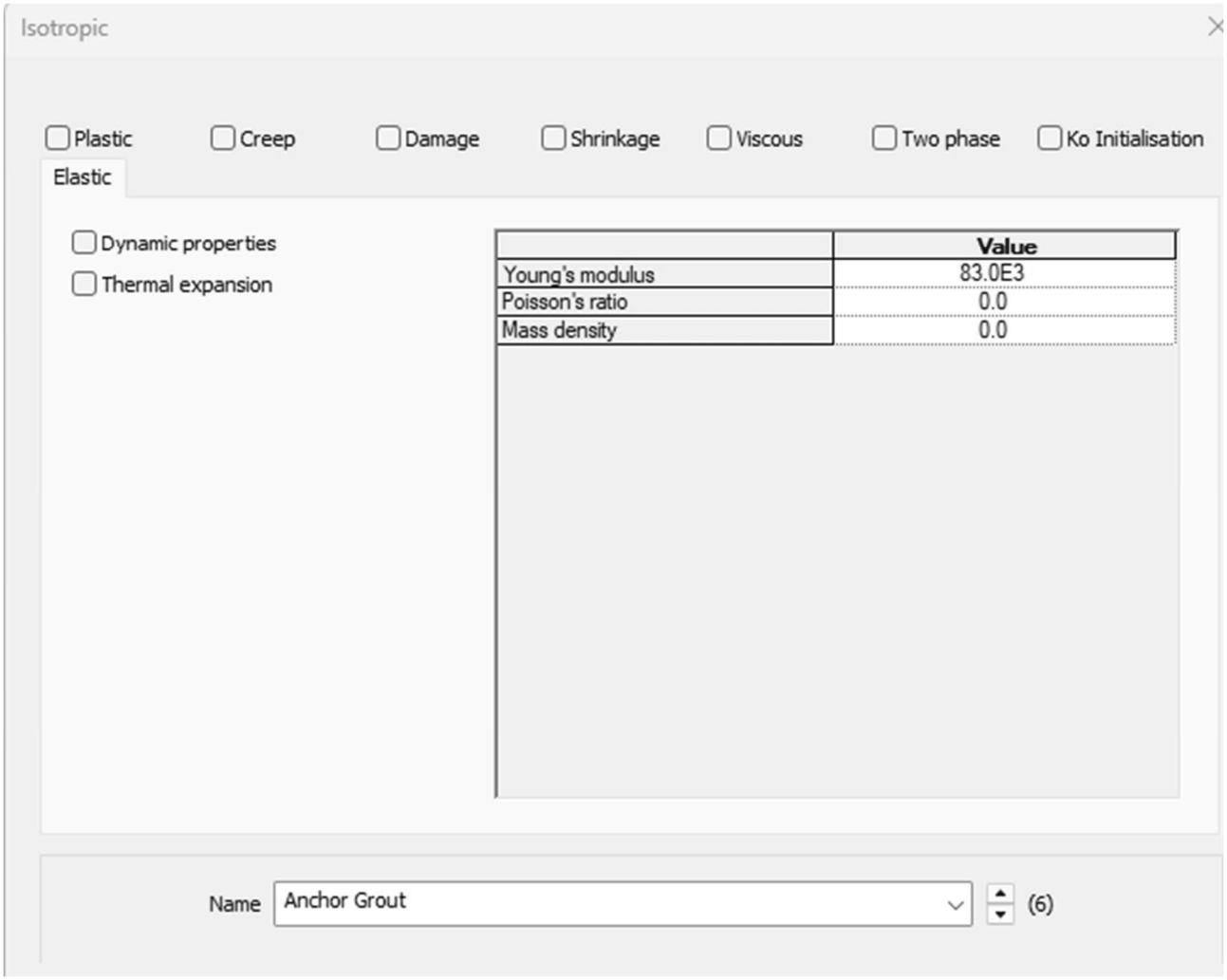
Anchor rods (c/c 3 m) :

The rods are placed c/c 3.0 m out of plain. This can be considered by reducing area of rods or by reducing stiffness corresponding to width 1 m. The later is used thus E-modulus is reduced to 1/3.



Anchor grouts (c/c 3 m) :

The anchor grouts are placed c/c 3.0 m out of plain. This can be considered by reducing area of rods or by reducing stiffness corresponding to width 1 m. The later is used thus E-modulus is reduced to 1/3.



2.7.2 Nonlinear material: soil

Soil is modelled modified Mohr-Coulomb. This model applies a Rankine tensile cut-off to standard Mohr-Coulomb model.

The standard model would predicts tensile stresses beyond the uniaxial tensile limit of the material, while the modified modell uses tension cut-off stress preventing this.

Definition	Parameter	Fill	Sand	Silt
Elastic	Young's Modulus	**8,000** kPa	**30,000** kPa	20,000 kPa
Elastic	Poisson's ratio	**0.3**	**0.3**	0.33
Elastic	Mass density (Fully Saturated)	**2.0**	**2.0**	**1.9**
Plastic	Friction angle	**30.0°**	**34.0°**	**29.0°**
Plastic	Dilation angle	**0 °**	**4.0°**	**0 °**
Plastic	Cohesion	**1.0** kPa	1.0 kPa	8.0°
Plastic (Rankine)	Tensile cut-off stress	**0** kPa	**0** kPa	**0** kPa

Definition	Parameter	Fill	Sand	Silt
Plastic (Rankine)	Compressive cut-off stress	**1E30** kPa	**1E30** kPa	1E30 kPa
Plastic (Rankine)	Damping factor	**0**		
Elastic (once Two-phase tab is selected)	Fully saturated soil density	**2.0** tonnes/m^3	**2.0** tonnes/m^3	**1.9** tonnes/m^3
Two phase (Partially saturated, Saturation)	Bulk modulus of fluid phase	**2.1** MPa	**2.1** MPa	**2.1** MPa
	Porosity of medium	**0.4**	**0.3**	**0.2**
	Hydraulic conductivity in global X, Y, Z	**0.5** m/day	**1.0** m/day	**0.1** m/day
	Density of fluid	**1** tonne/m^3	**1** tonne/m^3	**1** tonne/m^3
	Saturation at residual water content	**0.0**	**0.0**	**0.0**
	Saturation at full water content	**1.0**	**1.0**	**1.0**
(Constant water content)	Permeability factor in partially saturated zone	**1x10^{-3}**	**1x10^{-3}**	**1x10^{-3}**
Ko Initialisation	Coefficient of lateral earth pressure K_0	**0.5**	**0.441**	**0.515**

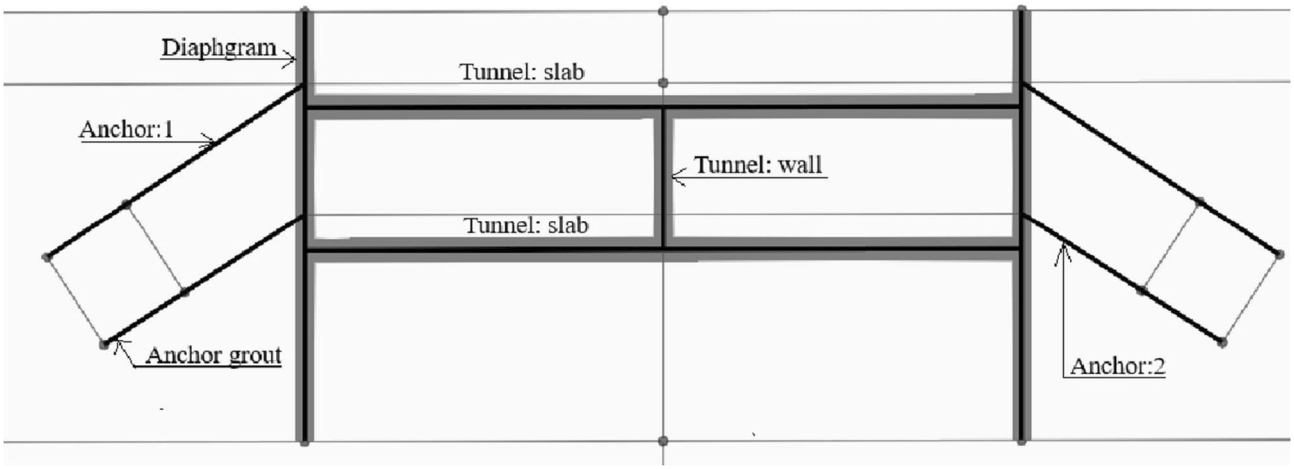
2.7.3 Nonlinear joint material between retaining wall and soil

The tangential slip surface is defined as seen below. No leakage is assumed through wall.

Defintion	**Parameter**	**Wall/Fill**	**Wall/Sand**
Soil structure interface (tangential slip)	Angle of friction	**20**^{o}	**24**^{o}
Soil structure interface (tangential slip)	Dilatency angle	0	0
Soil structure interface (tangential slip)	Cohesion	**0** kPa	**0.0** m/s

2.8 CROSS SECTIONS

Defined cross section properties.



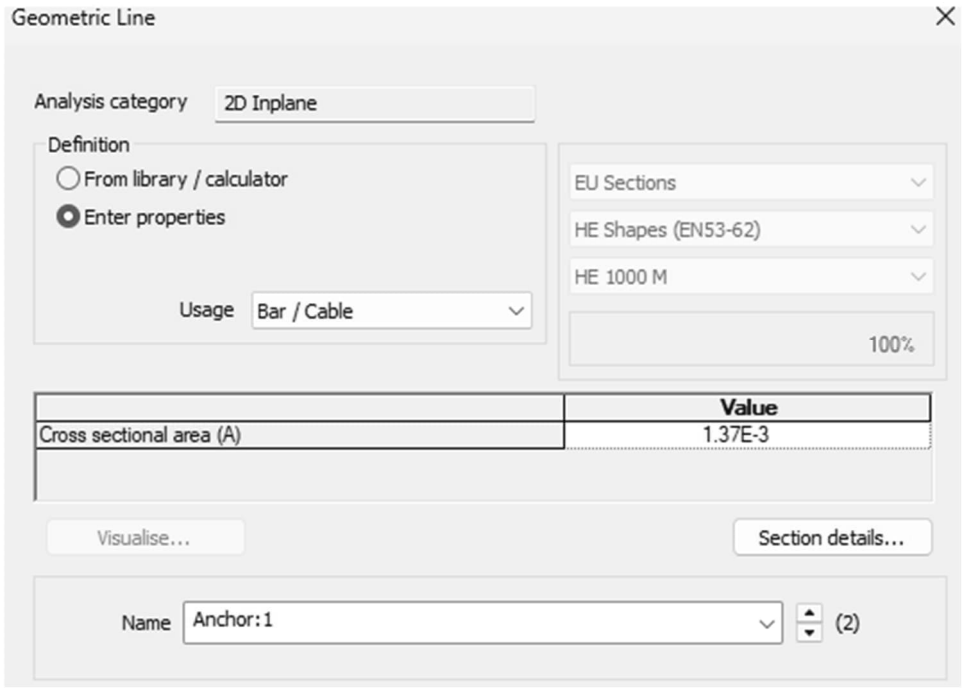
ELEVATION
Detail

2.8.1 Diaphragm

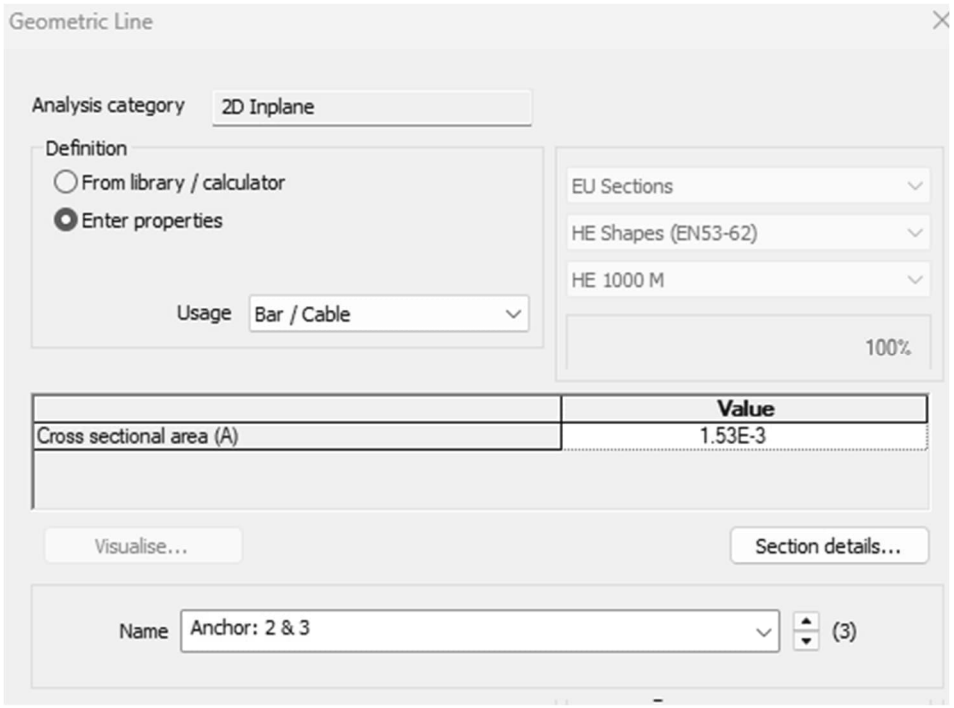
2.8.2 Rod anchor

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

Anchor 1 (c/c 2.3 m):

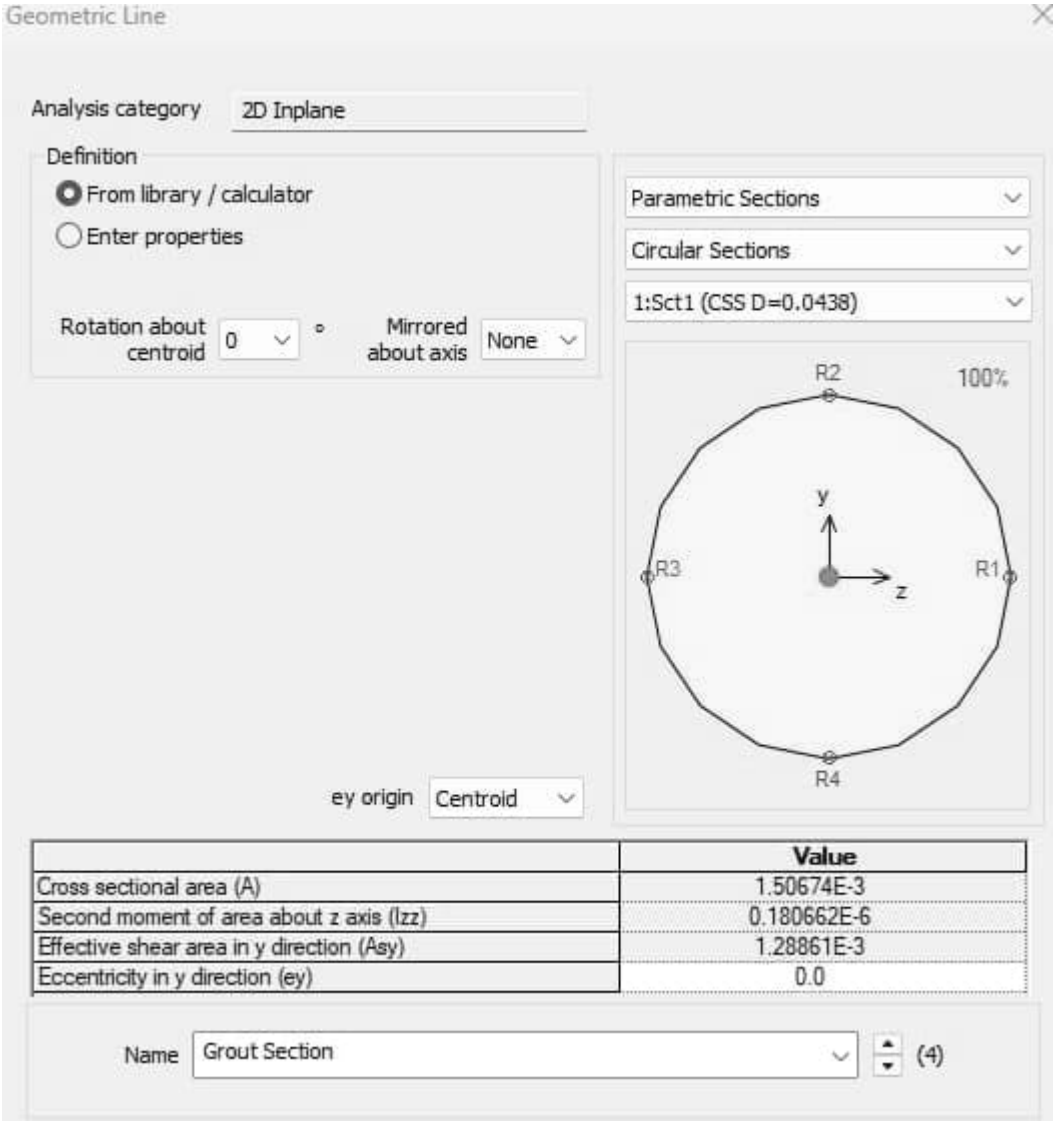


Anchor 2 (c/c 1.35 m):



2.8.3 Grout anchor

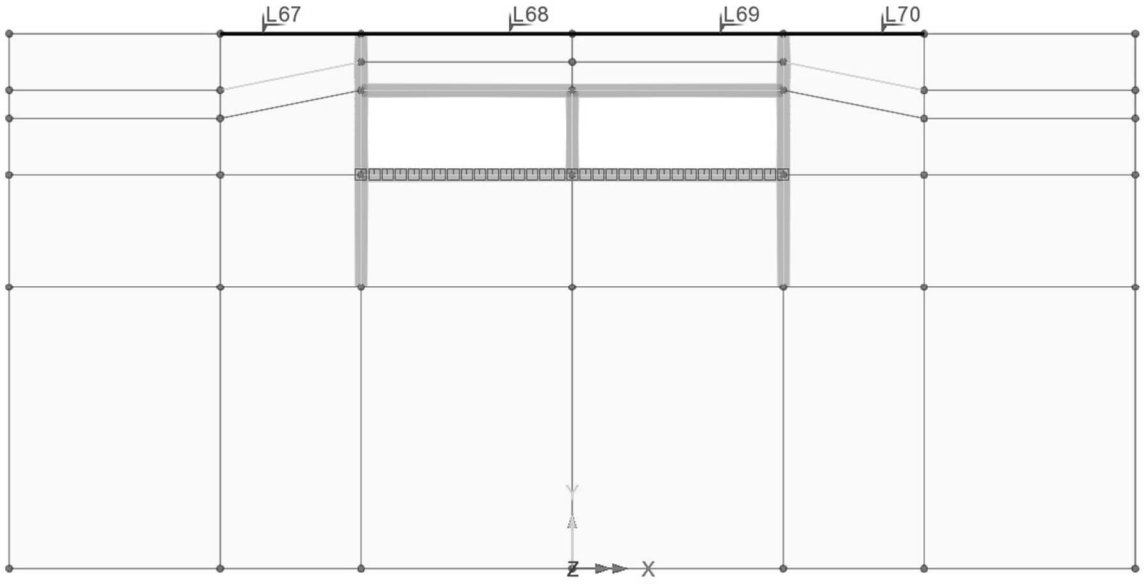
Same grout area is adapted to all grout anchors despite varying c/c of anchor rods. The simplification is considered negligible.



2.9 SEARCH AREA

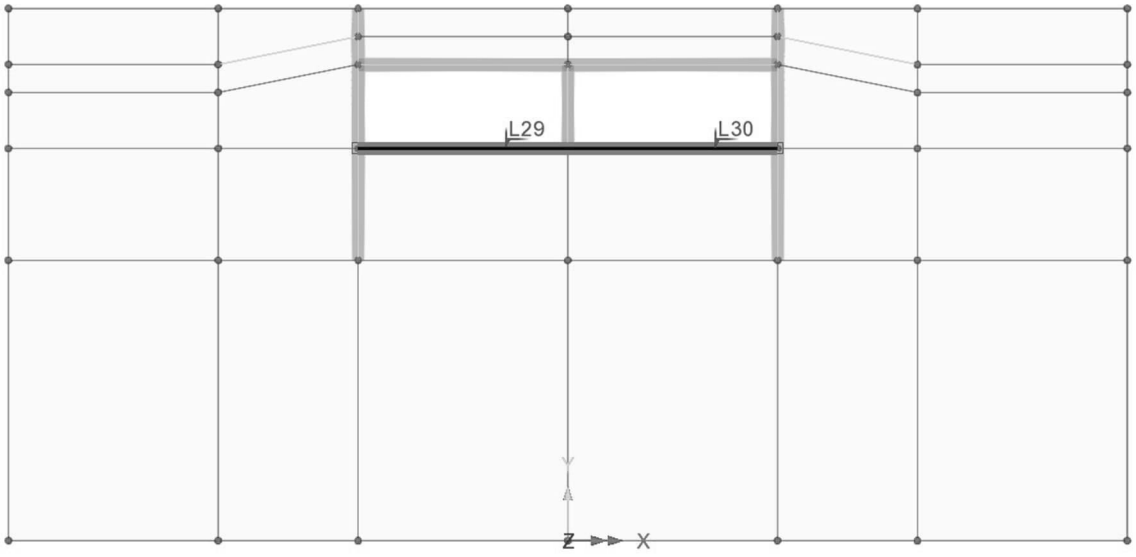
Discrete load can be applied to structure as geometrical load areas. The load areas are termed “Search Area”.

2.9.1 Search area: Fictive beam



ELEVATION

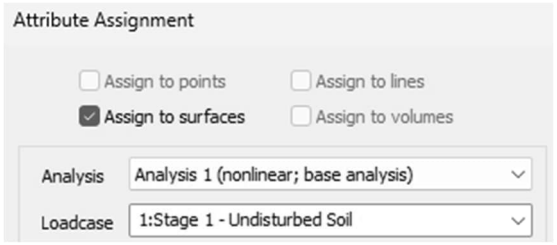
2.9.2 Search area: Bottom slab

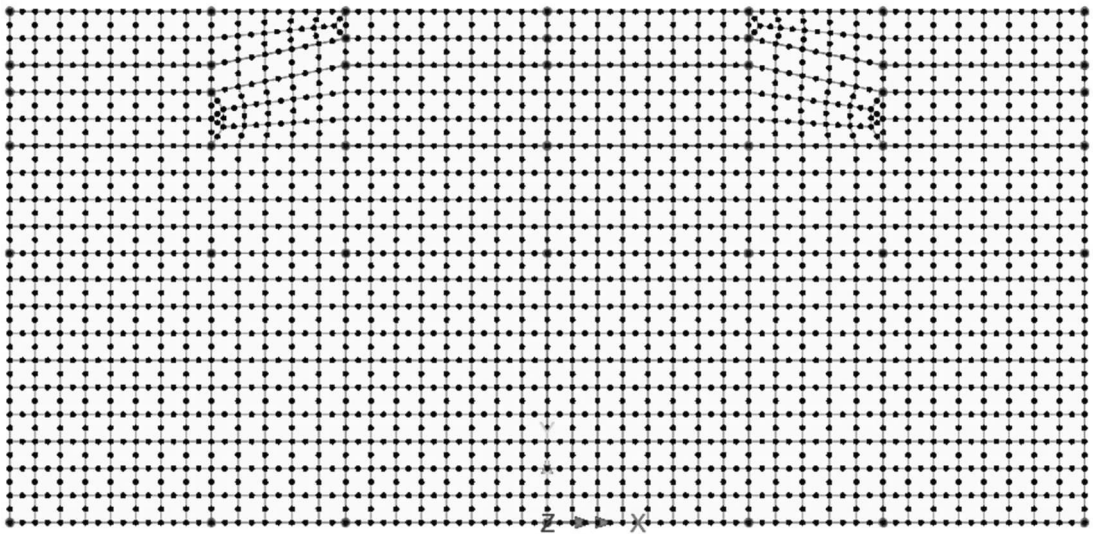


ELEVATION

2.10 RESET DEFORMATIONS

All node deformations at stage 1 are set to zero.



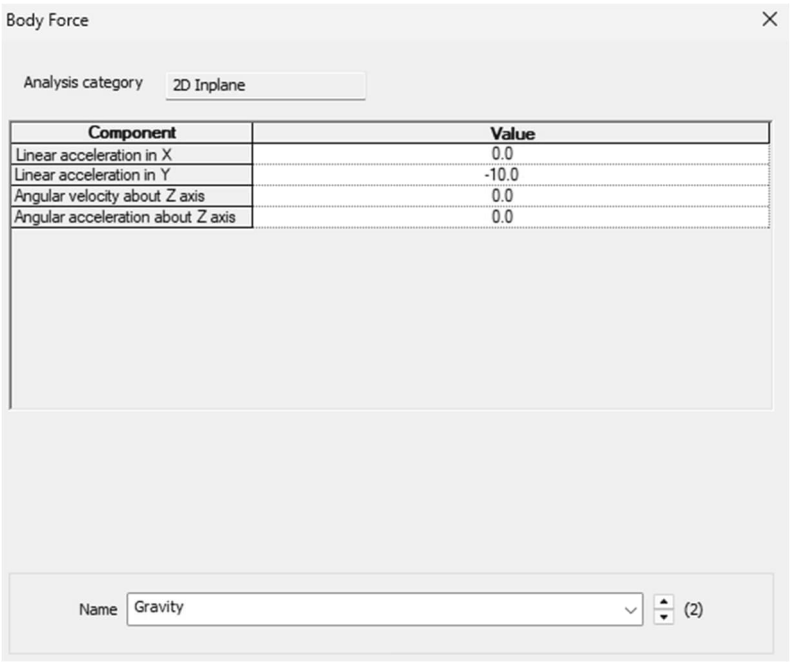


ELEVATION
Overall

3. LOADS

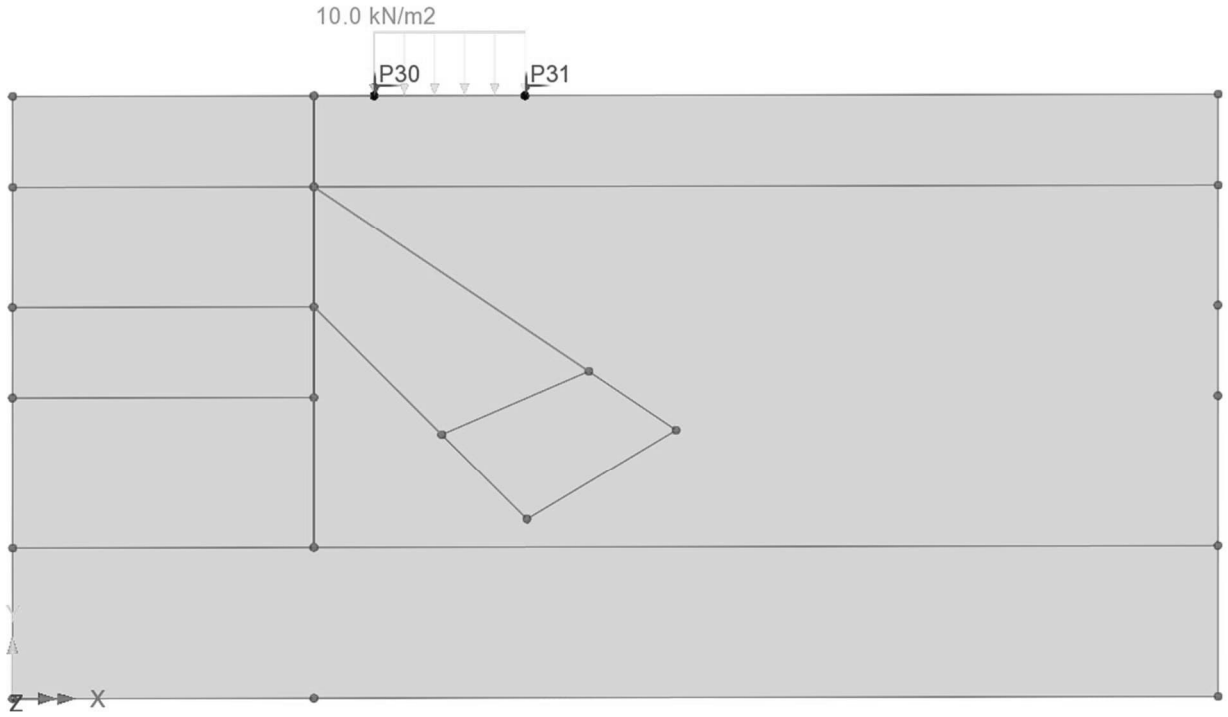
3.1 Soil weight (Gravity)

Soil weight is determined material density.



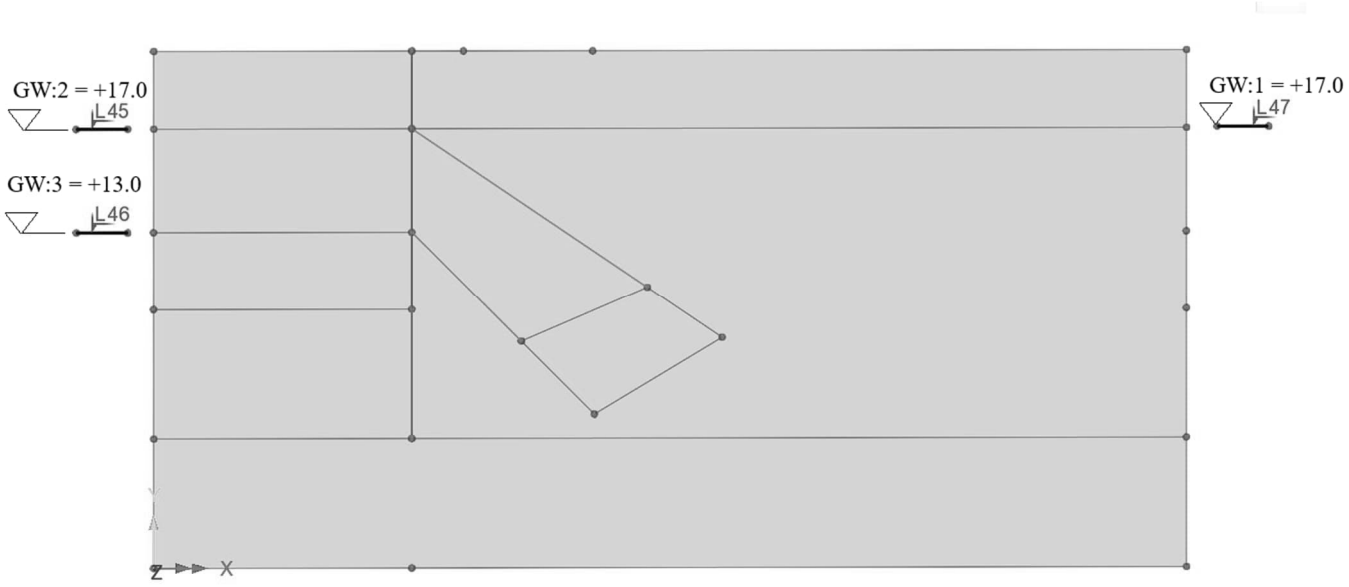
3.2 Surcharge

Surcharge (q = 10 kPa) on top of filling as seen below.



3.3 Ground water levels

Free groundwater surfaces (phreatic surfaces) are used to determine acting water pressures, see used levels.

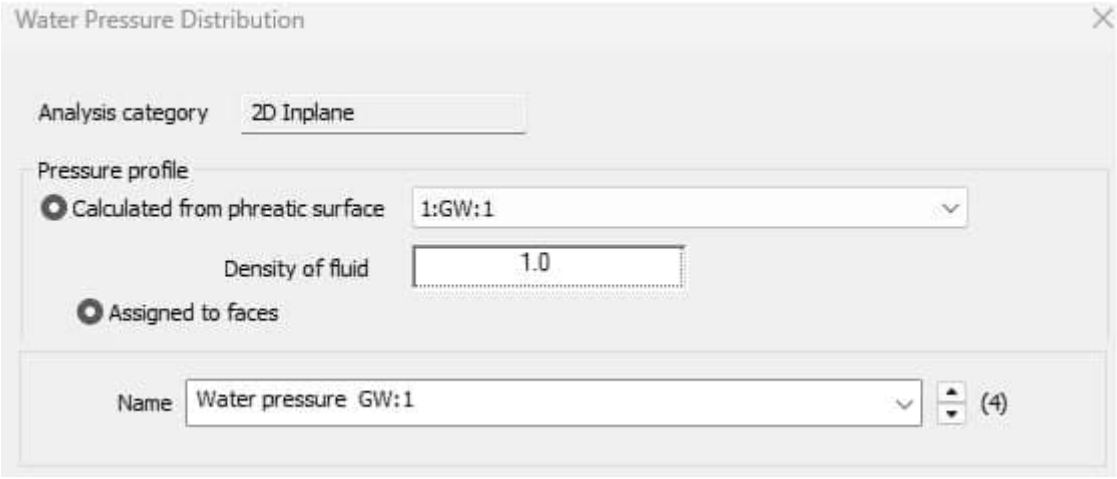


3.4 Water pressure

Water pressure varies according to load cases (construction stages).

3.4.1 Water pressure GW:1

Water pressure is associated to GW:1

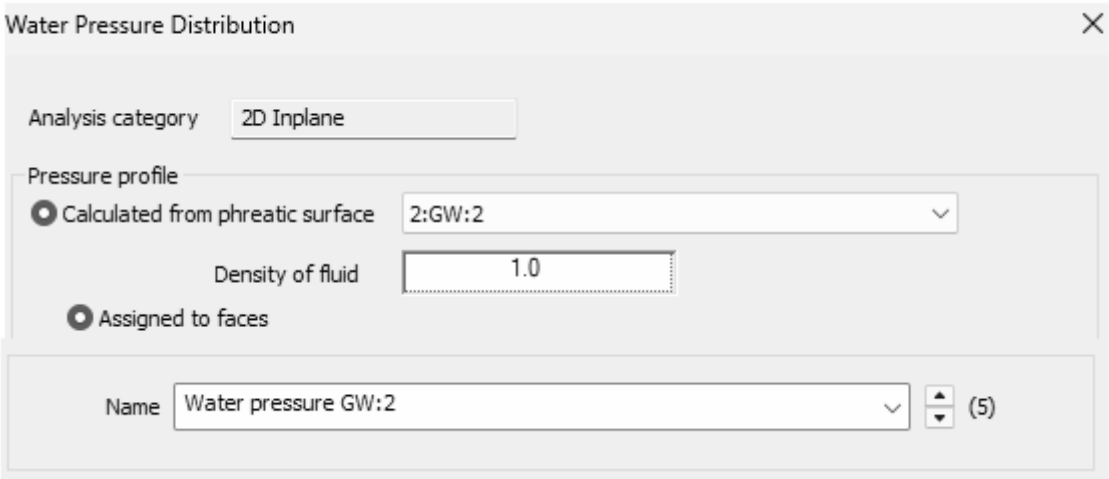


This load acts at load cases (stages) seen below.

Before excavation	☑
Install wall	☑
Surface load 10kPa	☑
Excavation:1	☐
Install anchor:1	☐
Set water level GW:2	☑
Reduction to GW:2	☐
Excavation:2	☐
Install anchor:2	☐
Set water level GW:3	☑
Reduction to GW:3	☐
Excavation:3	☐

3.4.2 Water pressure GW:2

Water pressure is associated to GW:2



This load acts at load cases (stages) seen below.

Before excavation	○
Install wall	○
Surface load 10kP	○
Excavation:1	○
Install anchor:1	○
Set water level G	●
Reduction to GW:	○
Excavation:2	○
Install anchor:2	○
Set water level G	○
Reduction to GW:	○
Excavation:3	○

3.4.3 Water pressure GW:3

Water pressure is associated to GW:3.

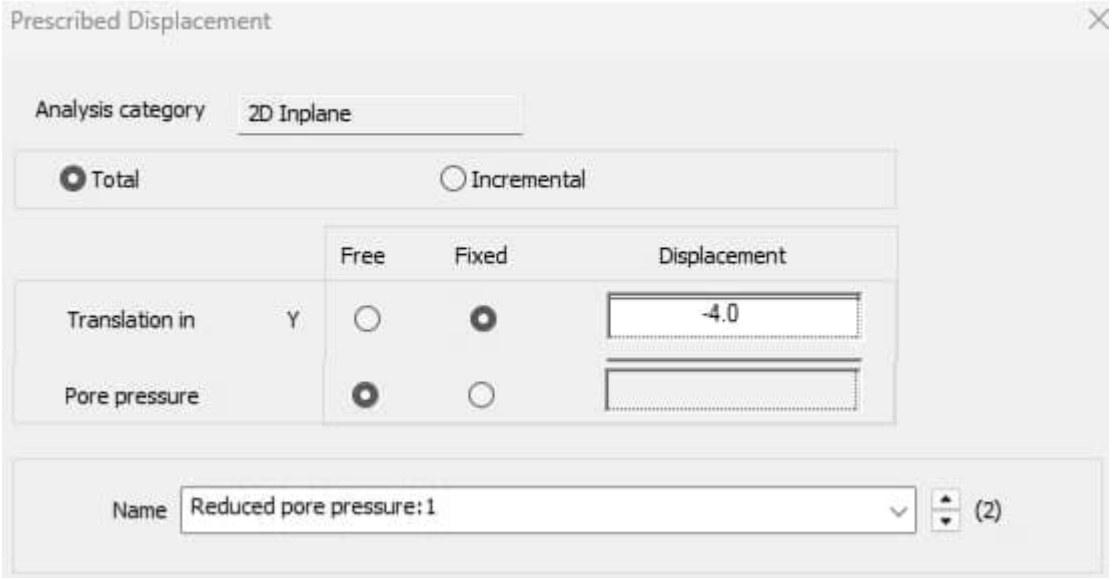
This load acts at load cases (stages) seen below.

Before excavation	○
Install wall	○
Surface load 10kP	○
Excavation:1	○
Install anchor:1	○
Set water level G	○
Reduction to GW:	○
Excavation:2	○
Install anchor:2	○
Set water level G	●
Reduction to GW:	○
Excavation:3	○

3.5 Reduced pore pressure

3.5.1 Reduced pore pressure:1

Reduction from GW:2 (+17.0 m) to GW:3 (+13.0 m) → -4.0 m

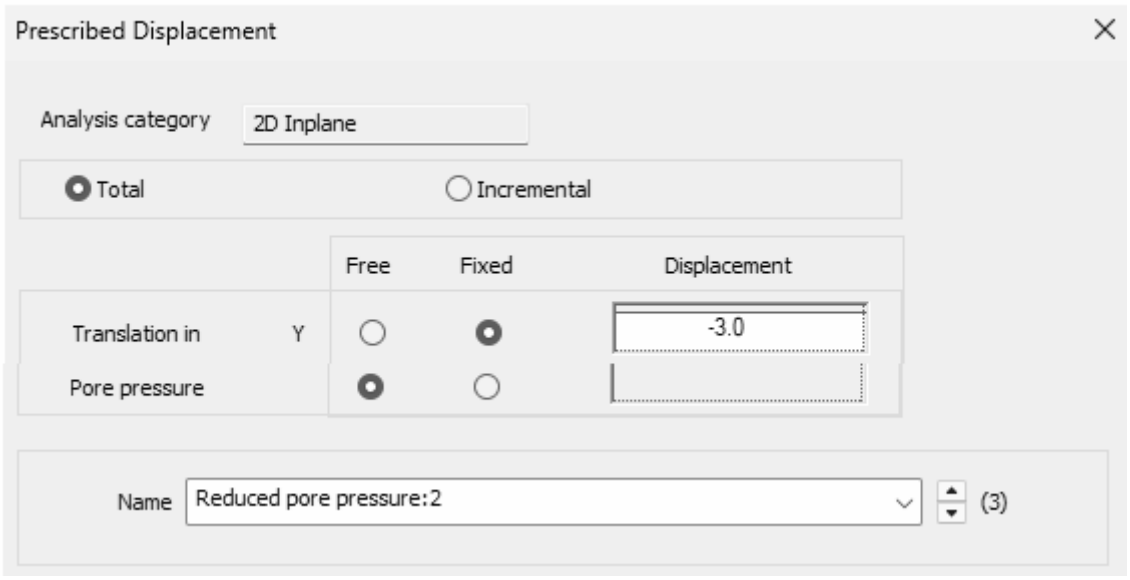


This load acts at load cases (stages) seen below.

Before excavation	○
Install wall	○
Surface load 10kPa	○
Excavation:1	○
Install anchor:1	○
Set water level GW:2	○
Reduction to GW:2	◉
Excavation:2	○
Install anchor:2	○
Set water level GW:3	○
Reduction to GW:3	○

3.5.2 Reduced pore pressure:2

Reduction from GW:3 (+13.0 m) to +10.0 m → -3.0 m



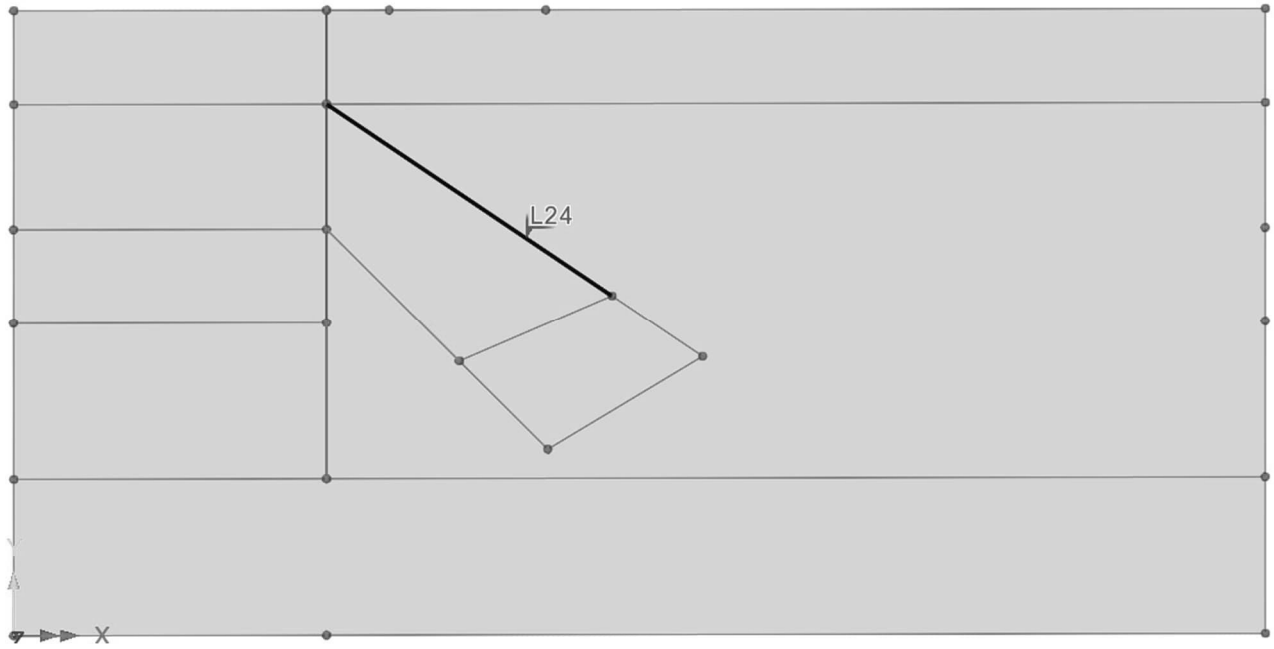
This load acts at load cases (stages) seen below.

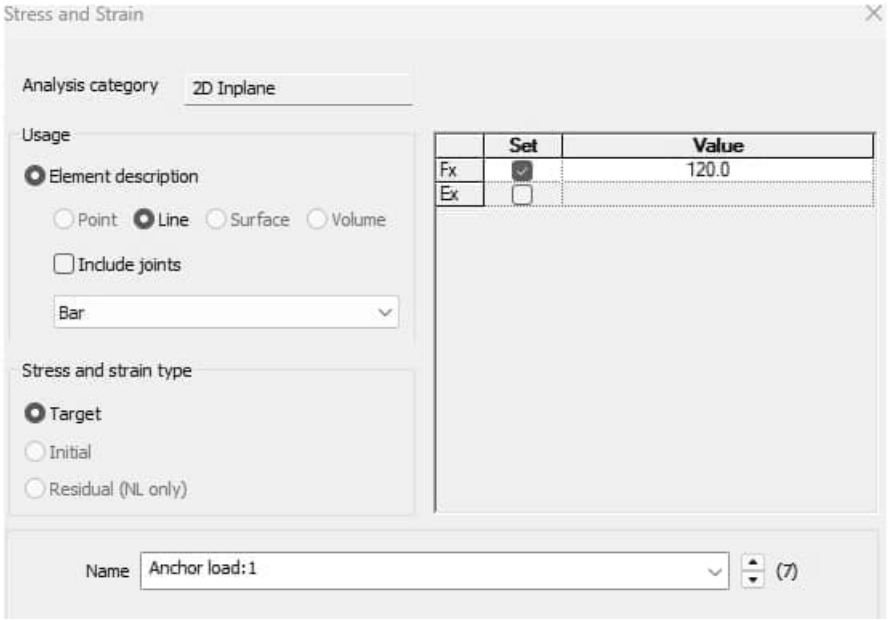
Before excavation	○
Install wall	○
Surface load 10kPa	○
Excavation:1	○
Install anchor:1	○
Set water level GW:2	○
Reduction to GW:2	○
Excavation:2	○
Install anchor:2	○
Set water level GW:3	○
Reduction to GW:3	●

3.6 Anchor loads

3.6.1 Anchor load:1

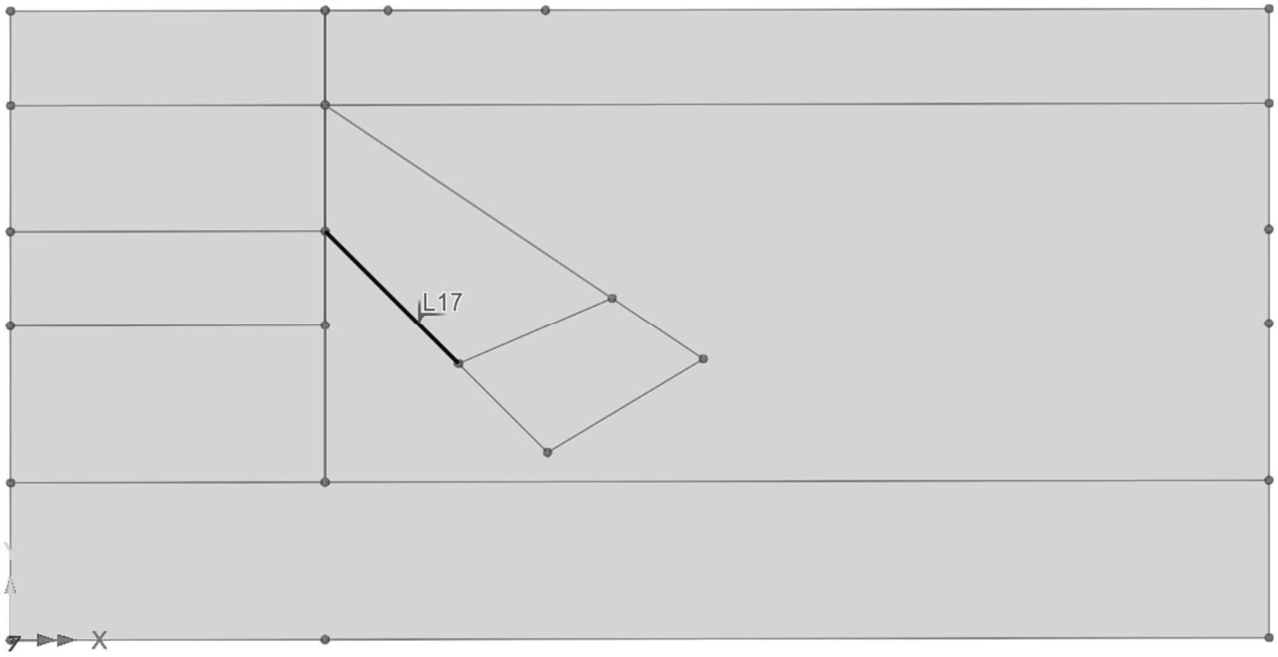
Total anchor load 360 kN (c/c 3 m) → Fx = 120 kN is applied to L24.

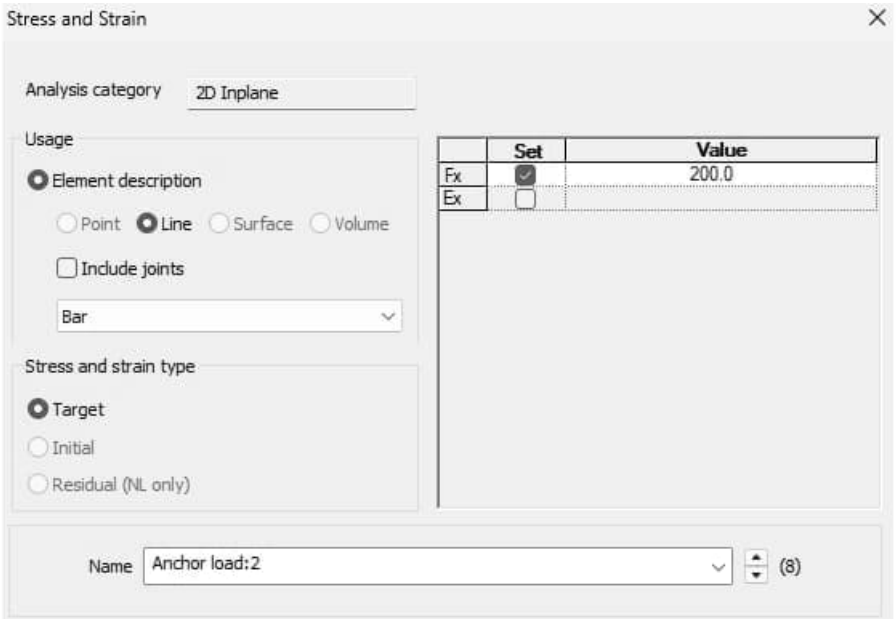




3.6.2 Anchor load:2

Total anchor load 600 kN (c/c 3 m) → Fx = 200 kN is applied to L17.





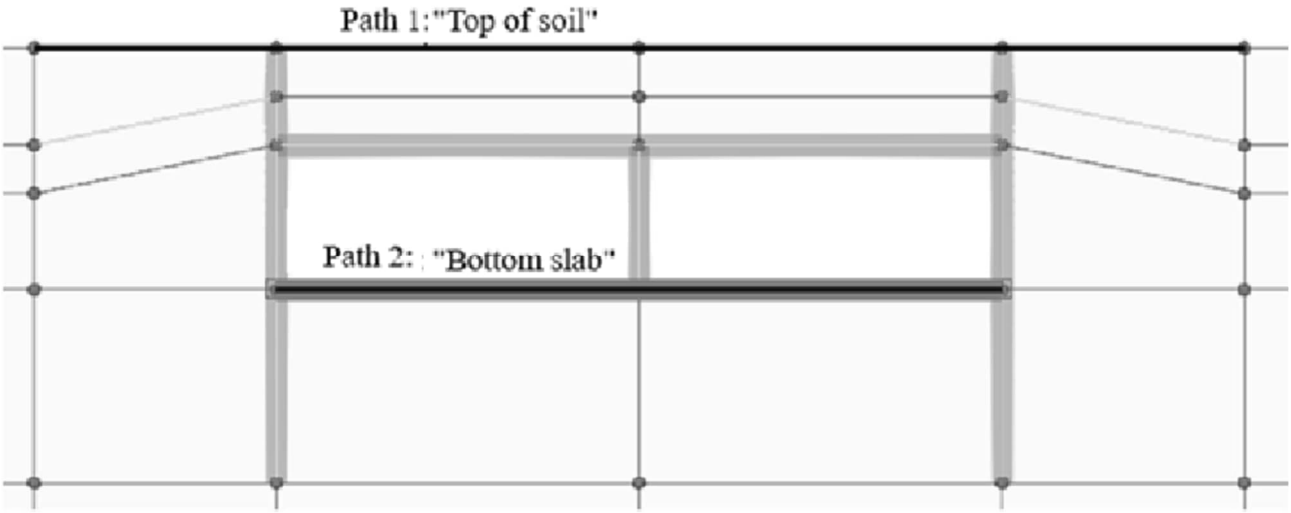
3.7 Traffic load – LM 1

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



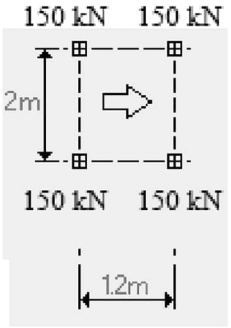
ELEVATION

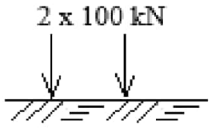
3.7.1 Road “Top of soil”

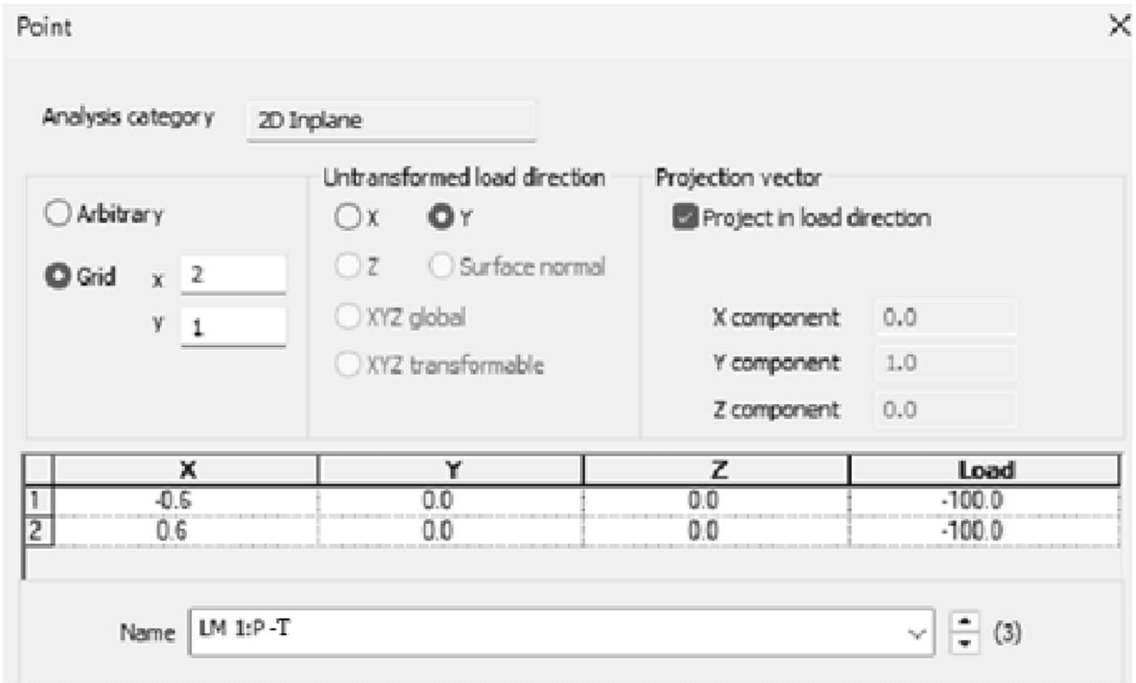
3.7.1.1 Traffic load

Axle load (LM 1:P-T):

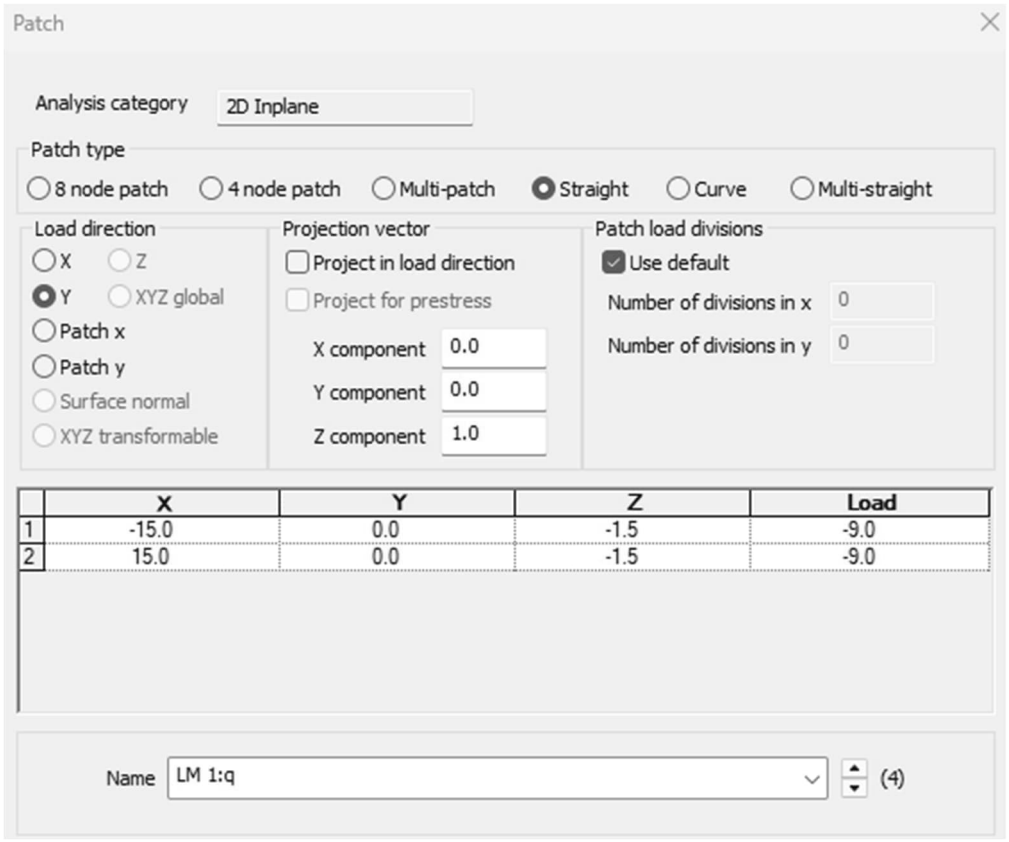
Distribution width 3.0 m I assumed in transversal traffic direction.



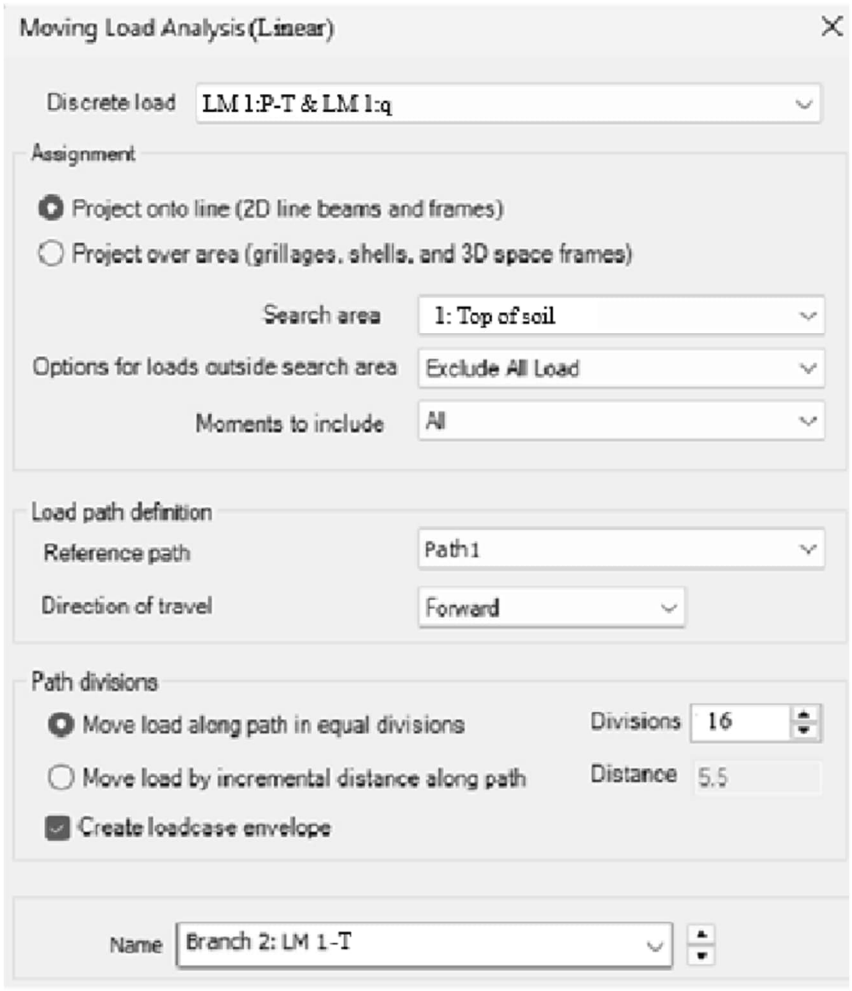




Surface load (LM 1:q):



3.7.1.2 Linear analysis



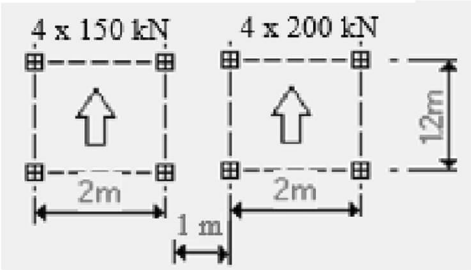
3.7.1.3 Nonlinear analysis

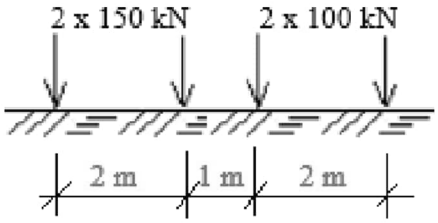
3.7.2 Road “Bottom slab”

3.7.2.1 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

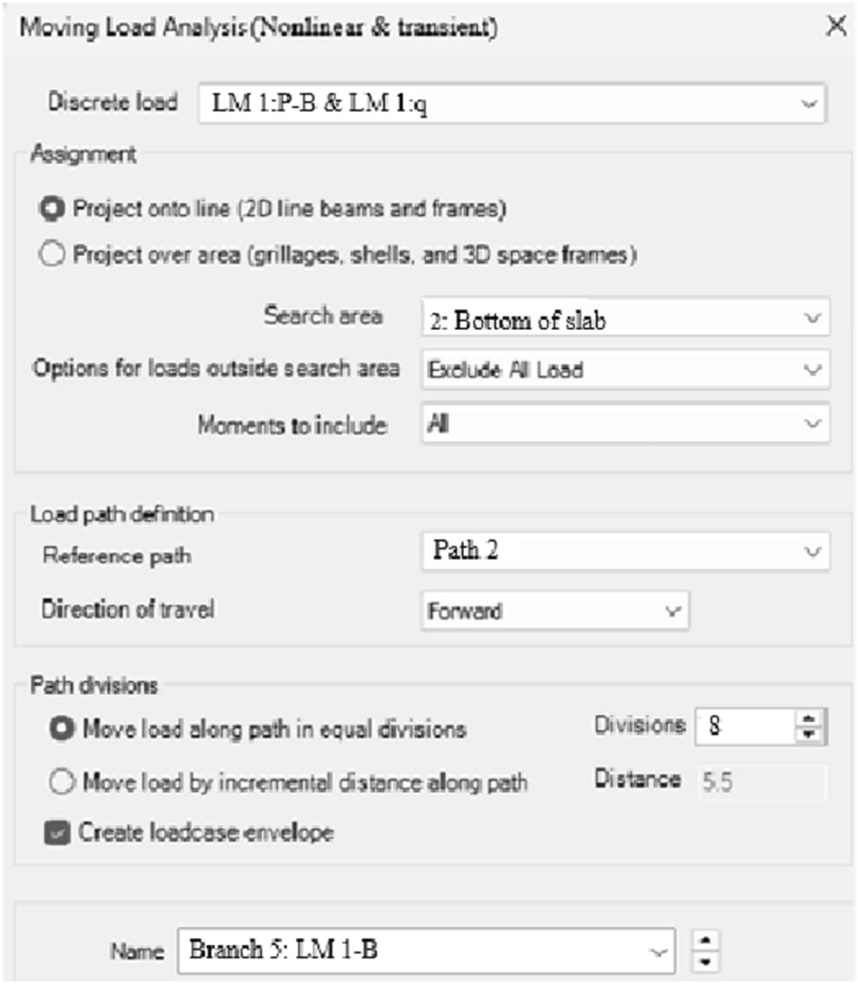
Name: LM 1:P-B (5)

Surface load (LM 1:q):

See page 37.

3.7.2.2 Linear analysis

3.7.2.3 Nonlinear analysis



4. RESULTS (FEM-program)

Vacant.