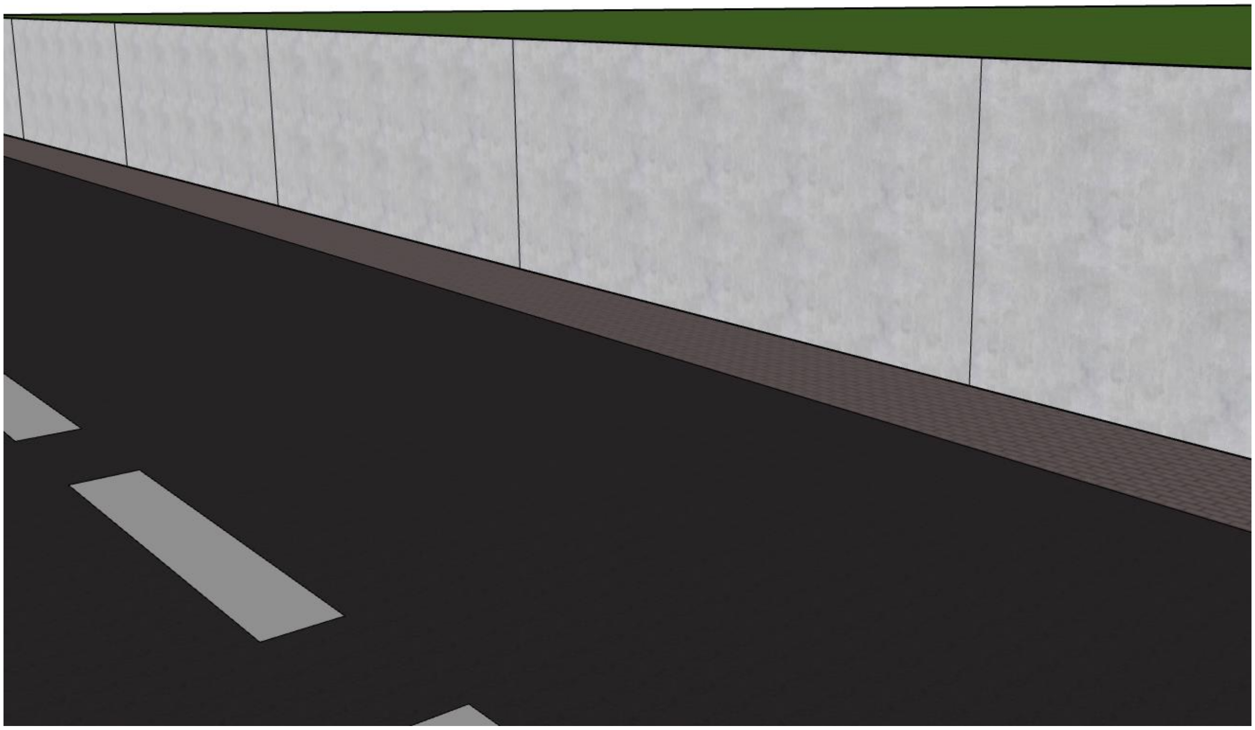
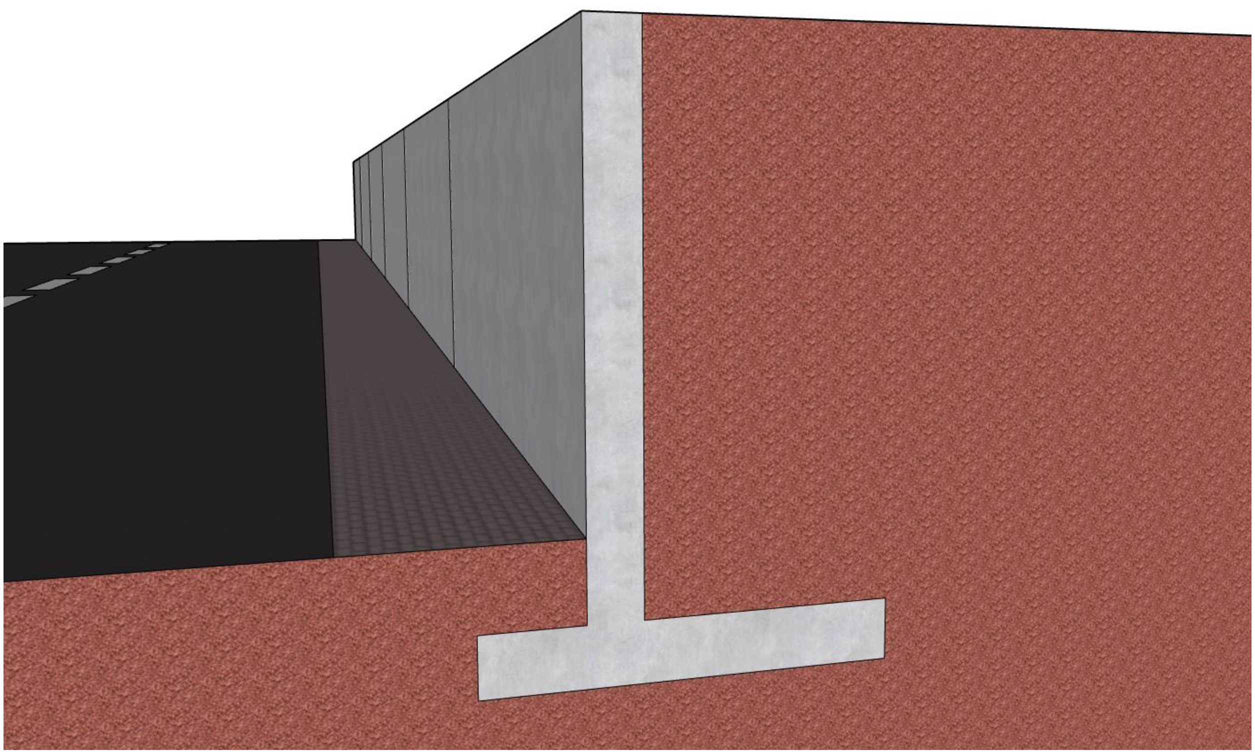
Reinforced Concrete Cantilever Retaining Wall Analysis and Design (ACI 318M-14)





Reinforced Concrete Cantilever Retaining Wall Analysis and Design (ACI 318M-14)

Reinforced concrete cantilever retaining walls consist of a relatively thin stem and a base slab. The stem may have constant thickness along the length or may be tapered based on economic and construction criteria. The base is divided into two parts, the heel and toe. The heel is the part of the base under the backfill. This system uses much less concrete than monolithic gravity walls, but require more design and careful construction. Cantilever retaining walls can be precast in a factory or formed on site and considered economical up to about 7.5 m in height. This case study focuses on the analysis and design of a cantilever retaining wall using the engineering software programs spWall and spMats. The retaining wall is fixed to the reinforced concrete slab foundation and have a uniform cross section. After examining the wall stability, it was concluded that shear key is not needed to resist wall sliding. More information and detailed hand calculations about tapered cantilever retaining wall with shear key are provided in "Reinforced Concrete Cantilever Retaining Wall Analysis and Design (ACI 318-14)" design example. The following figure and design data section will serve as input for detailed analysis and design.

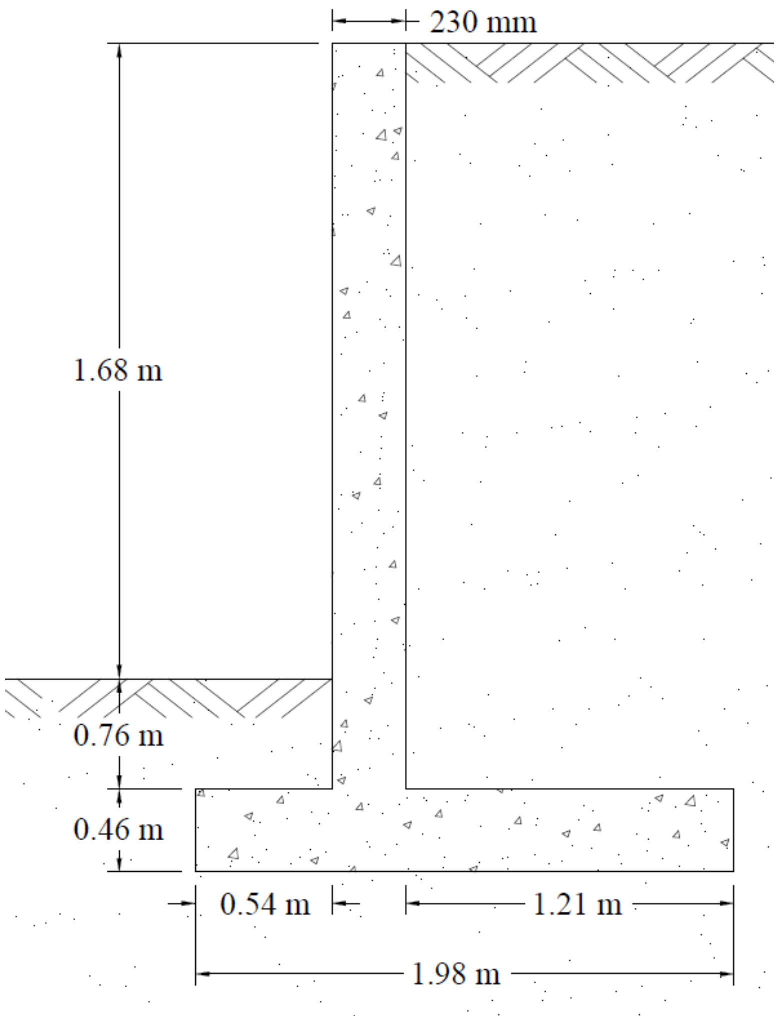


Figure 1 – Cantilever Retaining Wall Dimensions

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Code

Building Code Requirements for Structural Concrete (ACI 318M-14) and Commentary (ACI 318RM-14)

Reference

- Foundation Analysis and Design, 5th Edition, 1997, Joseph Bowles, McGraw-Hill Companies, Example 12.6
- spWall Engineering Software Program Manual v10.00, STRUCTUREPOINT, 2022
- spMats Engineering Software Program Manual v10.00, STRUCTUREPOINT, 2020

Design Data

Wall Stem Materials

f_c' = 21 MPa

f_y = 200 MPa

γ_c = 2400 kg/m^3

Wall Foundation Materials

f_c' = 21 MPa

f_y = 200 MPa

γ_c = 2400 kg/m^3

Wall Stem Dimensions

Width = 1.0 m strip

Height = 2.44 m

Thickness = 230 mm

Wall Foundation Dimensions

Width = 1.0 m strip

Length = 1.98 m

Thickness = 460 mm

Retaining Wall Loads

The following figure shows all the loads applied to the retaining wall where:

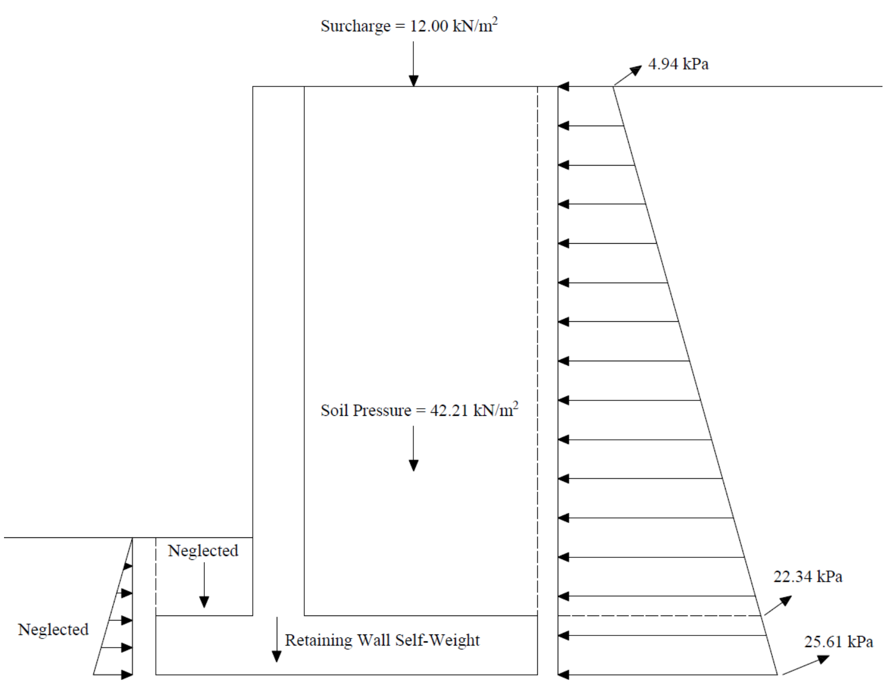

Figure 2 – Applied Loads

1. Cantilever Retaining Wall Analysis and Design – spWall Software

spWall is a program for the analysis and design of reinforced concrete shear walls, tilt-up walls, precast walls, retaining walls, tank walls and Insulated Concrete Form (ICF) walls. It uses a graphical interface that enables the user to easily generate complex wall models. Graphical user interface is provided for:

- Wall geometry (including any number of openings and stiffeners)
- Material properties including cracking coefficients
- Wall loads (point, line, and area)
- Support conditions (including translational and rotational spring supports)

spWall uses the Finite Element Method for the structural modeling, analysis, and design of slender and non-slender reinforced concrete walls subject to static loading conditions. The wall is idealized as a mesh of rectangular plate elements and straight line stiffener elements. Walls of irregular geometry are idealized to conform to geometry with rectangular boundaries. Plate and stiffener properties can vary from one element to another but are assumed by the program to be uniform within each element.

Six degrees of freedom exist at each node: three translations and three rotations relating to the three Cartesian axes. An external load can exist in the direction of each of the degrees of freedom. Sufficient number of nodal degrees of freedom should be restrained in order to achieve stability of the model. The program assembles the global stiffness matrix and load vectors for the finite element model. Then, it solves the equilibrium equations to obtain deflections and rotations at each node. Finally, the program calculates the internal forces and internal moments in each element. At the user's option, the program can perform second order analysis. In this case, the program takes into account the effect of in-plane forces on the out-of-plane deflection with any number of openings and stiffeners.

In spWall, the required flexural reinforcement is computed based on the selected design standard (ACI 318-14 is used in this case study), and the user can specify one or two layers of wall reinforcement. In stiffeners and boundary elements, spWall calculates the required shear and torsion steel reinforcement. Wall concrete strength (in-plane and out-of-plane) is calculated for the applied loads and compared with the code permissible shear capacity.

For illustration purposes, the following figures provide a sample of the input modules and results obtained from an spWall model created for the retaining wall in this case study.

1.1. Cantilever Retaining Wall Model Input

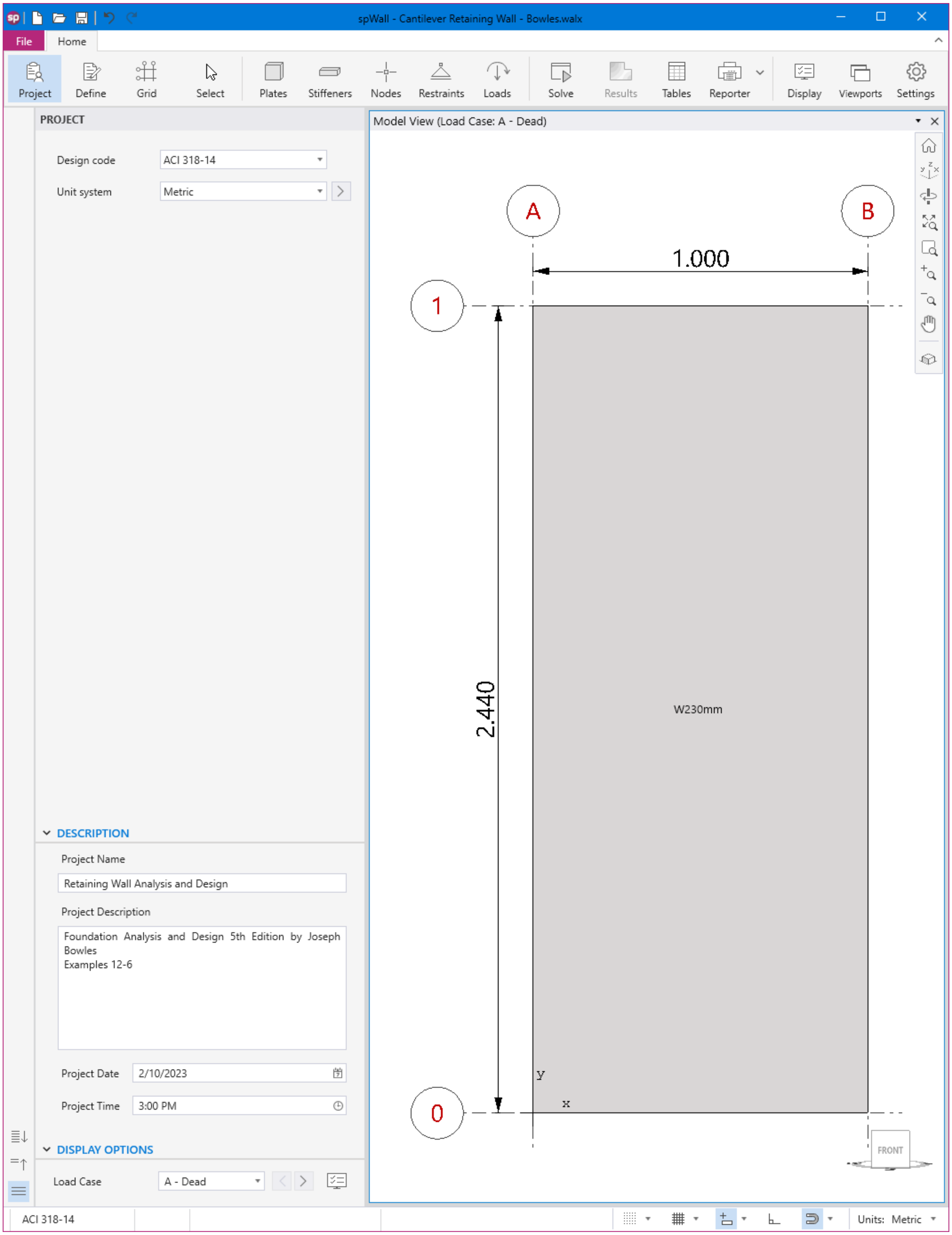

Figure 3 – spWall Interface

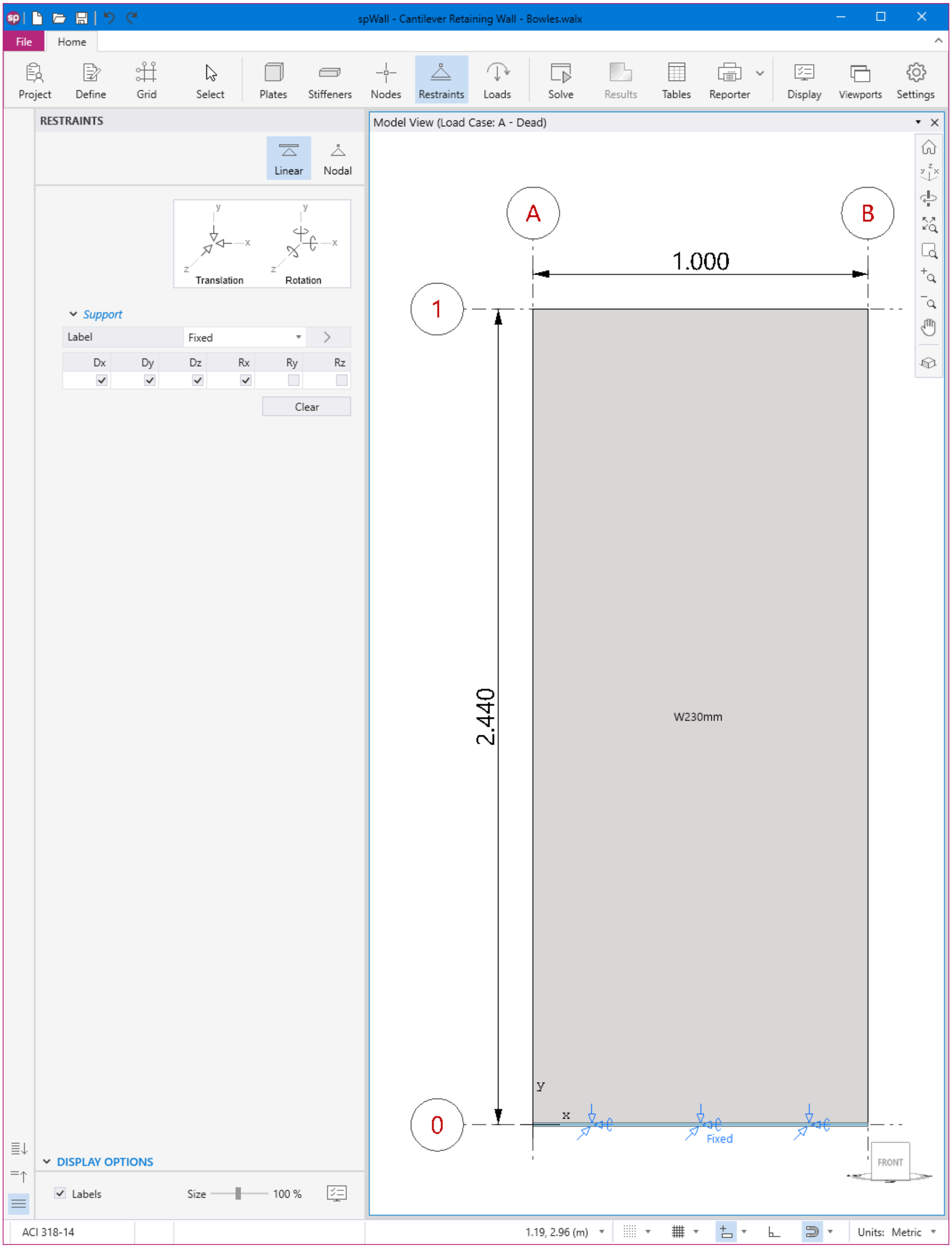

Figure 4 – Assigning Wall Stem Restraints for Cantilever Retaining Wall (spWall)

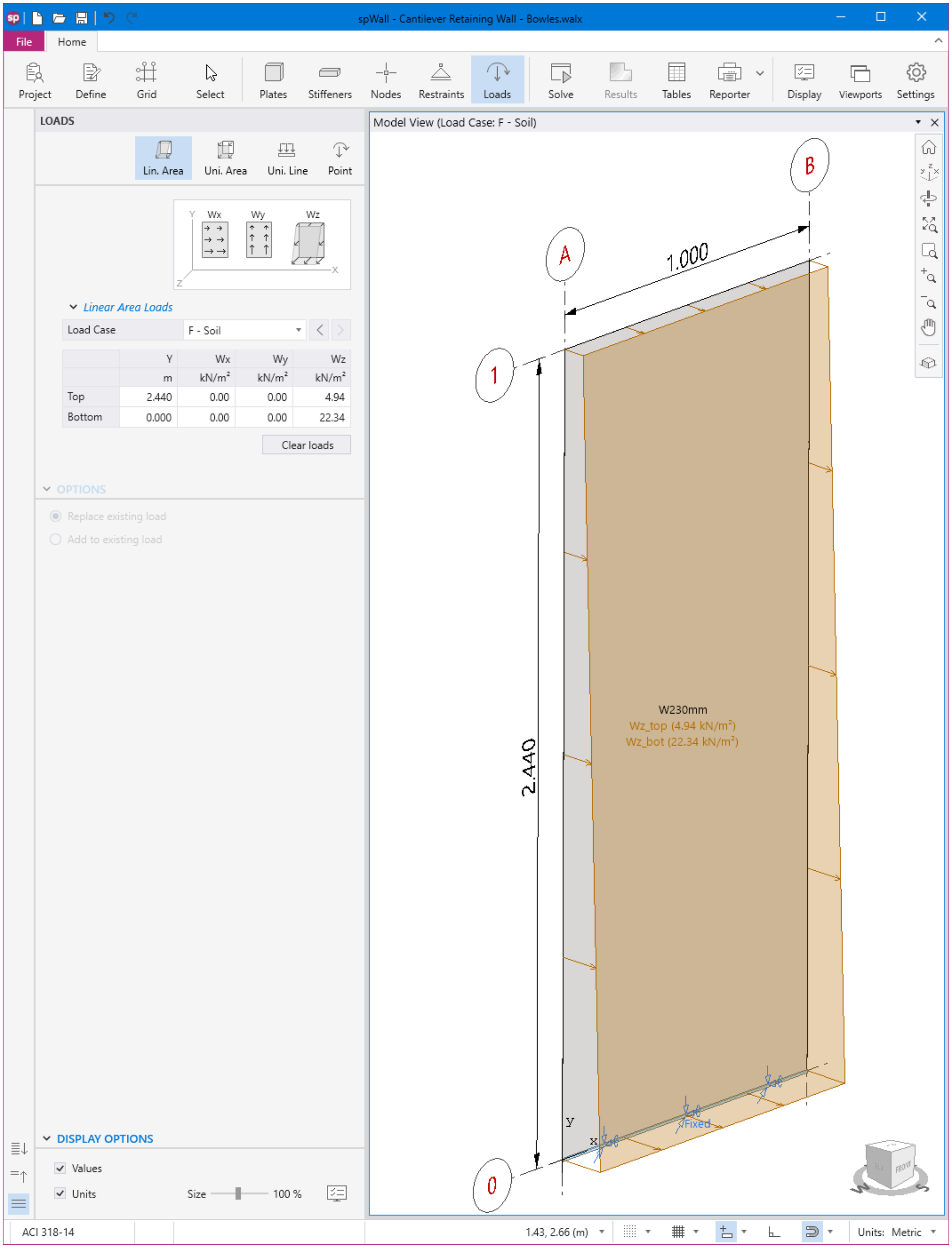

Figure 5 – Assigning Soil Loads for Cantilever Retaining Wall (spWall)

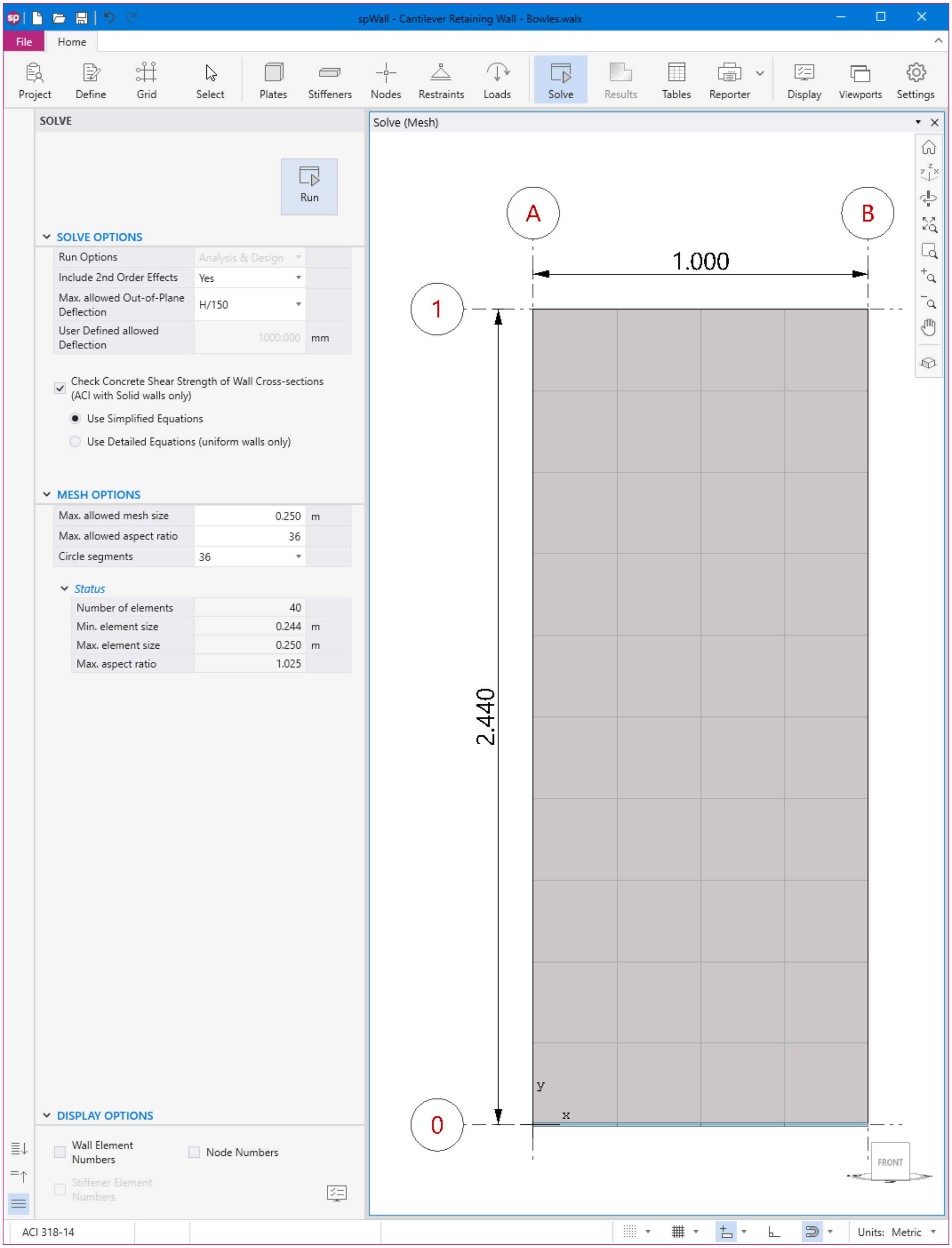

Figure 6 – Solve and Mesh Options (spWall)

1.2. Cantilever Retaining Wall Results Contours

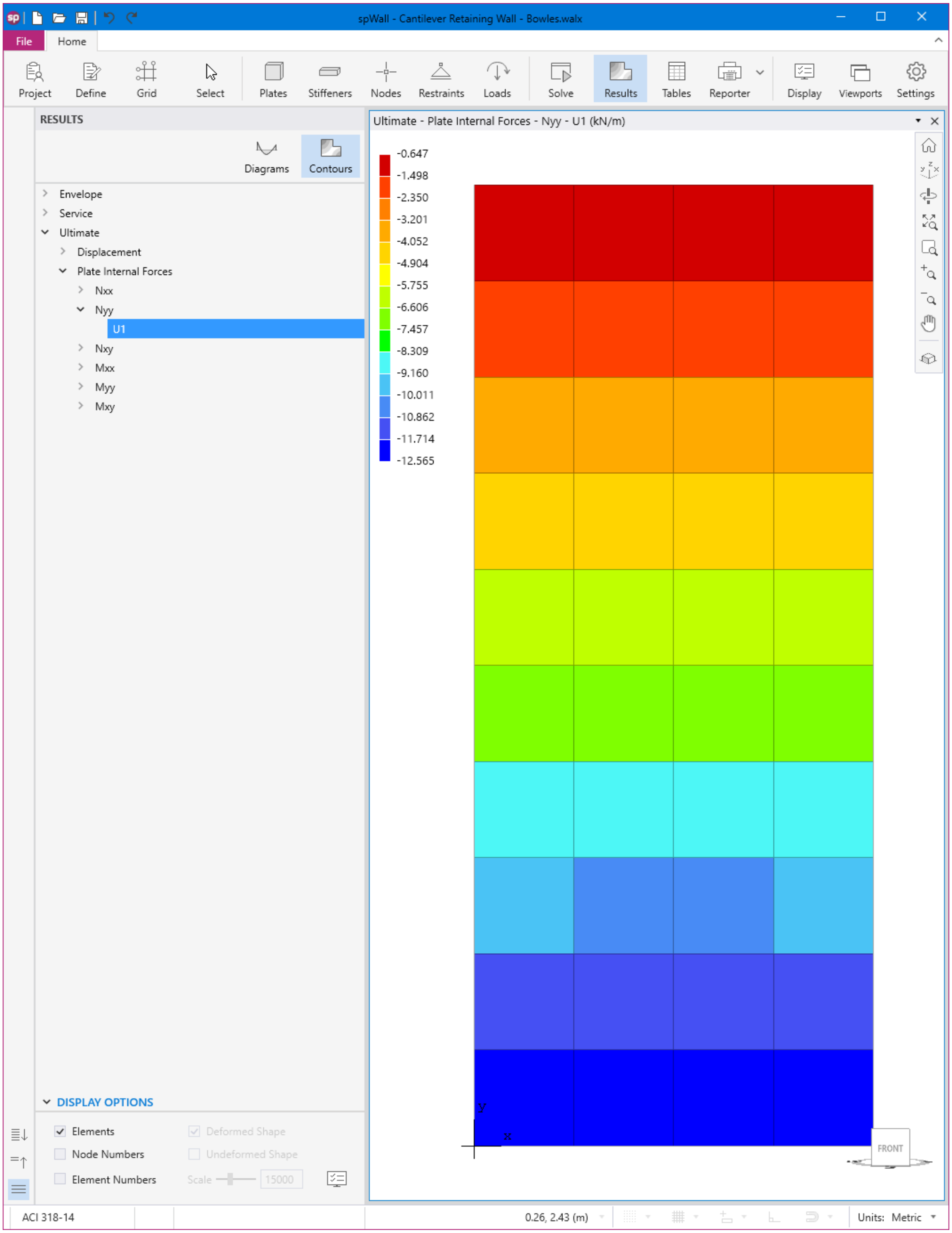

Figure 7 – Factored Axial Force Contour (spWall)

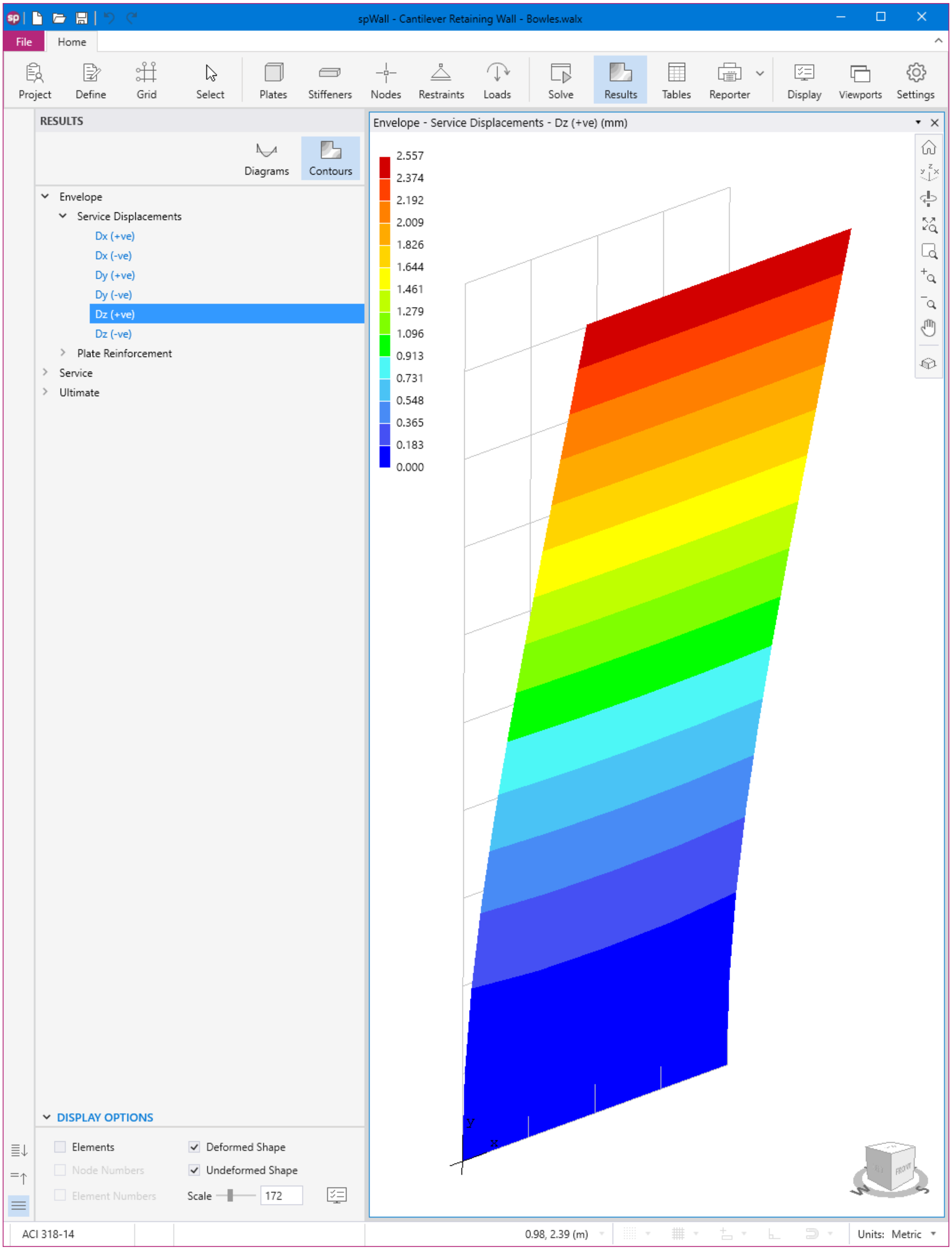

Figure 8 – Lateral Displacement Contour (Out-of-Plane) (spWall)

1.3. Cantilever Retaining Wall Cross-Sectional Forces

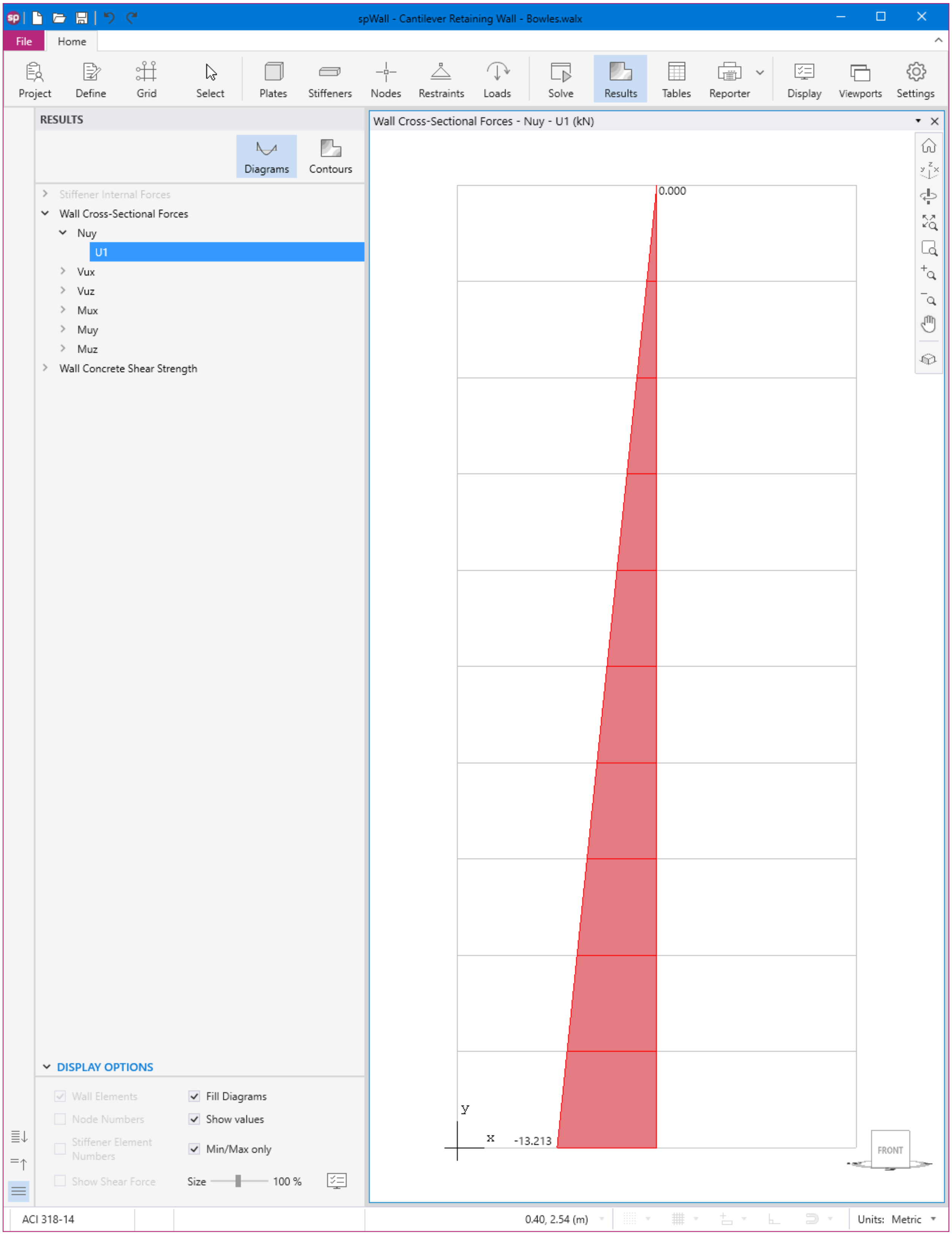

Figure 9 – Axial Load Diagram (spWall)

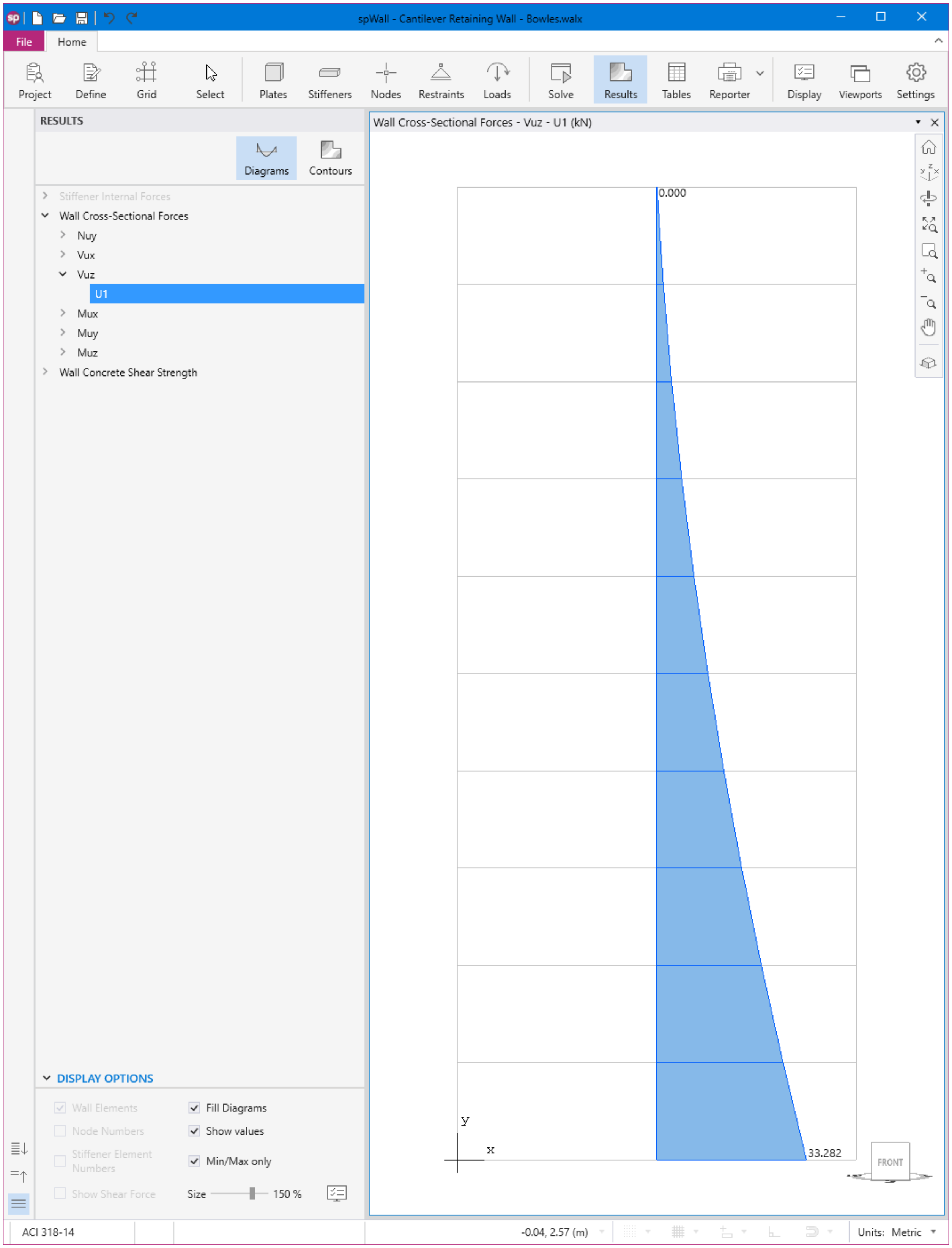

Figure 10 – Out-of-plane Shear Diagram (spWall)

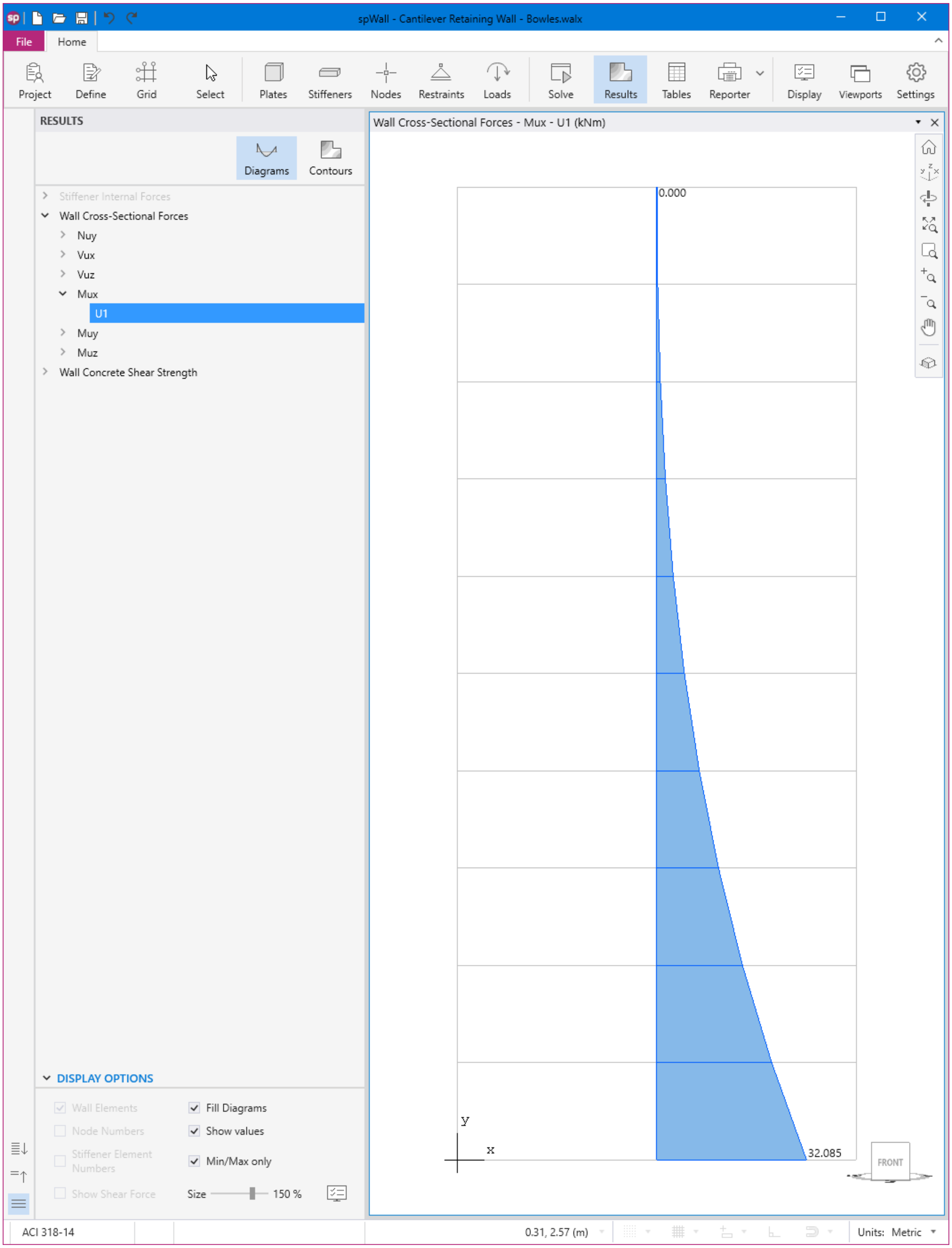

Figure 11 – Bending Moment Diagram (spWall)

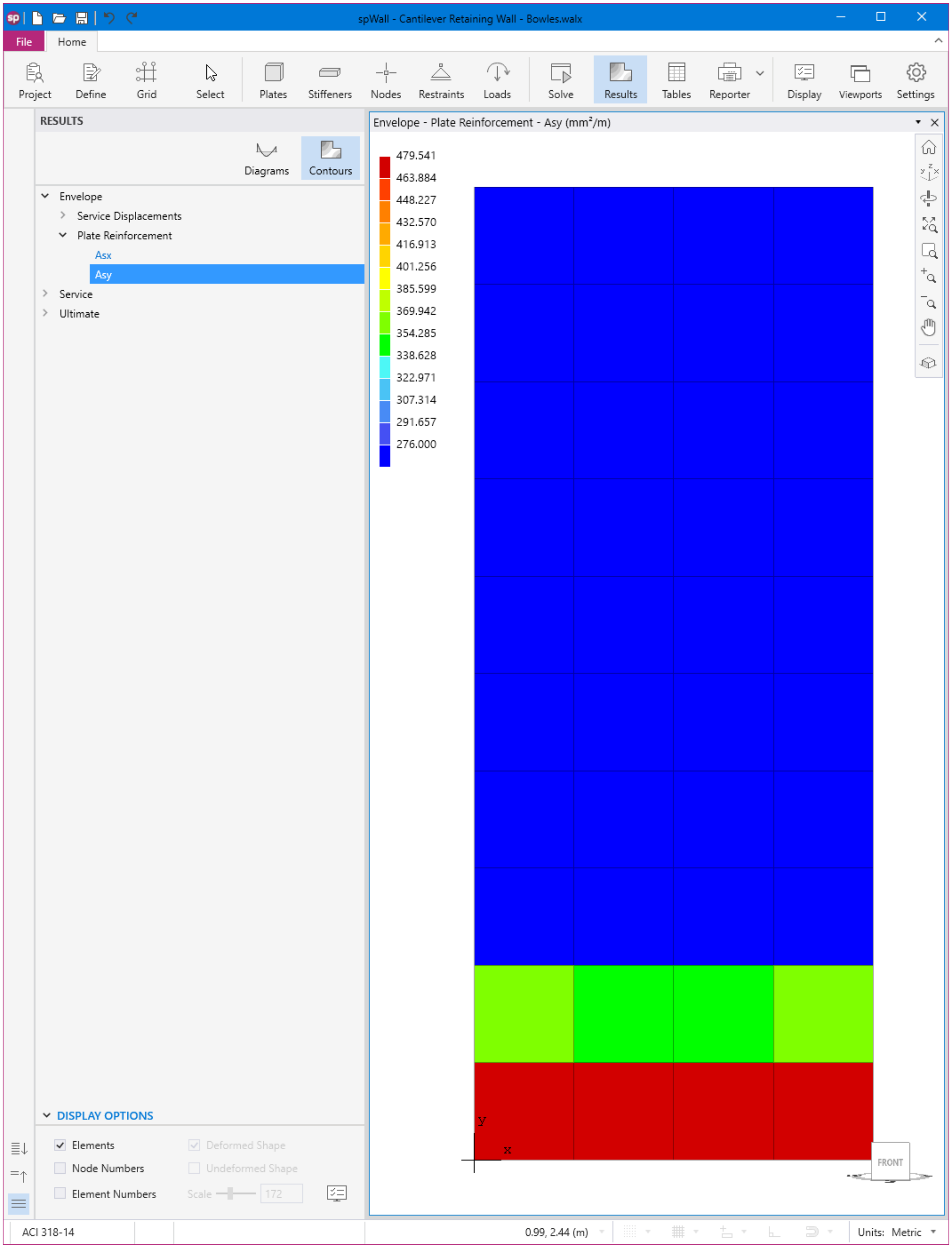

Figure 12 – Required Vertical Reinforcement (spWall)

1.4. Cantilever Retaining Wall Maximum Displacement

1. Results

1.1. Service

1.1.1. Nodal Displacements

1.1.1.1. S1

Coordinate System: Global

Node	Dx	Dy	Dz
	mm	mm	mm
1	0.000	0.000	0.000
2	0.000	0.000	0.000
3	0.000	0.000	0.000
4	0.000	0.000	0.000
5	0.000	0.000	0.000

Figure 13 – Displacement at Critical Section (Service Combinations) (spWall)

1.2. Ultimate

1.2.1. Nodal Displacements

1.2.1.1. U1

Coordinate System: Global

Node	Dx	Dy	Dz
	mm	mm	mm
1	0.000	0.000	0.000
2	0.000	0.000	0.000
3	0.000	0.000	0.000
4	0.000	0.000	0.000
5	0.000	0.000	0.000

Figure 14 – Displacement at Critical Section (Ultimate Combinations) (spWall)

1.5. Cantilever Retaining Wall Cross-Sectional Forces at Stem Base

1.2.2. Wall Cross-Sectional Forces

1.2.2.1. U1

Coordinate System: Global
(+) Horizontal cross-section above Y-coordinate
(-) Horizontal cross-section below Y-coordinate

Wall Crossection			In-Plane Forces			Out-Of-Plane Forces		
No.	Y coordinate	X-Centroid	Vux	Nuy	Muz	Vuz	Mux	Muy
	m	m	kN	kN	kNm	kN	kNm	kNm
1+	0.000	0.500	0.00	-13.21	0.00	33.28	32.08	0.00

Figure 15 – Wall Cross-Sectional Forces (spWall)

2. Cantilever Retaining Wall Foundation Analysis and Design – spMats Software

spMats uses the Finite Element Method for the structural modeling, analysis and design of reinforced concrete slab systems or mat foundations subject to static loading conditions.

The slab, mat, or footing is idealized as a mesh of rectangular elements interconnected at the corner nodes. The same mesh applies to the underlying soil with the soil stiffness concentrated at the nodes. Slabs of irregular geometry can be idealized to conform to geometry with rectangular boundaries. Even though slab and soil properties can vary between elements, they are assumed uniform within each element. Piles and/or supporting soil are modeled as springs connected to the nodes of the finite element model.

For illustration purposes, the following figures provide a sample of the input modules and results obtained from an spMats model created for the cantilever retaining wall foundation in this case study.

2.1. Cantilever Retaining Wall Foundation Model Input

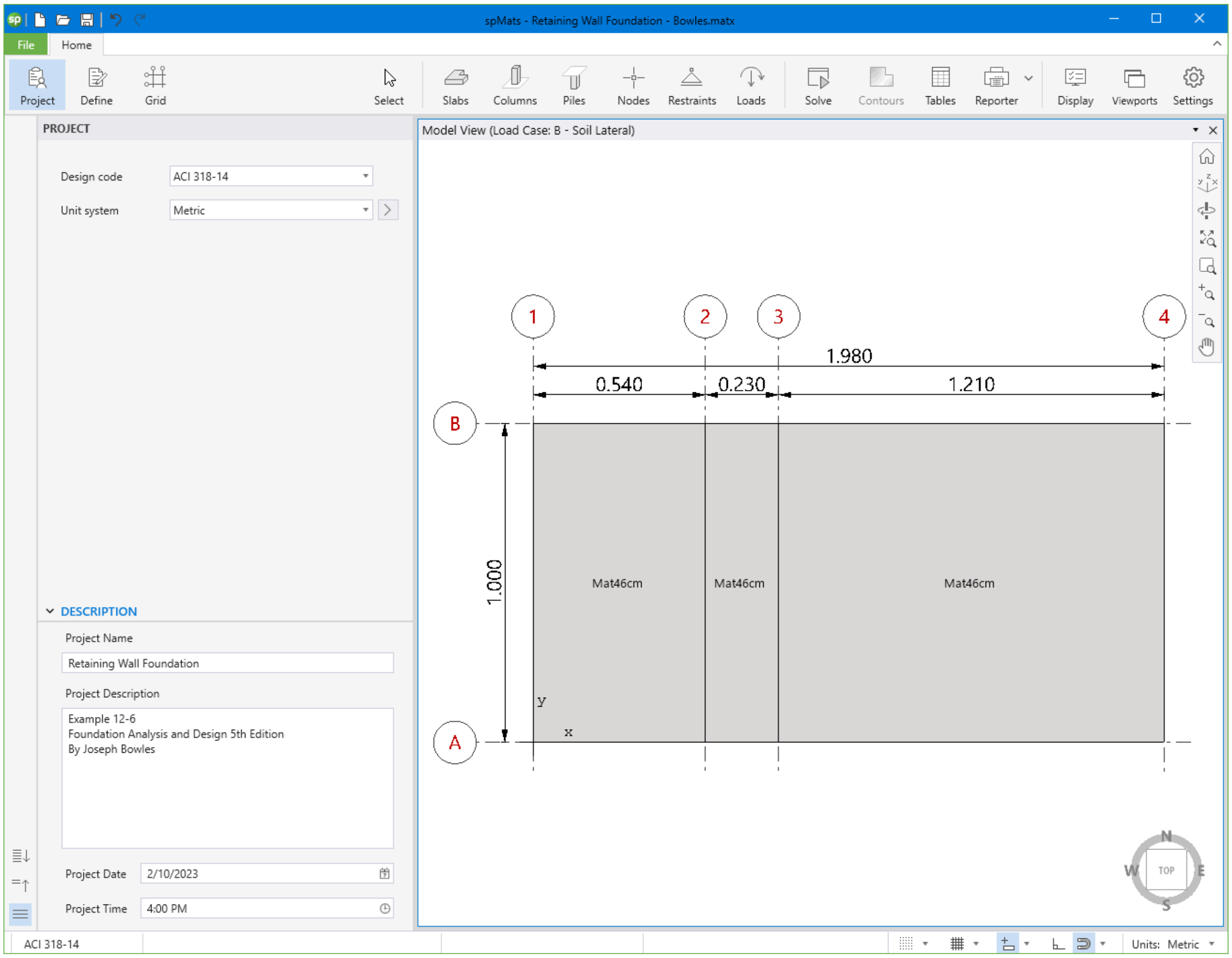

Figure 16 – spMats Interface

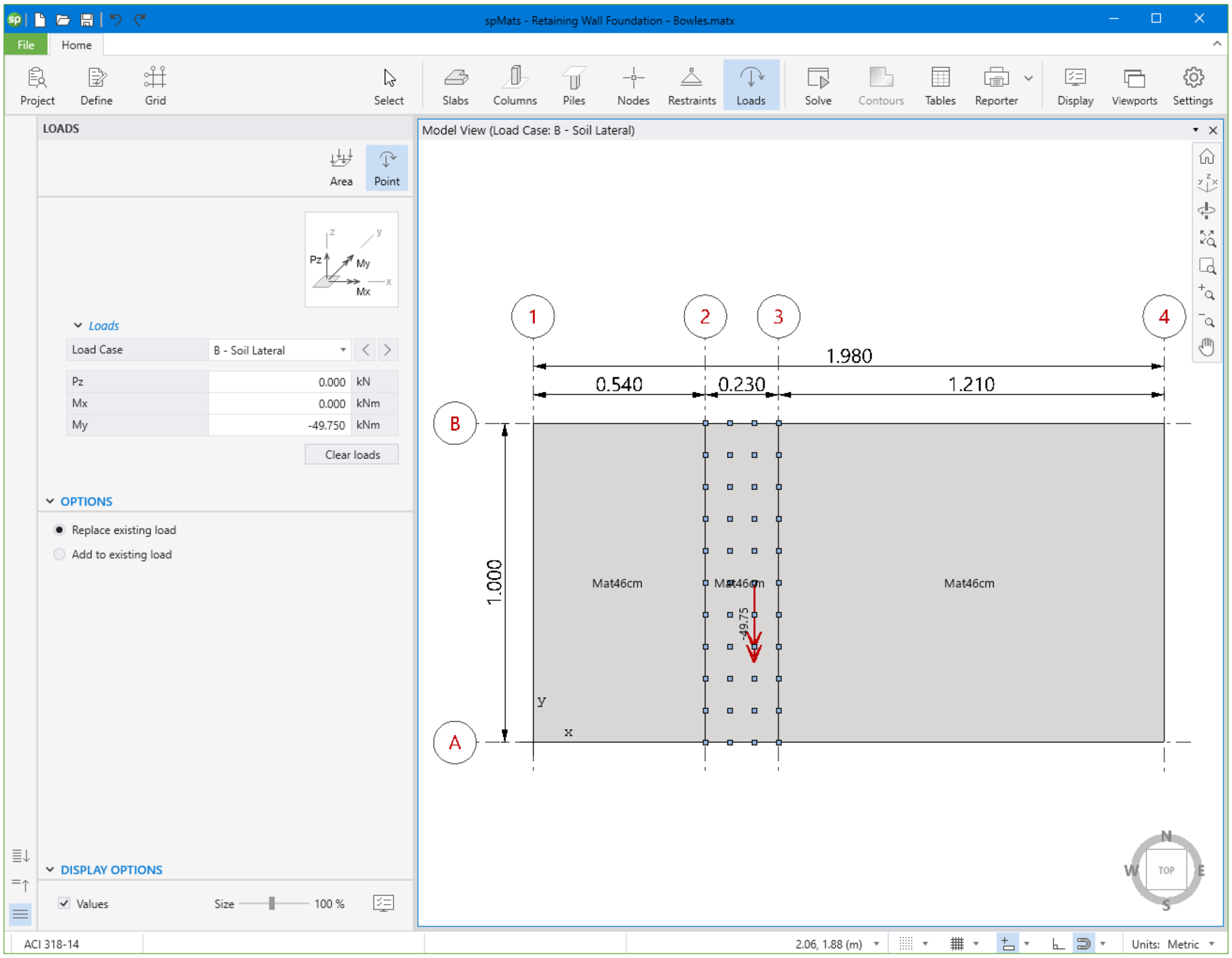

Figure 17 – Assigning Soil Lateral Moment for Cantilever Retaining Wall Foundation (spMats)

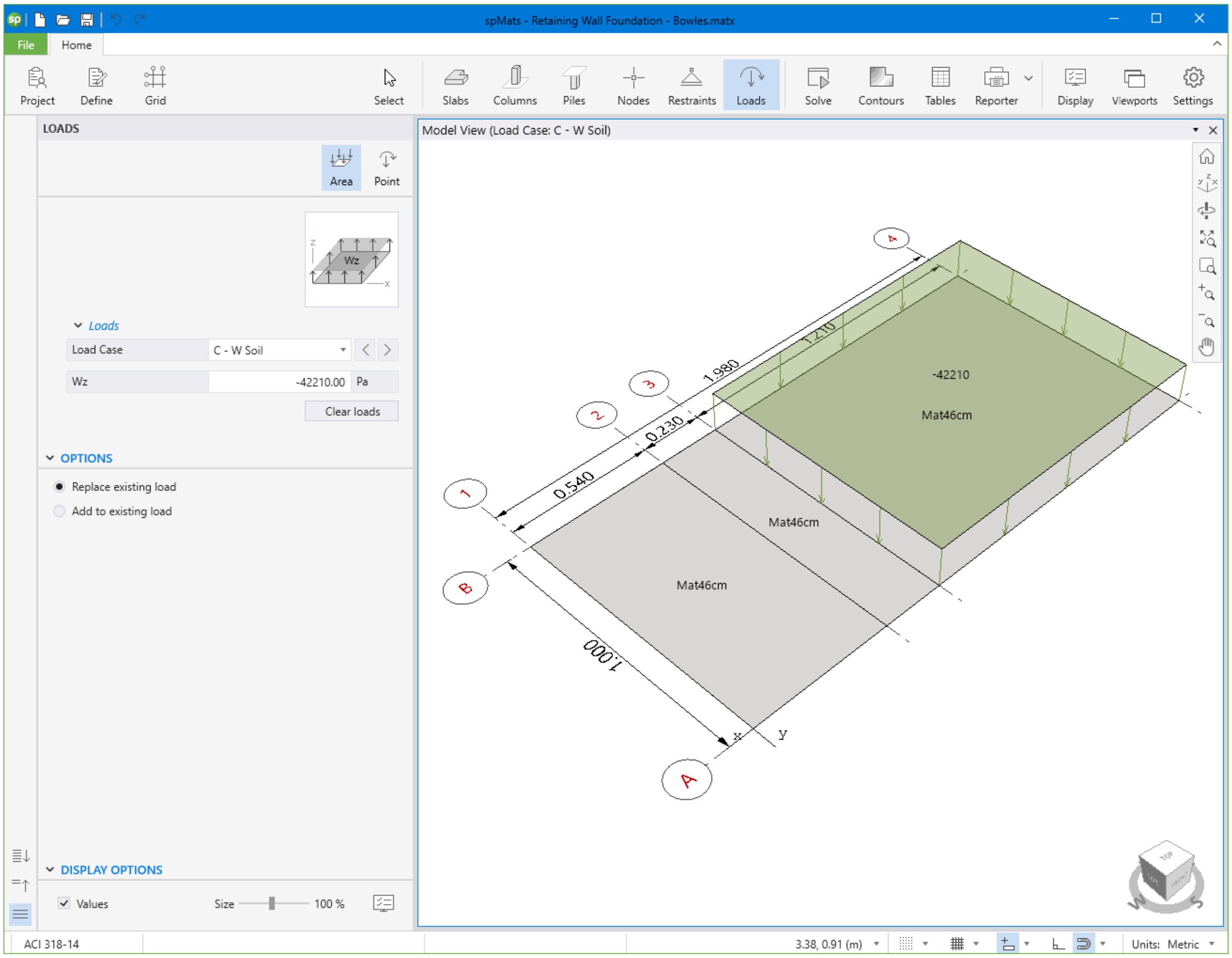

Figure 18 – Assigning Soil Heel Load for Cantilever Retaining Wall Foundation (spMats)

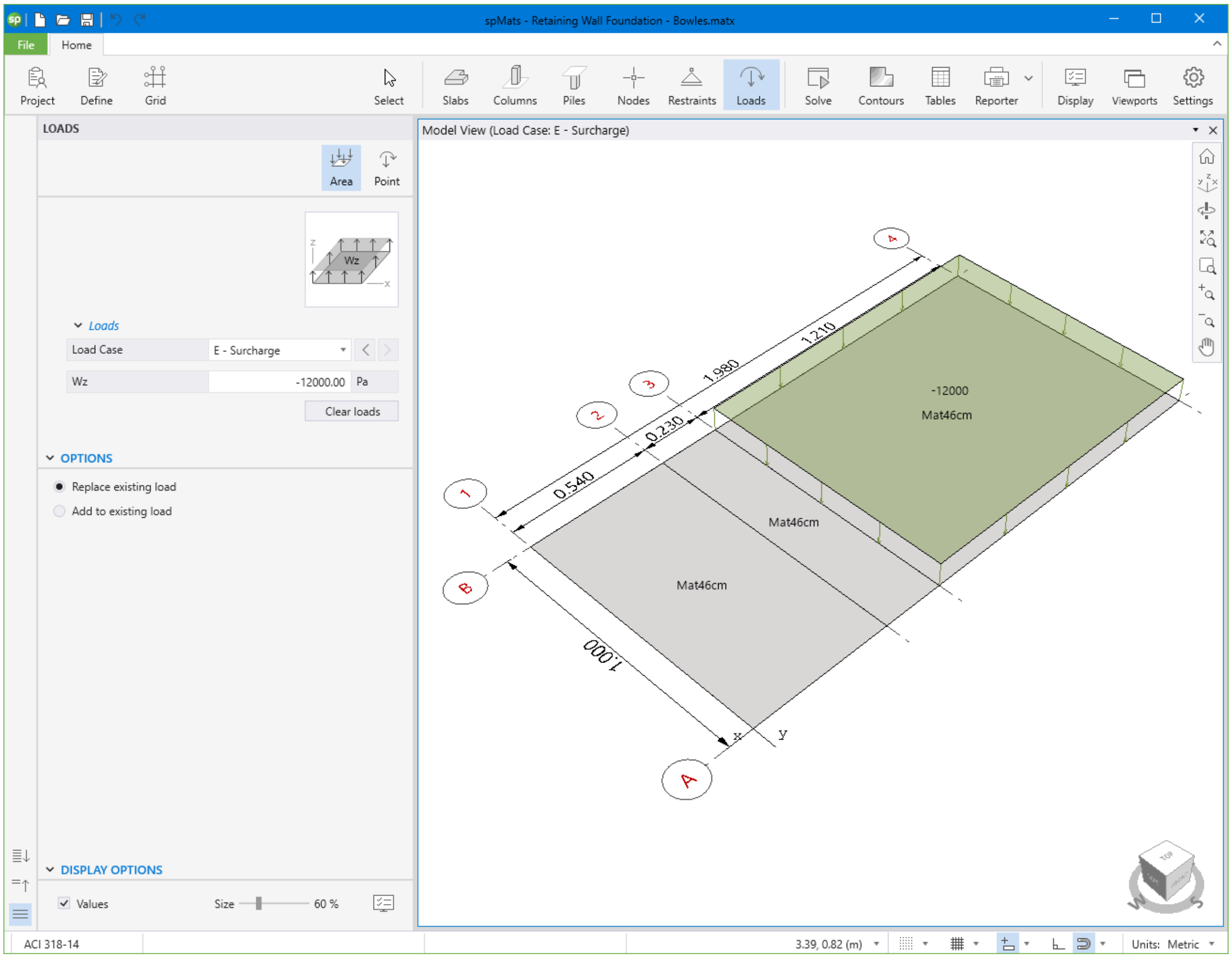

Figure 19 – Assigning Surcharge Load for Cantilever Retaining Wall Foundation (spMats)

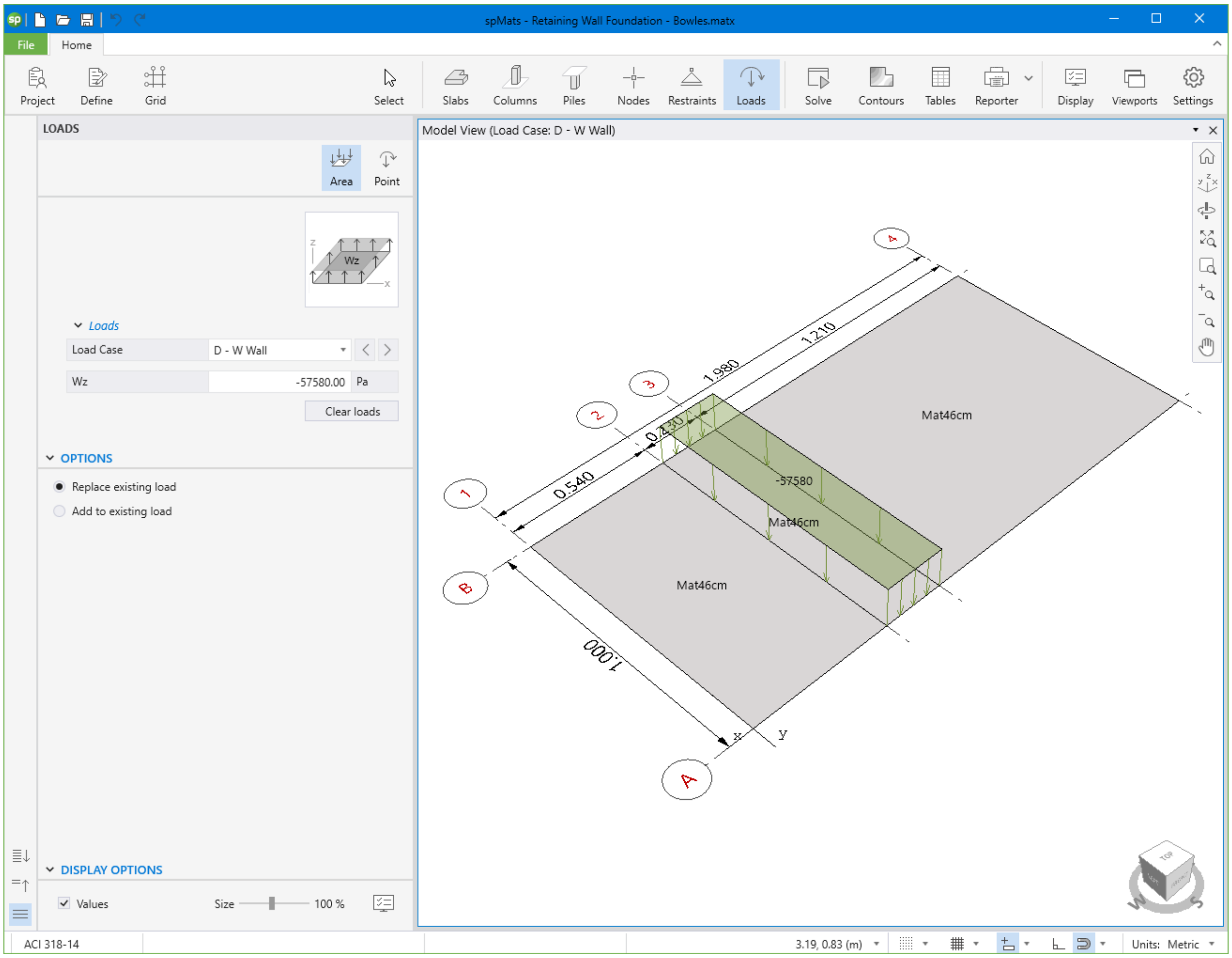

Figure 20 – Assigning Wall Load for Cantilever Retaining Wall Foundation (spMats)

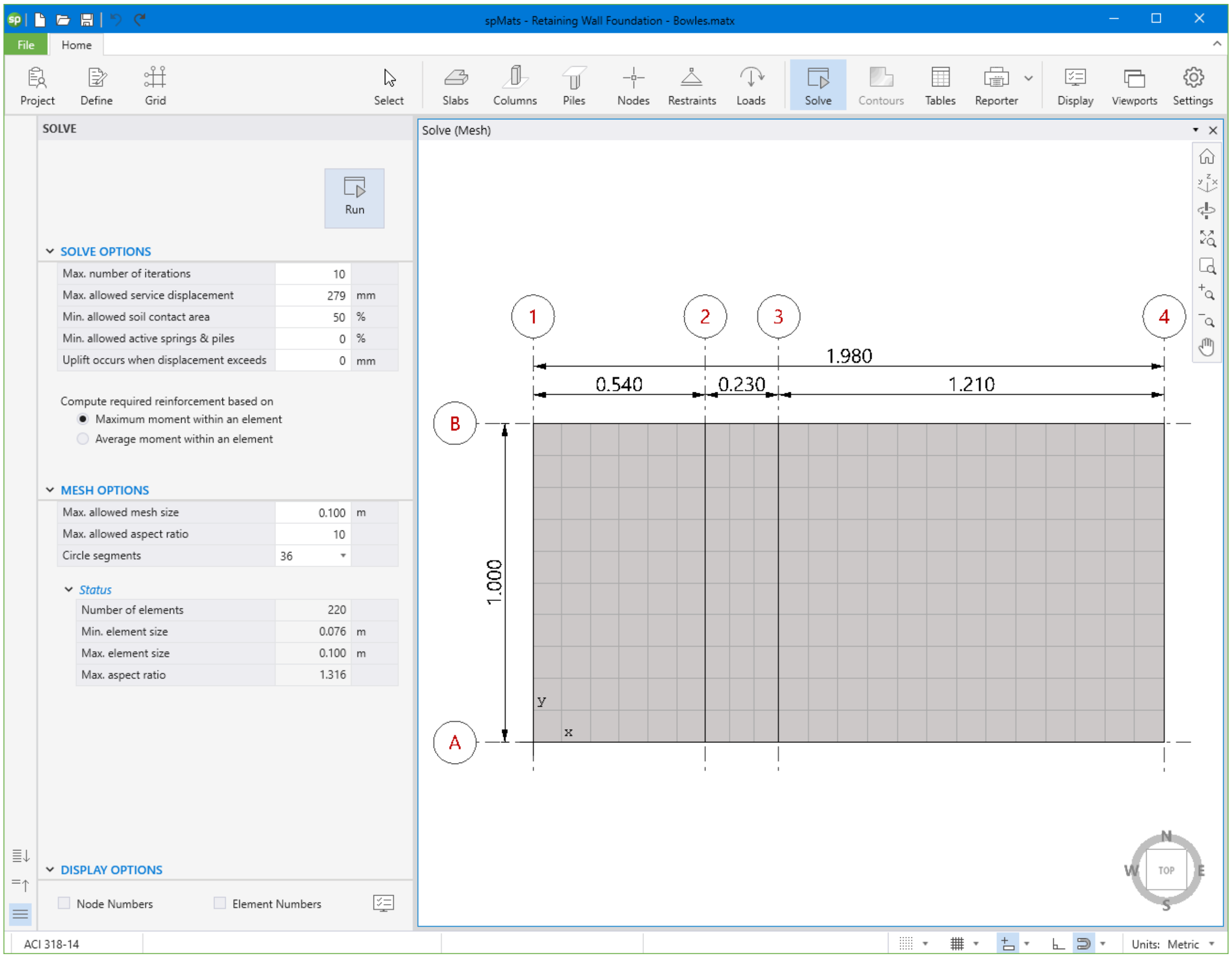

Figure 21 – Solve and Mesh Options (spMats)

2.2. Cantilever Retaining Wall Foundation Result Contours

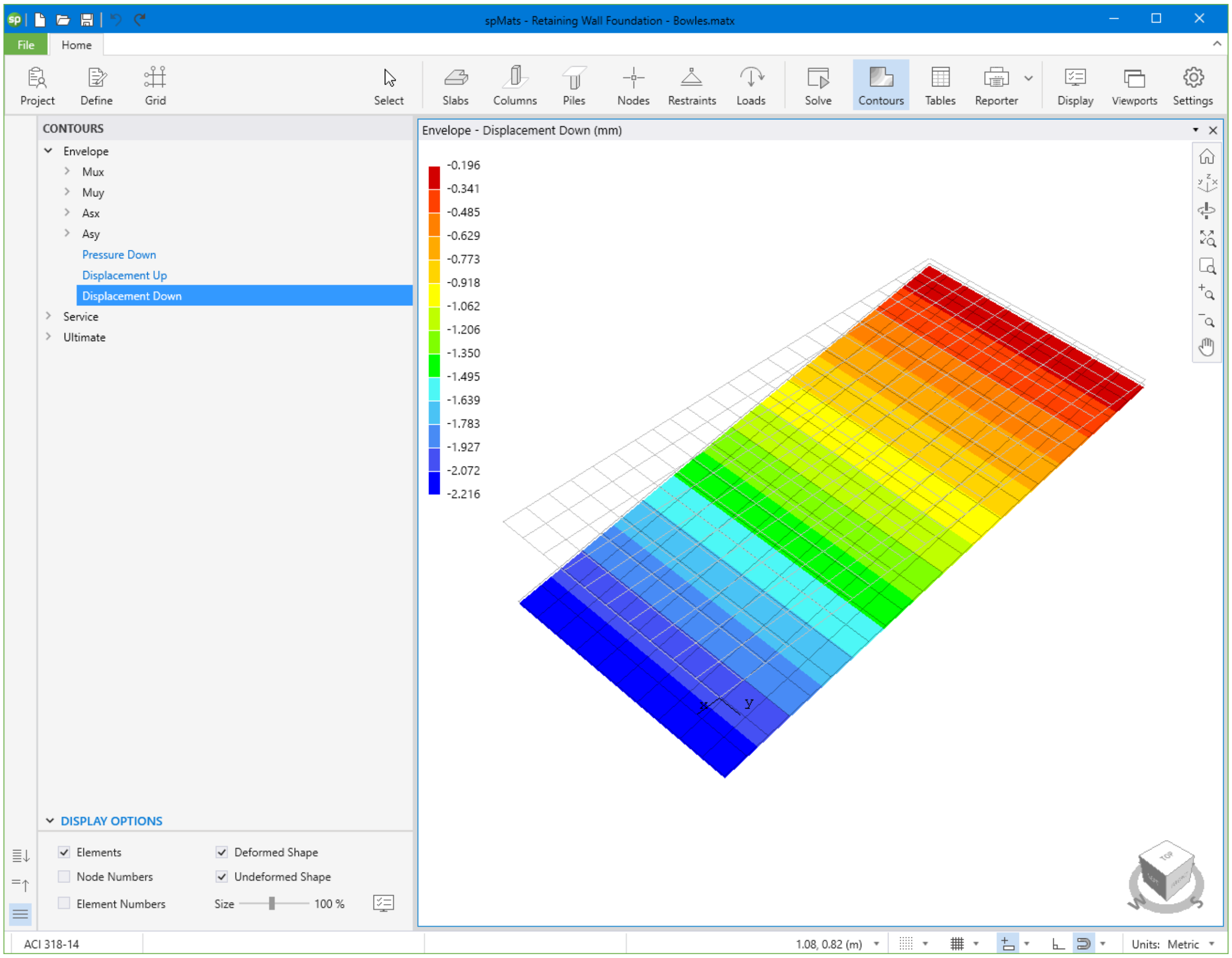

Figure 22 – Vertical (Down) Displacement Contour (spMats)

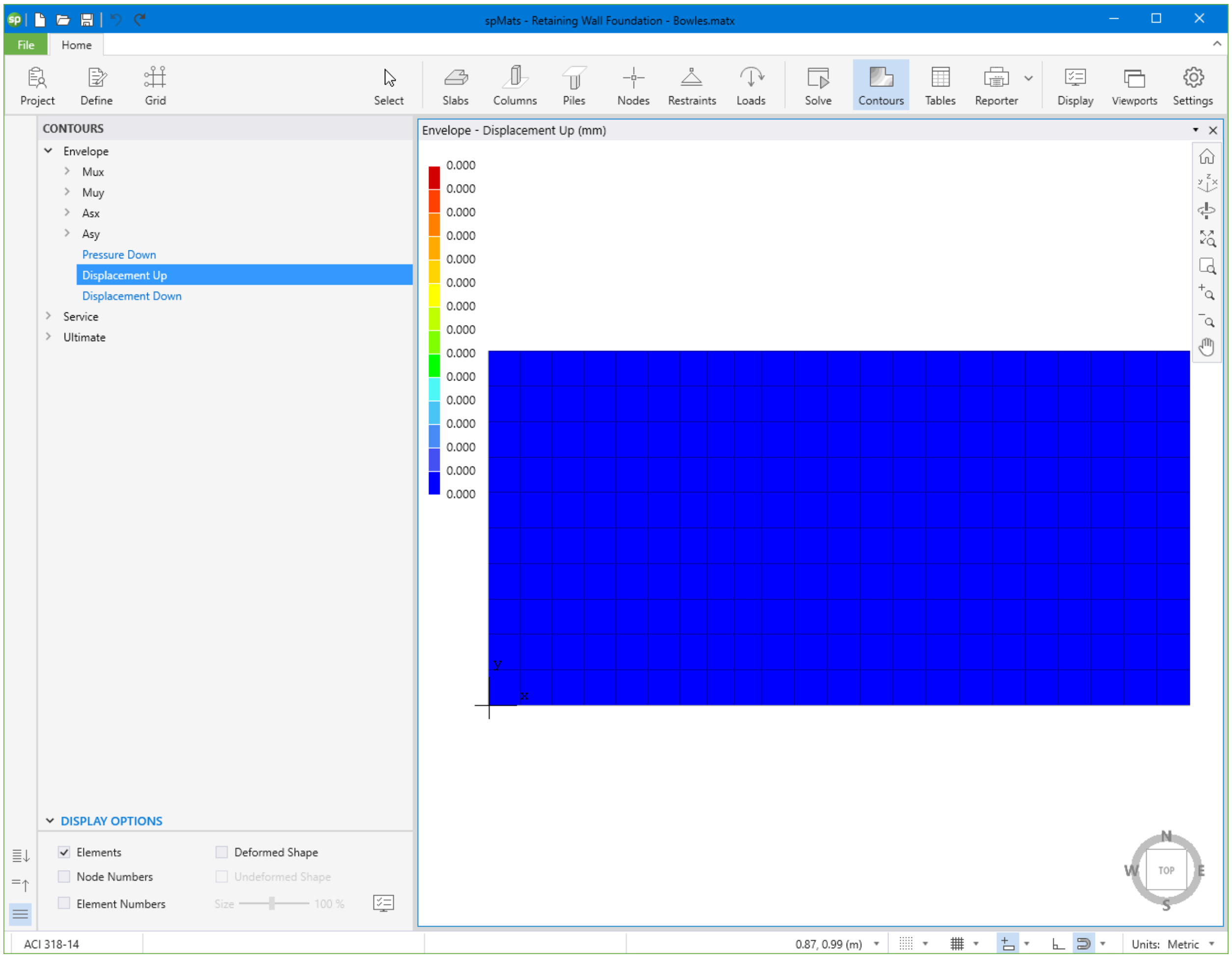

Figure 23 – Vertical (Up) Displacement Contour (spMats)
(Note: figure indicates no uplift in the wall base)

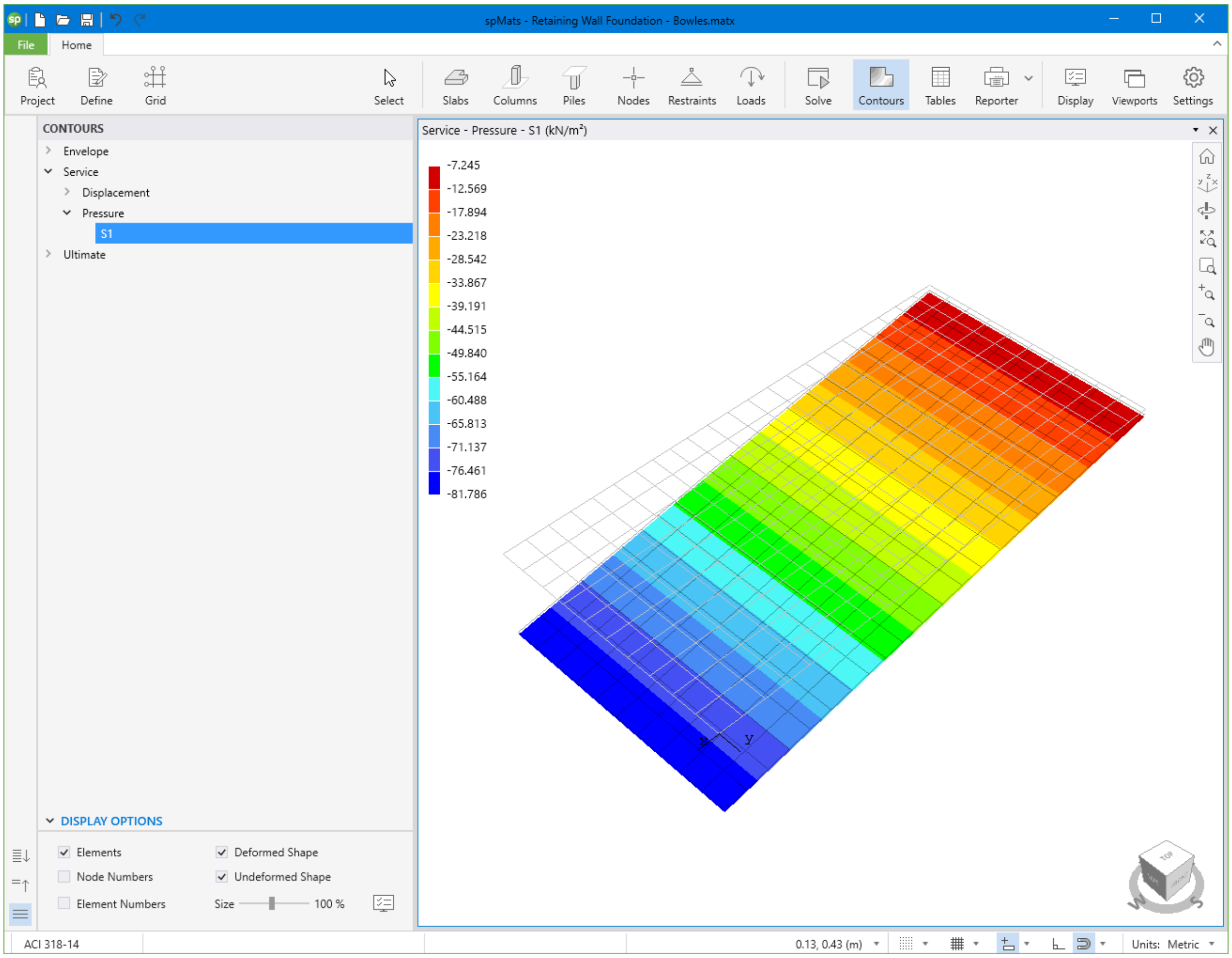

Figure 24 – Soil Bearing Pressure Contour (spMats)

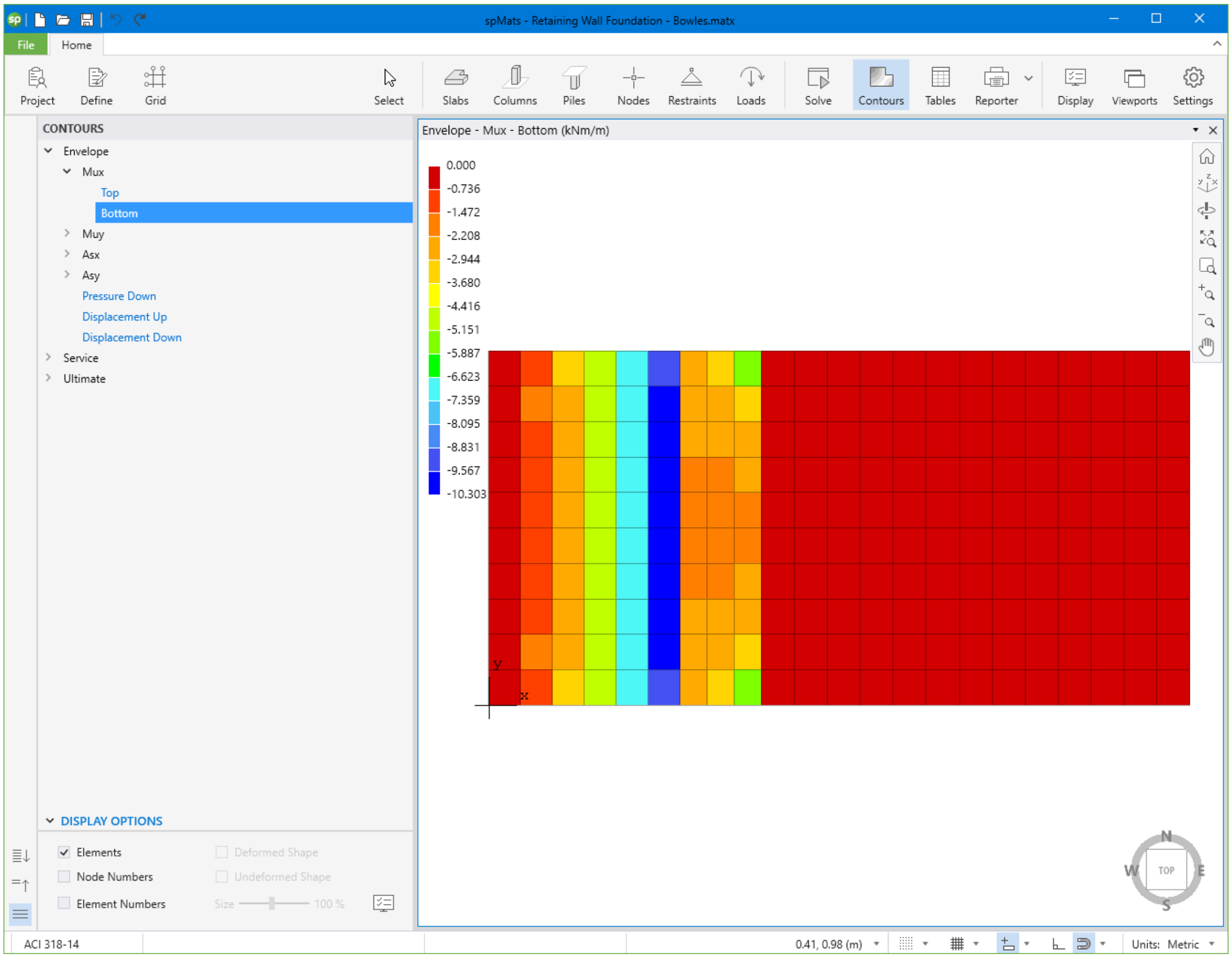

Figure 25 – Moment Contour along X-Axis (Max for Toe) (spMats)

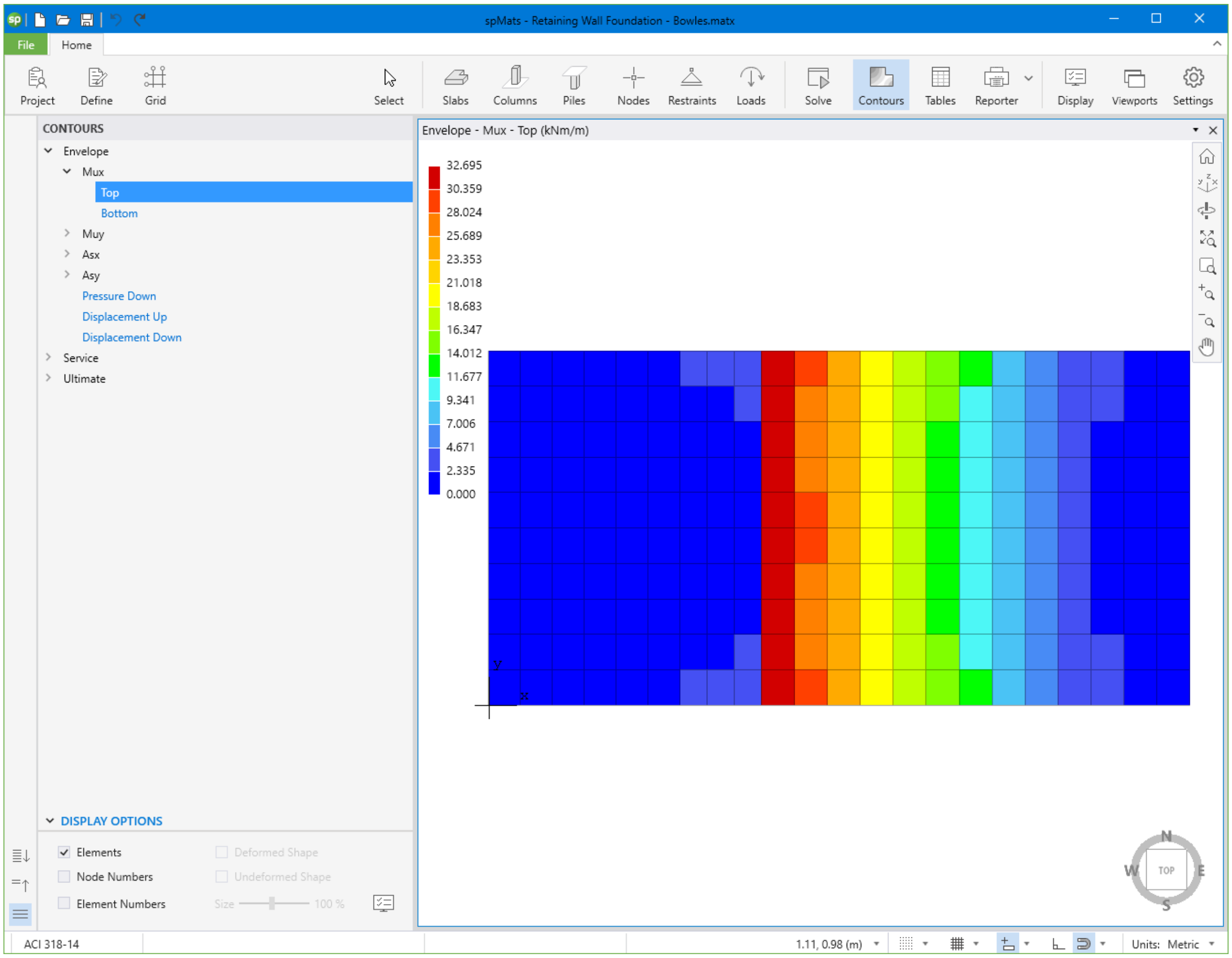

Figure 26 – Moment Contour along X-Axis (Max for Heel) (spMats)

2.3. Cantilever Retaining Wall Foundation Required Reinforcement

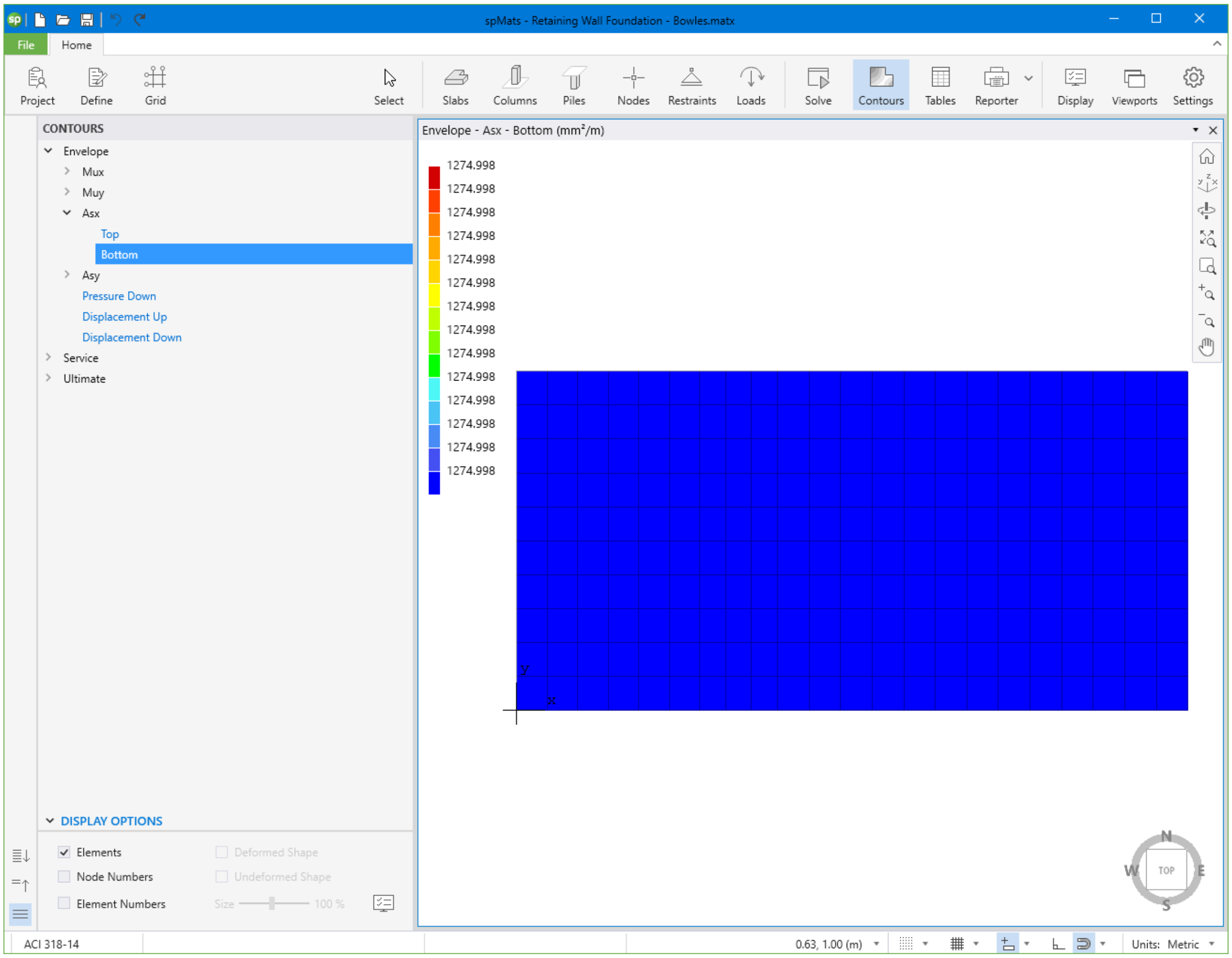

Figure 27 – Required Reinforcement Contour along X Direction (Bottom – Toe Design) (spMats)
(Note: minimum reinforcement governs)

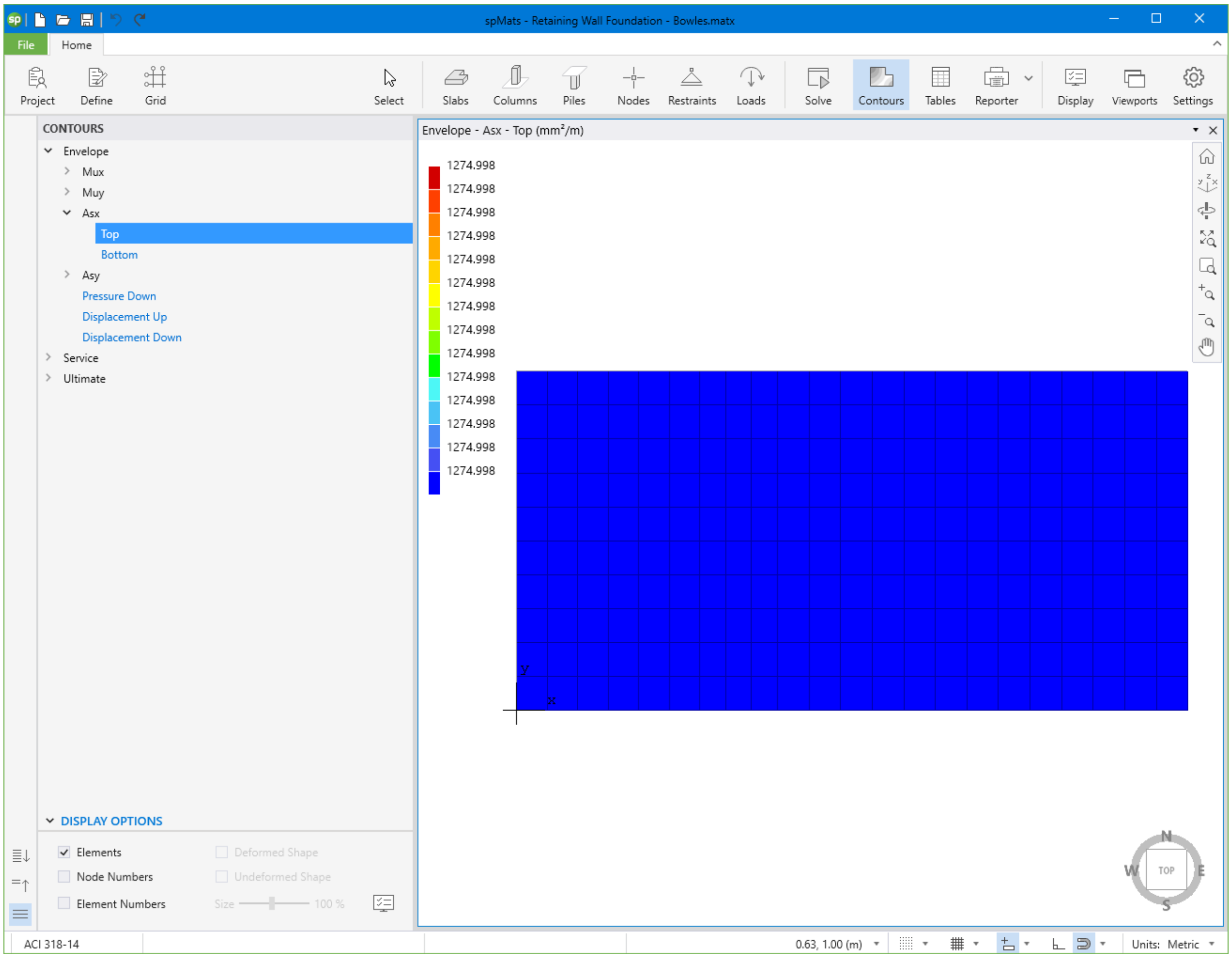

Figure 28 – Required Reinforcement Contour along X Direction (Top – Heel Design) (spMats)
(Note: minimum reinforcement governs)

2.4. Soil Reactions / Pressure

1. Results
1.1. Service
1.1.1. Sum of Reactions
1.1.1.1. S1

NOTES:
Sum of all forces and moments with respect to center of gravity (X,Y) = (0.990, 0.500) m

Sum of Reactions	Fz kN	Mx kNm	My kNm
Soil	87.03	0.00	24.50
Springs	-	-	-
Piles	-	-	-
Restraints	-	-	-
Slaved nodes	0.00	0.00	0.00
Total Reactions	87.03	0.00	24.50
Total loads	-87.03	0.00	-24.50

Figure 29 – Soil Service Reactions (spMats)

1.1.2. Soil Disp. & Pressure
1.1.2.1. S1

NOTES:
[x] Indicates allowable pressure is exceeded.

Element	Node	Disp, Dz mm	Pressure, Qz kN/m²	Node	Disp, Dz mm	Pressure, Qz kN/m²
111	140	-2.122	-78.313	117	-2.122	-78.313
	139	-2.216	-81.785	116	-2.216	-81.786
132	161	-0.197	-7.266	138	-0.197	-7.267
	160	-0.288	-10.638	137	-0.288	-10.639

Figure 30 – Soil Bearing Pressure (spMats)

2.5. Cantilever Retaining Wall Foundation Mesh Status

Since spMats is utilizing finite element analysis to model and design the foundation. It is useful to track the number of elements used in the model to optimize the model results (accuracy) and running time (processing stage). spMats provides mesh status to keep tracking the mesh sizing as a function of the number of elements, minimum and maximum element sizes, and maximum aspect ratio.

Status

Number of elements	220	
Min. element size	0.076	m
Max. element size	0.100	m
Max. aspect ratio	1.316	

Figure 31 – Mesh Status (spMats)

3. Cantilever Retaining Wall Analysis and Design Observations & Conclusions

The reference considered the toe and heel as cantilever projecting outward and inward from the face of the stem, respectively. spMats provides the flexibility of modeling the foundation with the exact geometry and boundary conditions to achieve more accurate results leading to potential savings in the reinforcement required.

Some load cases are usually neglected in the hand solution for simplicity and to achieve a more conservative design. spMats takes into account all the applied load cases and include them in the calculations of the required reinforcement for the toe and heel. Additional load combination can be easily employed in spMats to explore more loading scenarios to meet project criteria.

If the designer decided to transfer the wall reactions to the foundation (reactions from the spWall model to spMats model) instead of applying the loads directly on the foundation as shown in this case study, the designer is advised to take the care required in exporting the wall reactions carefully to the foundation model to ensure completeness and accuracy in the sign convention.

The effect of buoyancy is not shown in this case study as the water table was assumed to be below the bottom of the retaining wall. Additional loading considerations would be needed to adequately address this condition.