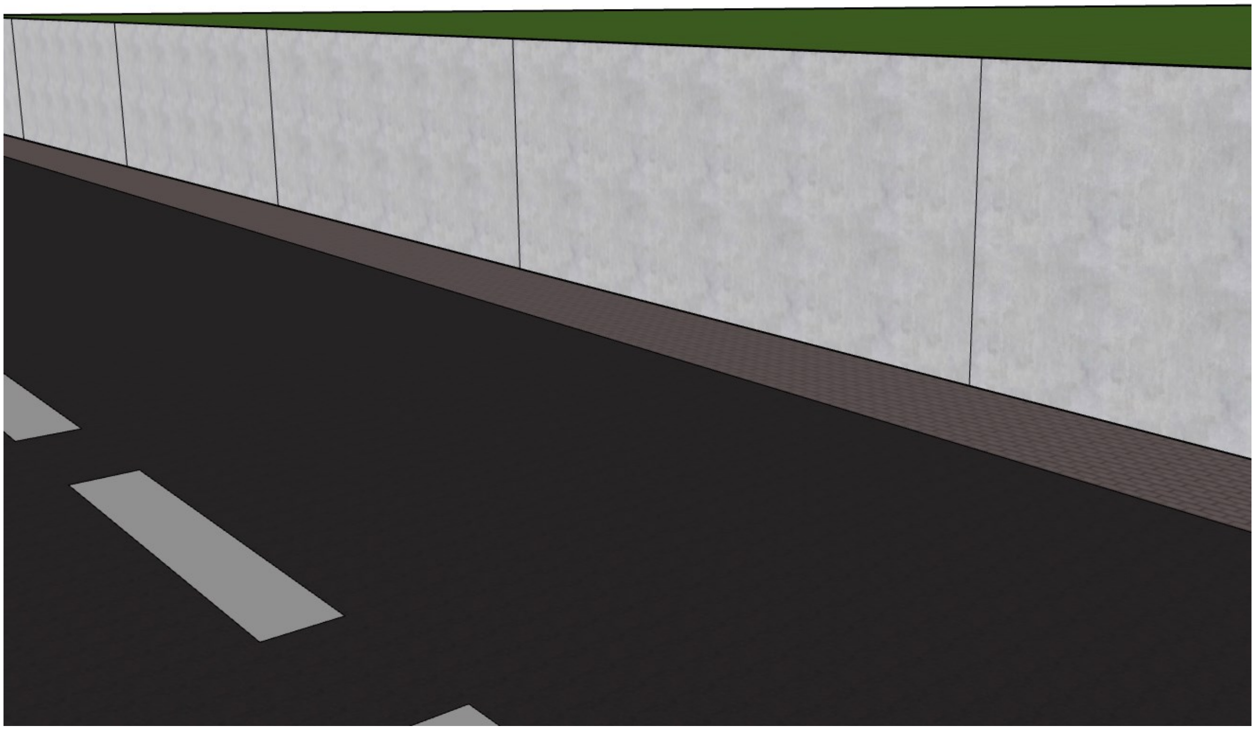
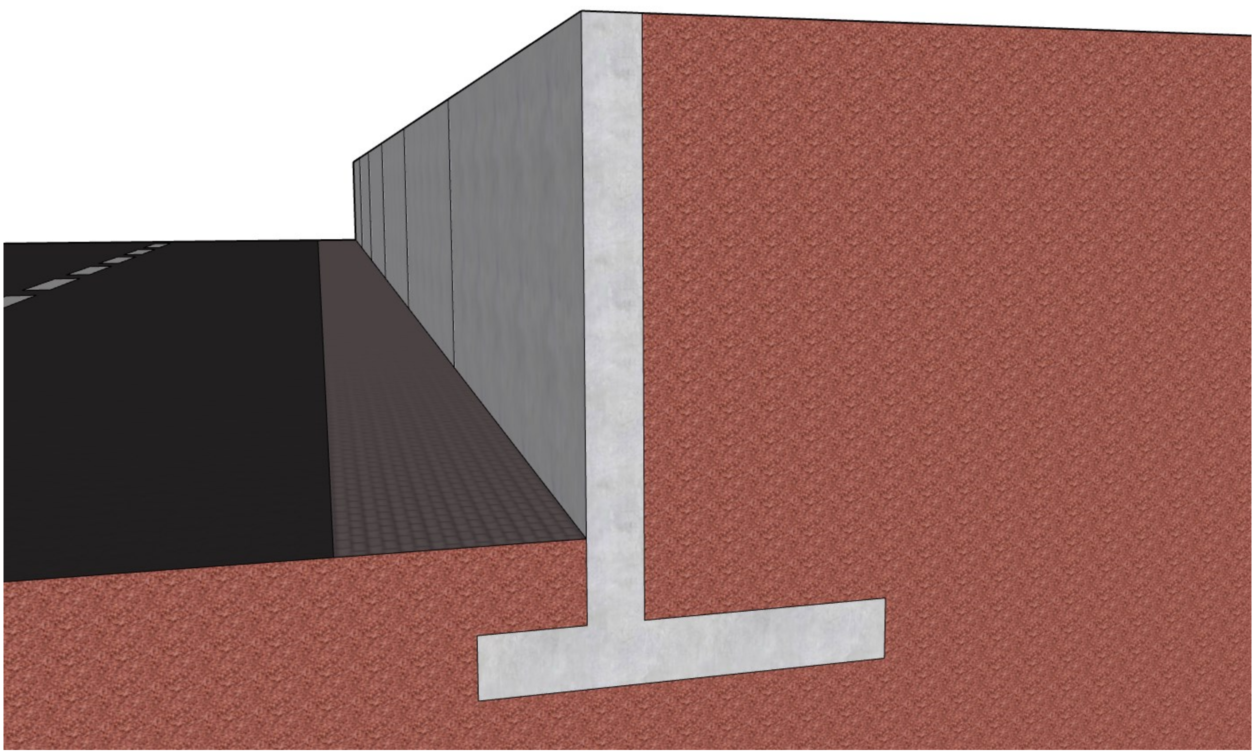
Reinforced Concrete Cantilever Retaining Wall Analysis and Design (ACI 318M-14)





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.

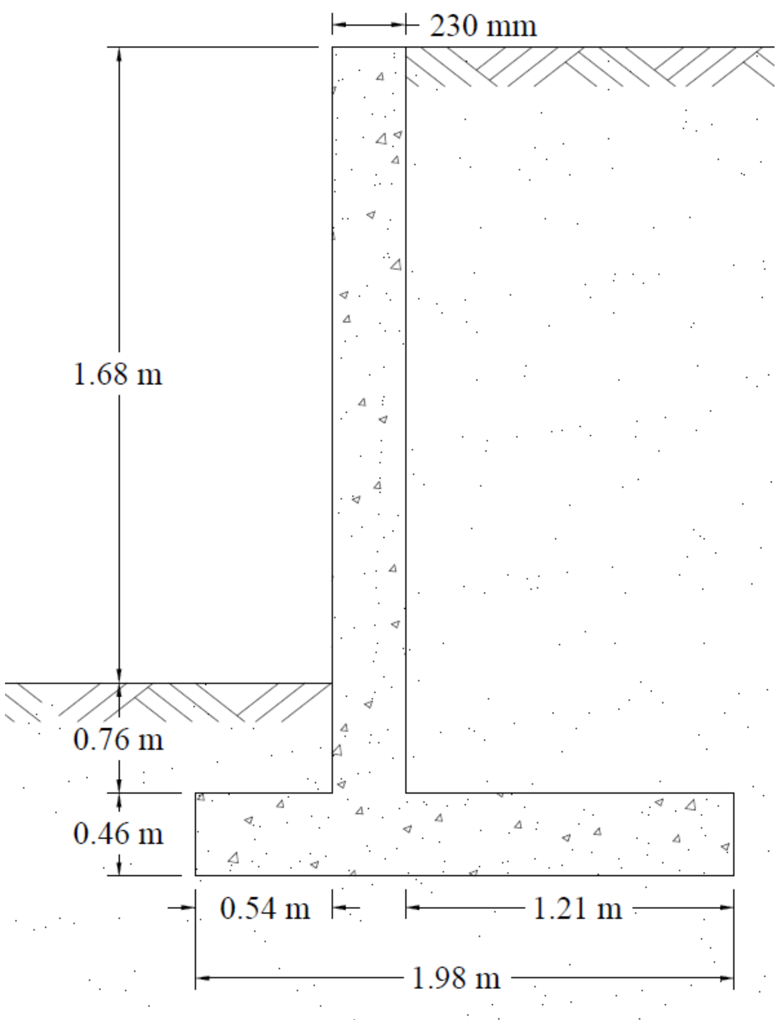


Figure 1 – Cantilever Retaining Wall Dimensions

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 v5.01, StucturePoint LLC., 2016

spMats Engineering Software Program Manual v8.50, StucturePoint LLC., 2016

Design Data

<u>Wall Stem Materials</u>

f_c' = 21 MPa

f_y = 200 MPa

γ_c = 2400 kg/m^3

<u>Wall Foundation Materials</u>

f_c' = 21 MPa

f_y = 200 MPa

γ_c = 2400 kg/m^3

<u>Wall Stem Dimensions</u>

Width = 1.0 m strip

Height = 2.44 m

Thickness = 230 mm

<u>Wall Foundation Dimensions</u>

Width = 1.0 m strip

Length = 1.98 m

Thickness = 460 mm

<u>Retaining Wall Loads</u>

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

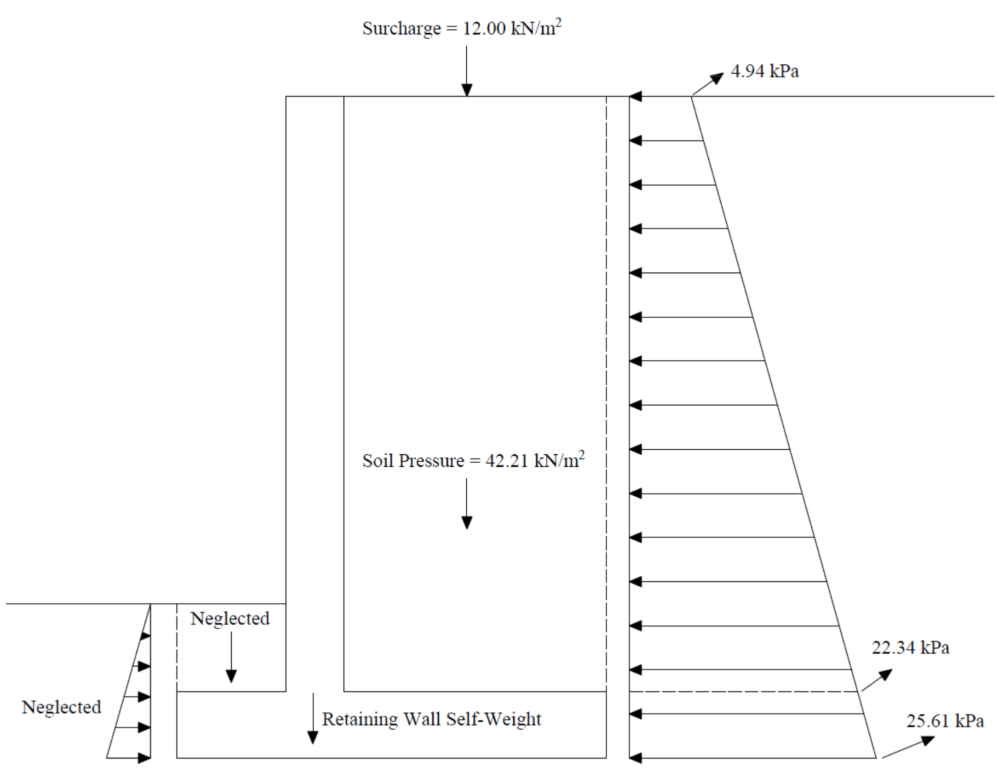


Figure 2 – Applied Loads

Contents

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

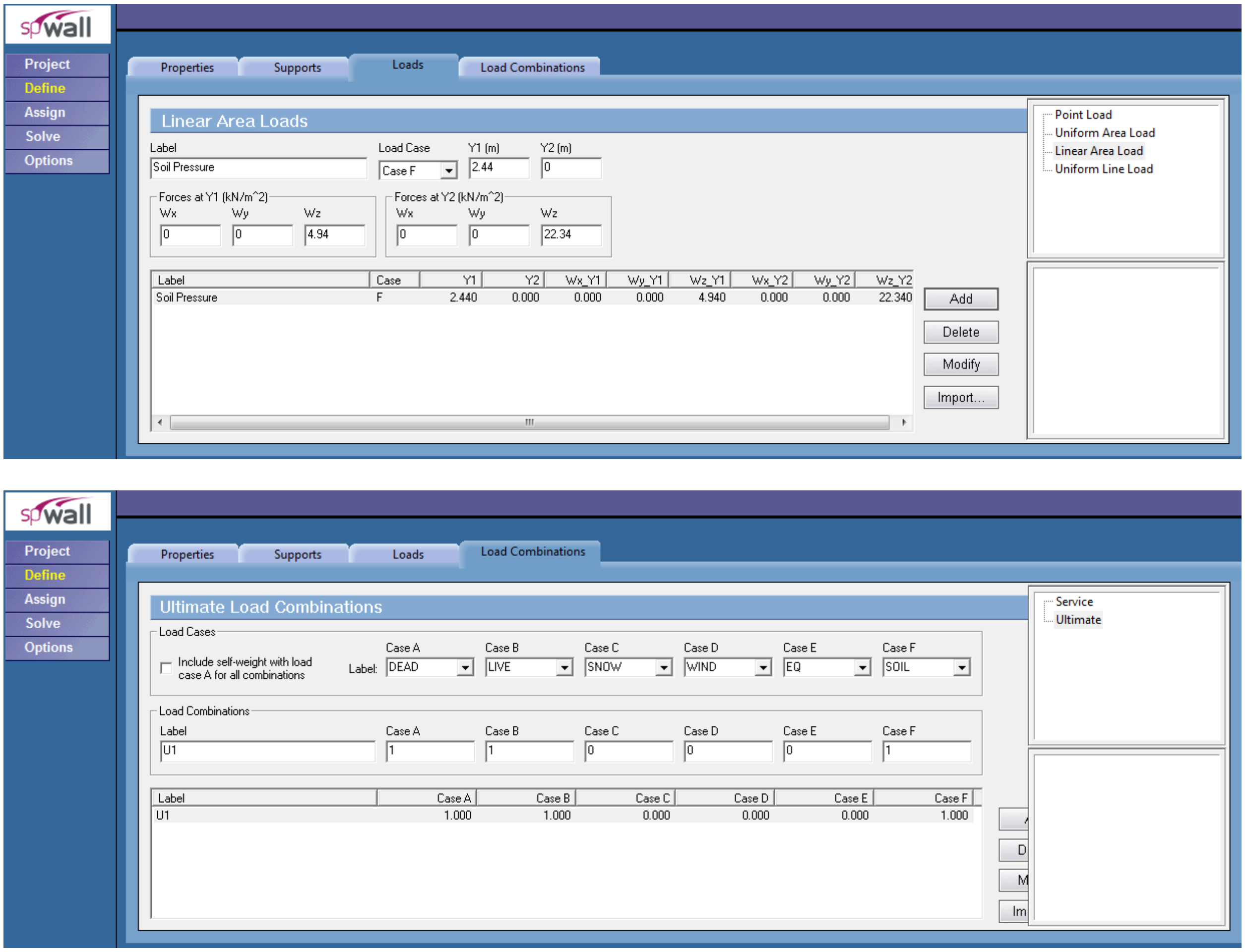


Figure 3 – Cantilever Retaining Wall Loads and Load Combinations

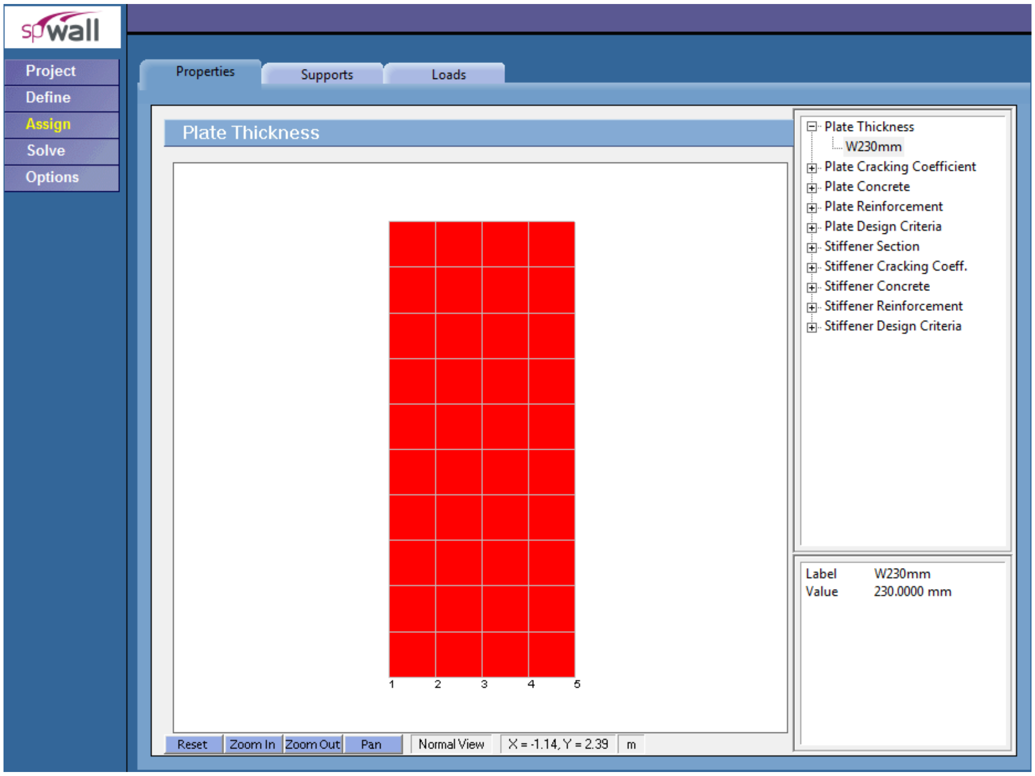


Figure 4 – Assigning Wall Stem Thickness

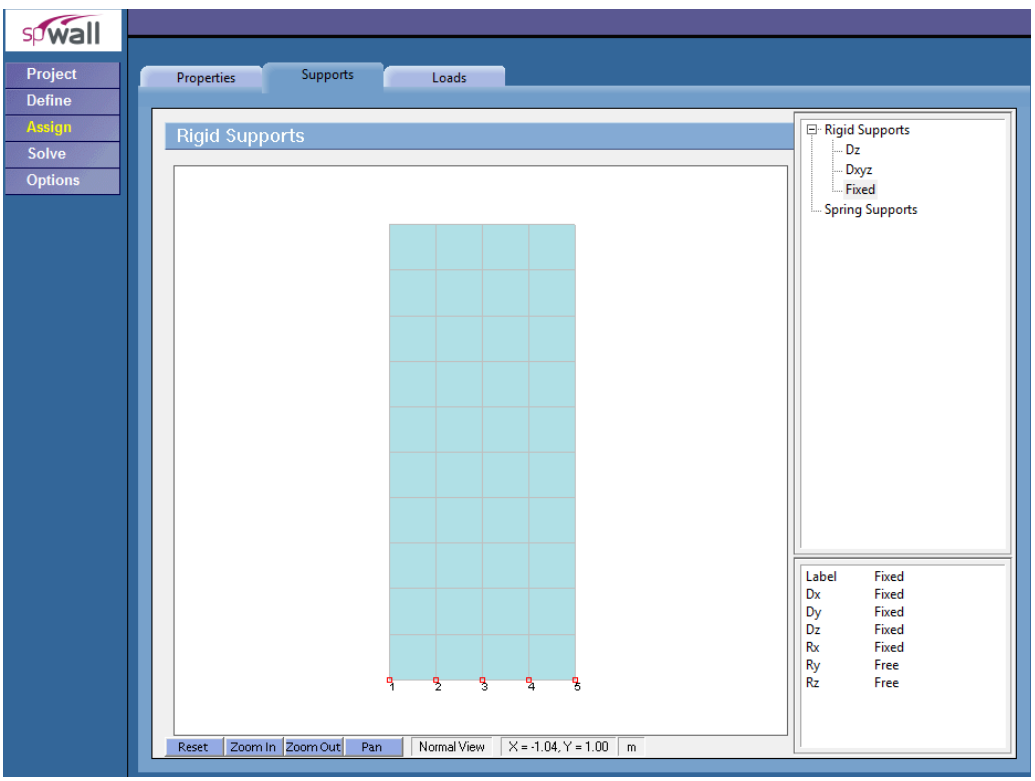


Figure 5 – Assigning Wall Stem Restraints

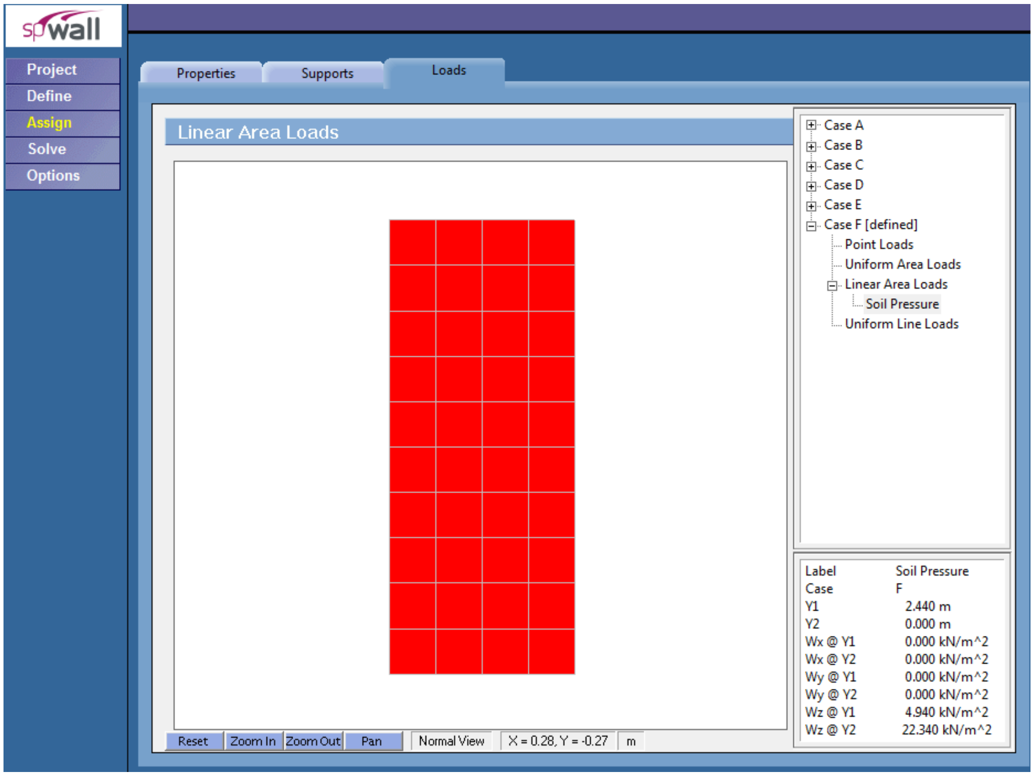


Figure 6 – Assigning Soil Lateral Pressure

1.2. Cantilever Retaining Wall Result Contours

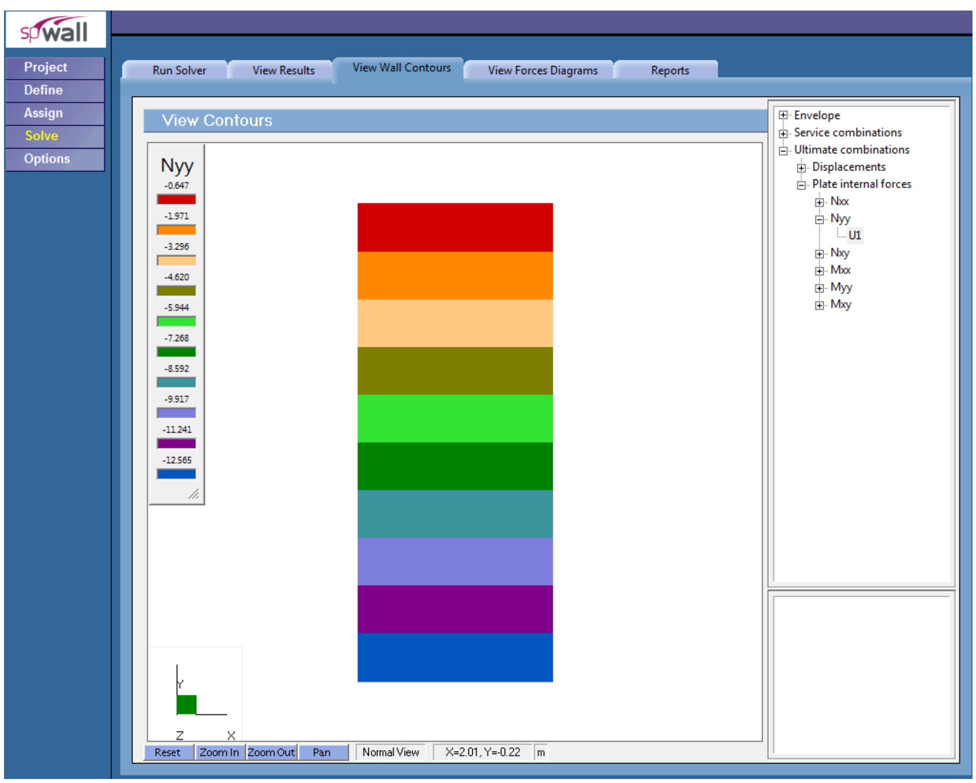


Figure 7 – Factored Axial Force Contour

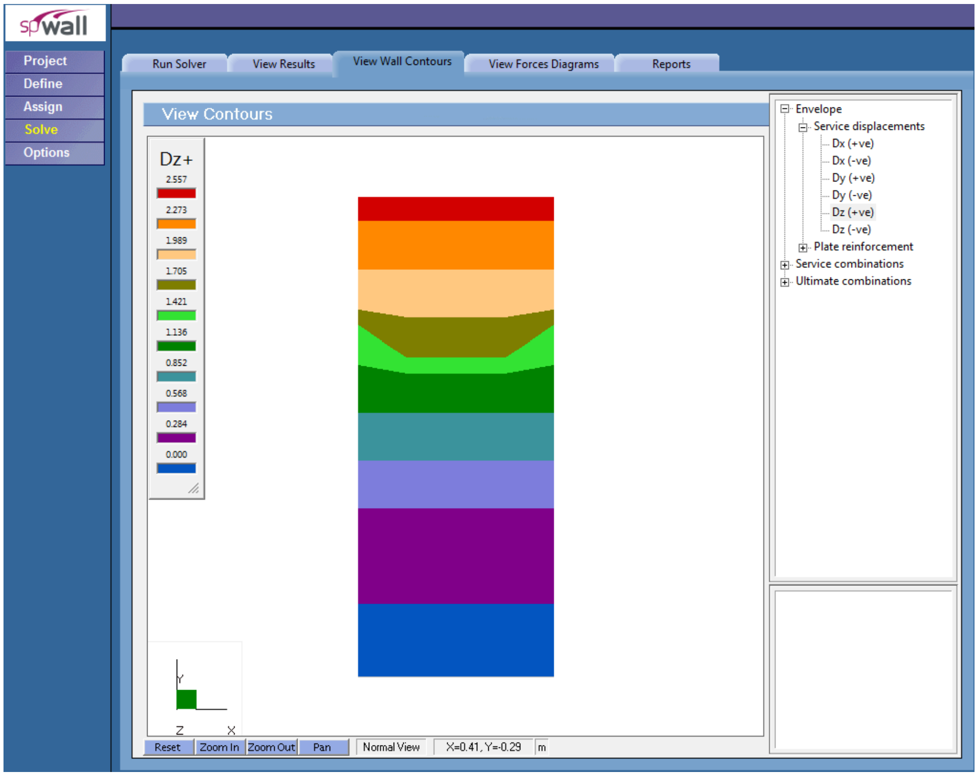


Figure 8 – Lateral Displacement Contour (Out-of-Plane)

1.3. Cantilever Retaining Wall Cross-Sectional Forces

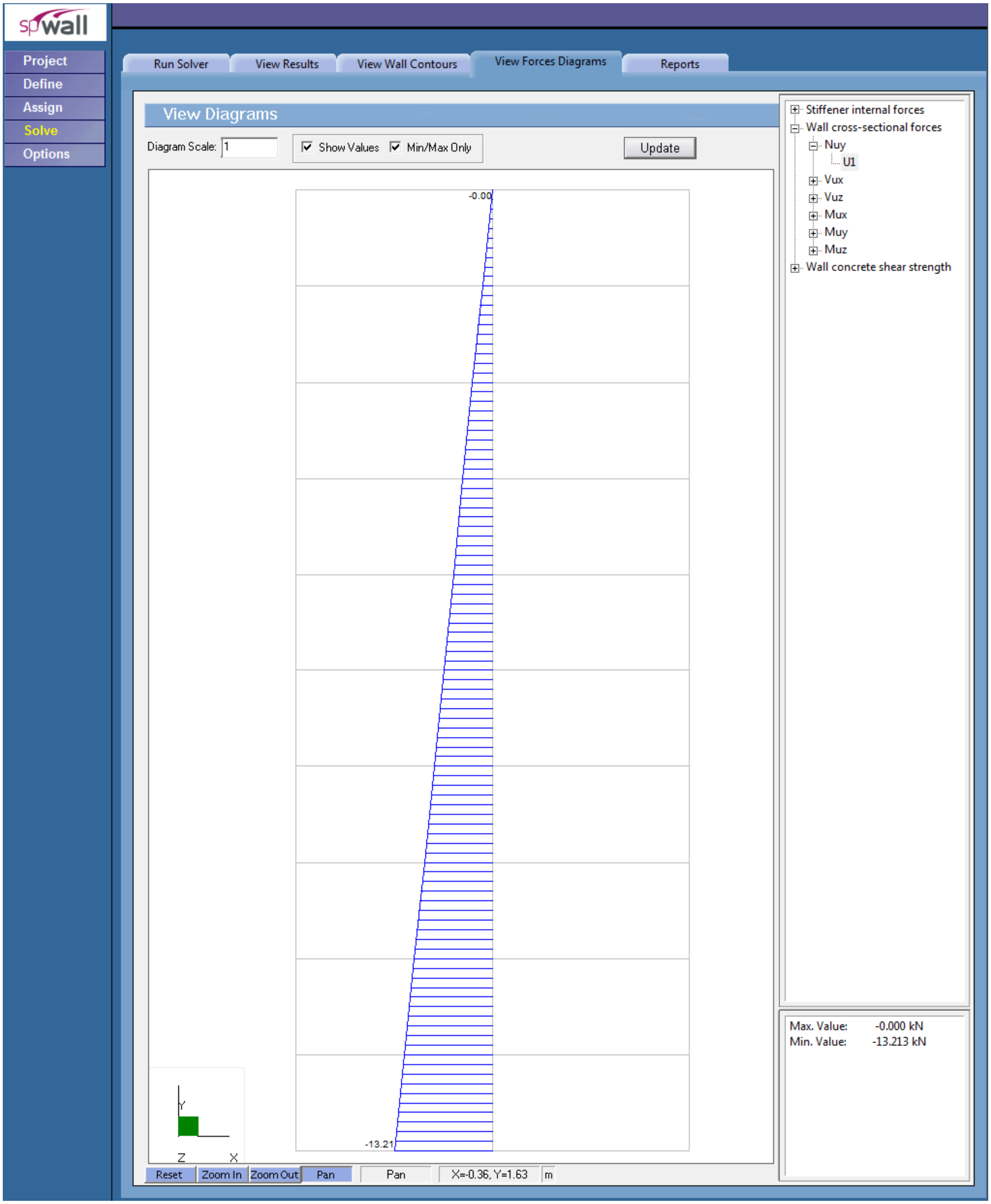


Figure 9 – Axial Load Diagram

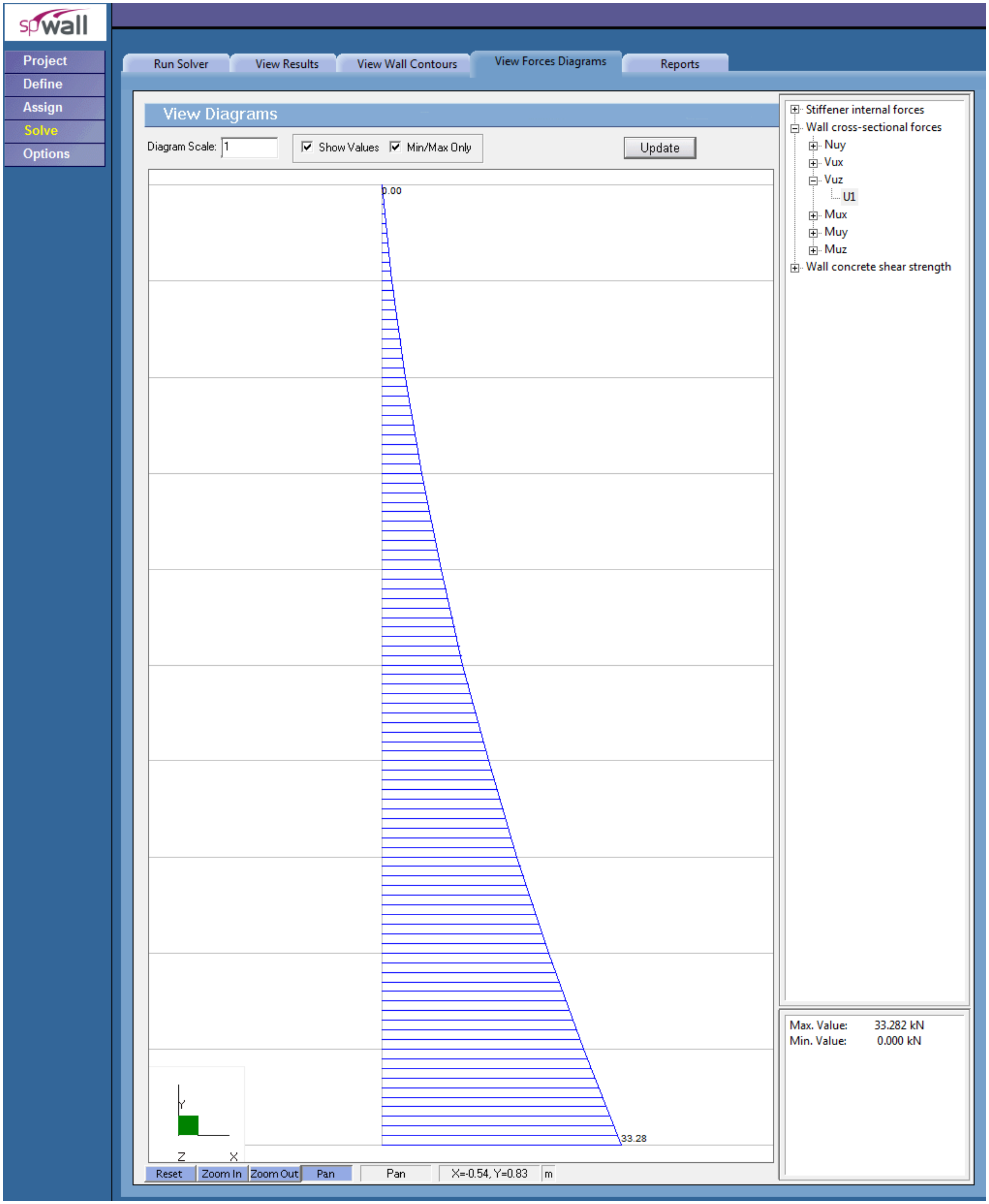


Figure 10 – Out-of-Plane Shear Diagram

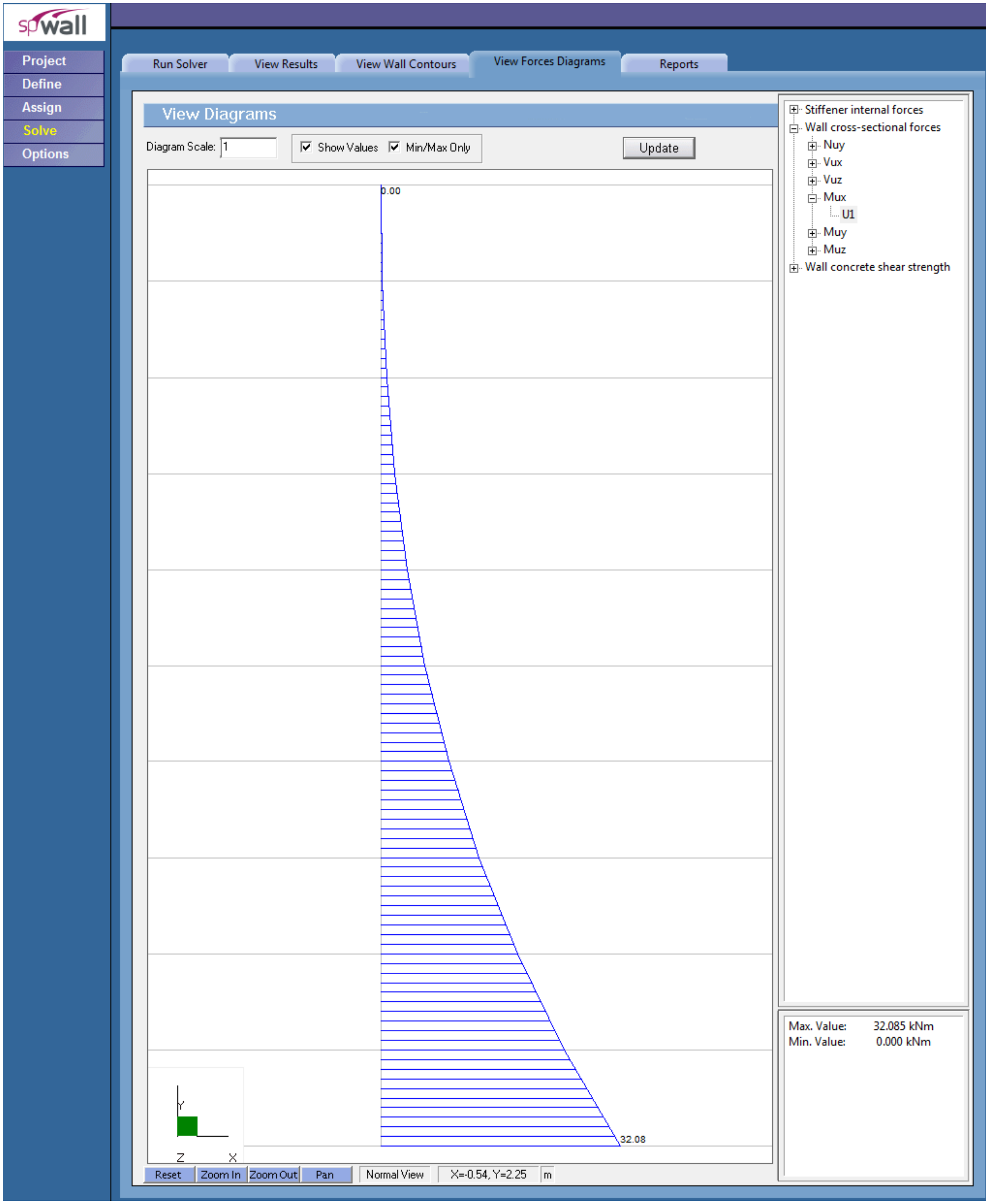


Figure 11 – Bending Moment Diagram

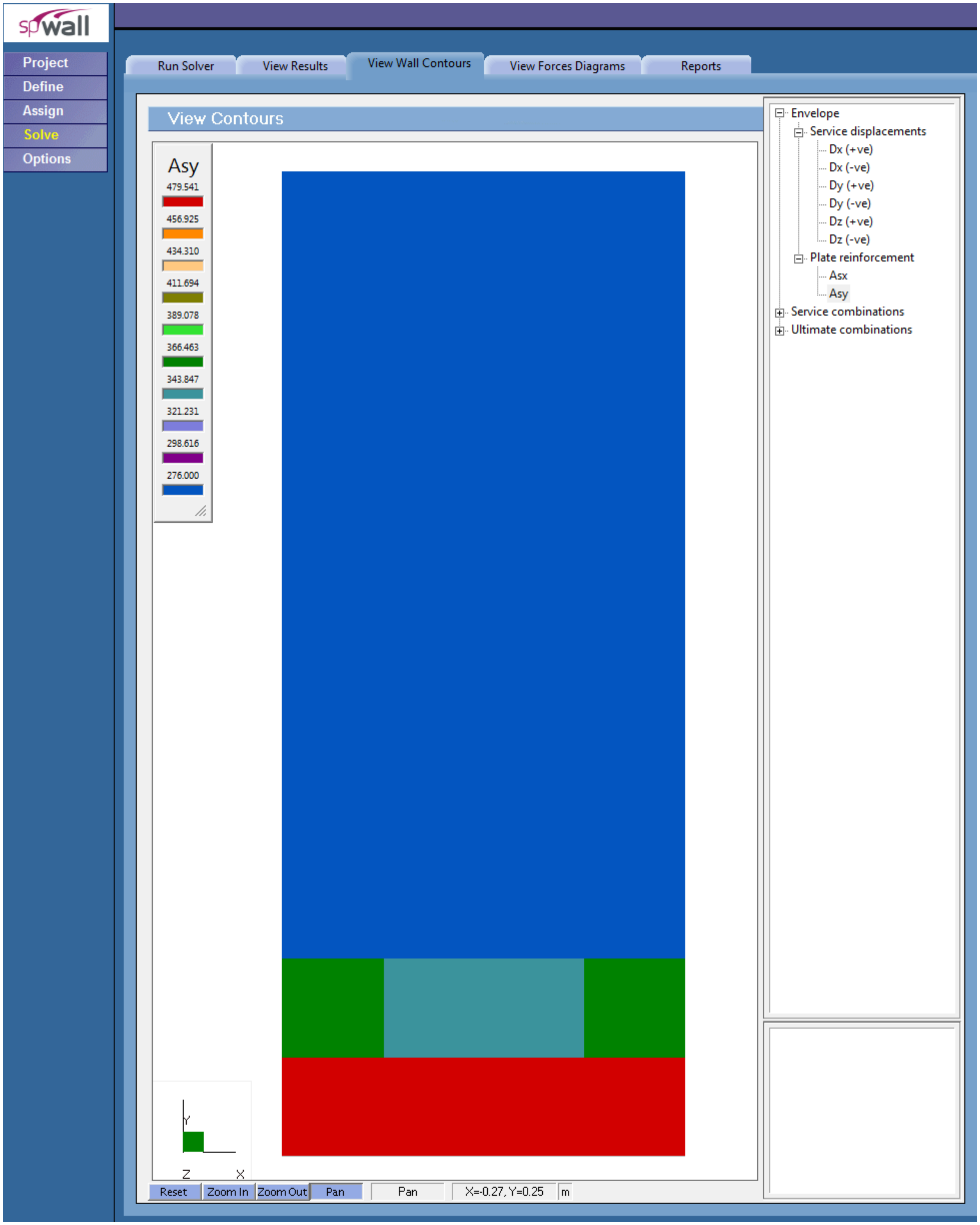


Figure 12 – Required Vertical Reinforcement

1.4. Cantilever Retaining Wall Maximum Displacement

```
Service combinations | Displacements | S1
==========================================

  Coordinate System:  Global
  ==================

  Units:
  ======
  Displacement (Dx, Dy, Dz): mm

   Node      Dx          Dy          Dz
  ----- ---------- ---------- ----------
      1 -5.76e-017 -1.37e-016 -5.16e-016
      2  1.34e-017 -2.95e-016  1.61e-015
      3  2.09e-031 -2.77e-016  9.83e-016
      4 -1.34e-017 -2.95e-016  1.61e-015
      5  5.76e-017 -1.37e-016 -5.16e-016
```

Figure 13 – Displacement at Critical Section (Service Combinations)

```
Ultimate combinations | Displacements | U1
==========================================

  Coordinate System:  Global
  ==================

  Units:
  ======
  Displacement (Dx, Dy, Dz): mm

   Node      Dx          Dy          Dz
  ----- ---------- ---------- ----------
      1 -5.76e-017 -1.37e-016 -1.03e-015
      2  1.34e-017 -2.95e-016  3.22e-015
      3  2.09e-031 -2.77e-016  1.97e-015
      4 -1.34e-017 -2.95e-016  3.22e-015
      5  5.76e-017 -1.37e-016 -1.03e-015
```

Figure 14 – Displacement at Critical Section (Ultimate Combinations)

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

```
Ultimate combinations | Wall cross-sectional forces | U1
========================================================

  Coordinate System:  Global
  ==================

  Units:
  ======
  Y-coordinate, X-centroid: m
  Force (Vux, Nuy, Vuz): kN, Moment (Mux, Muy, Muz): kNm

  Notes:
  ======
  (-) Horizontal cross-section below Y-coordinate
  (+) Horizontal cross-section above Y-coordinate

  ______Wall Cross-section______ ____________In-plane Forces___________ __________Out-of-plane Forces_________
  No.  Y-coordinate  X-centroid           Vux          Nuy          Muz          Vuz          Mux          Muy
  ---- ------------ ------------ ------------ ------------ ------------ ------------ ------------ ------------
    1+        0.000        0.500  0.0000e+000 -1.3213e+001 -4.4409e-017  3.3282e+001  3.2085e+001  1.4211e-016
```

Figure 15 – Wall Cross-Sectional Forces

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. Unlike for springs, however, punching shear check is performed around piles.

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

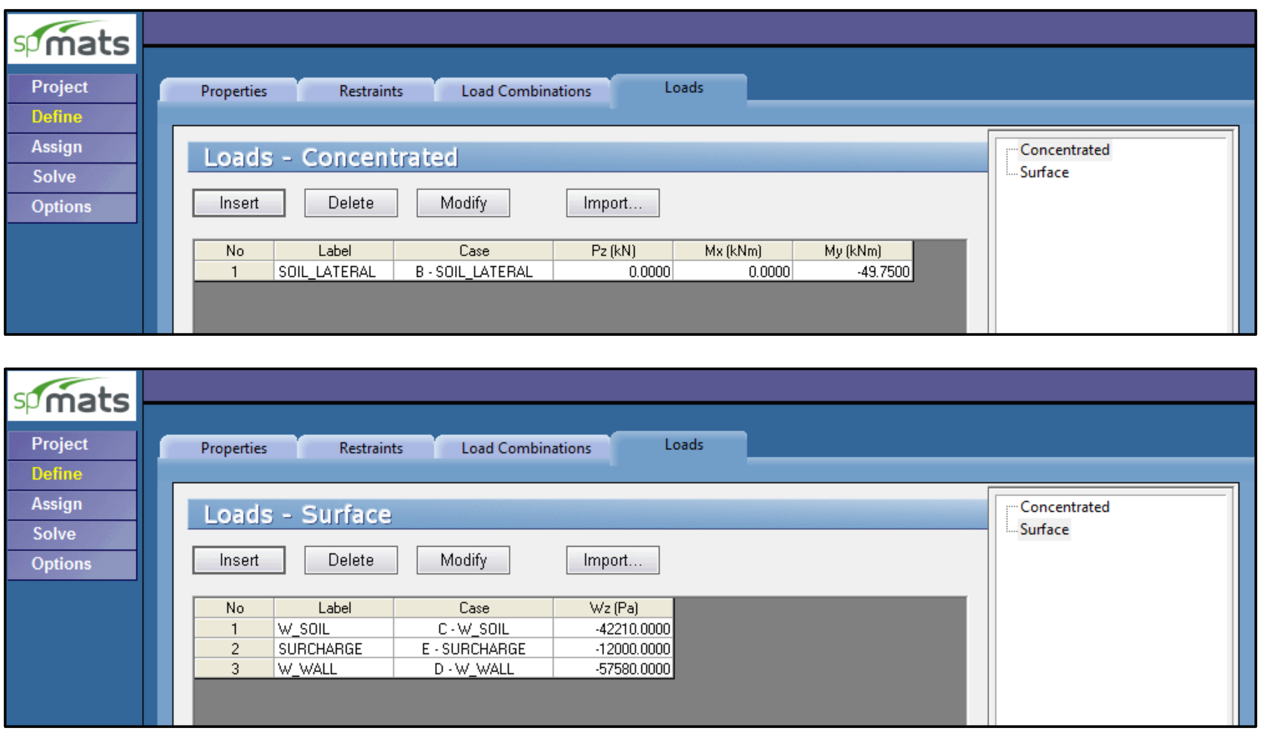


Figure 16 – Defining Loads

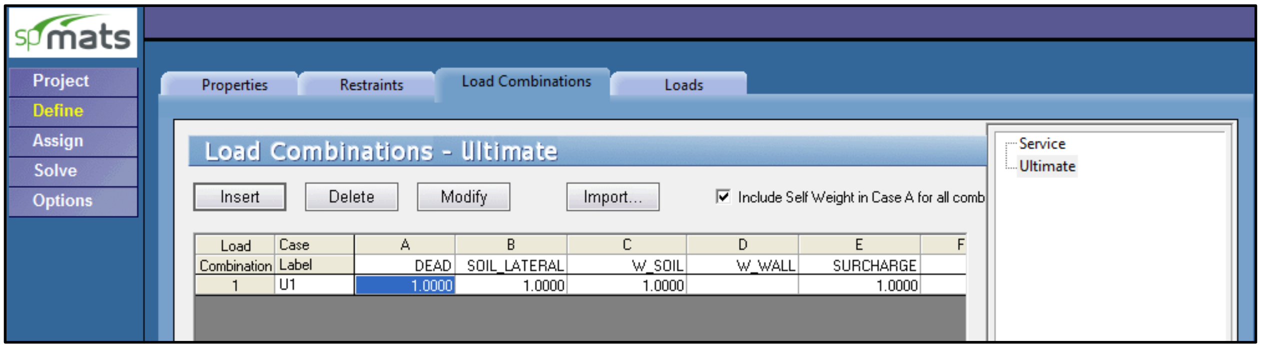


Figure 17 – Defining Load Combinations

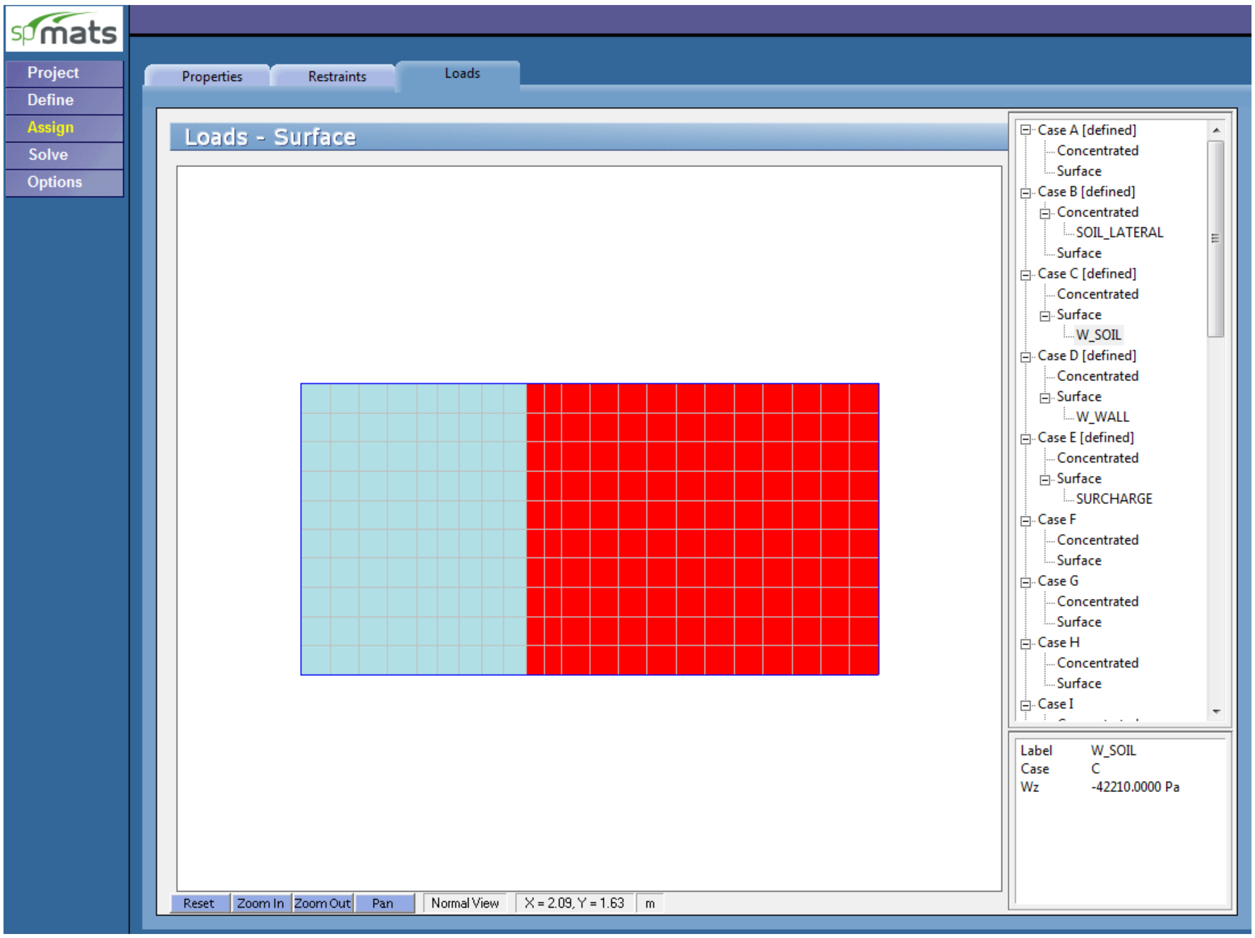


Figure 18 – Assigning Loads

2.2. Cantilever Retaining Wall Foundation Result Contours

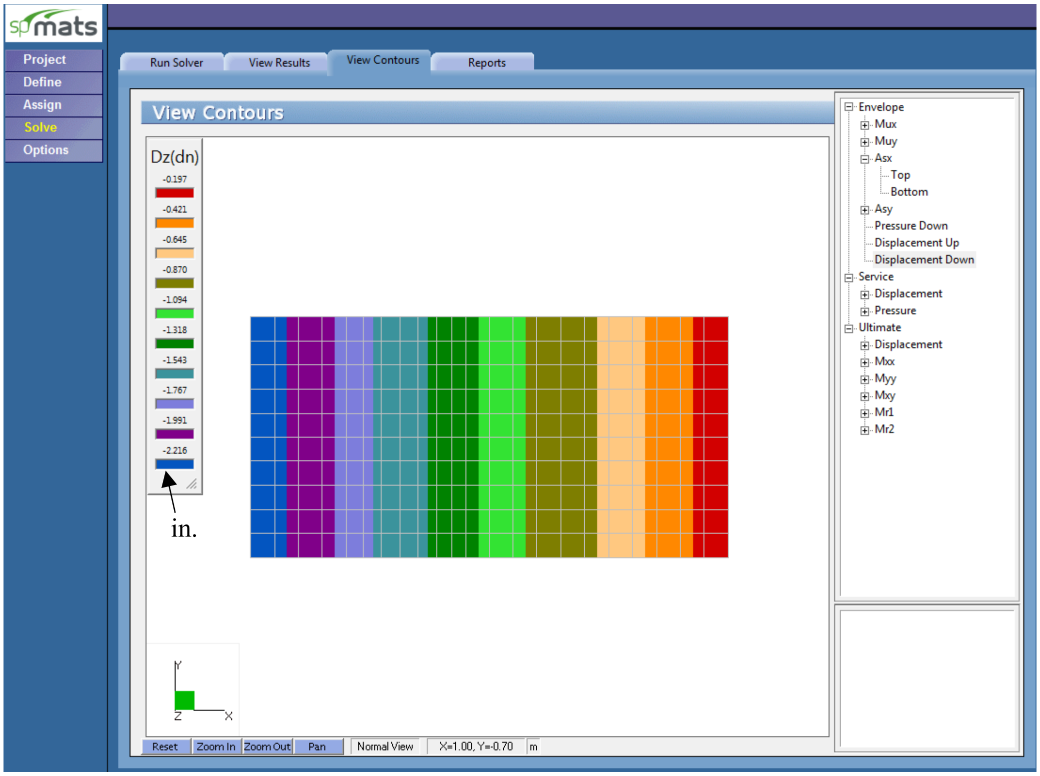


Figure 19 – Vertical (Down) Displacement Contour

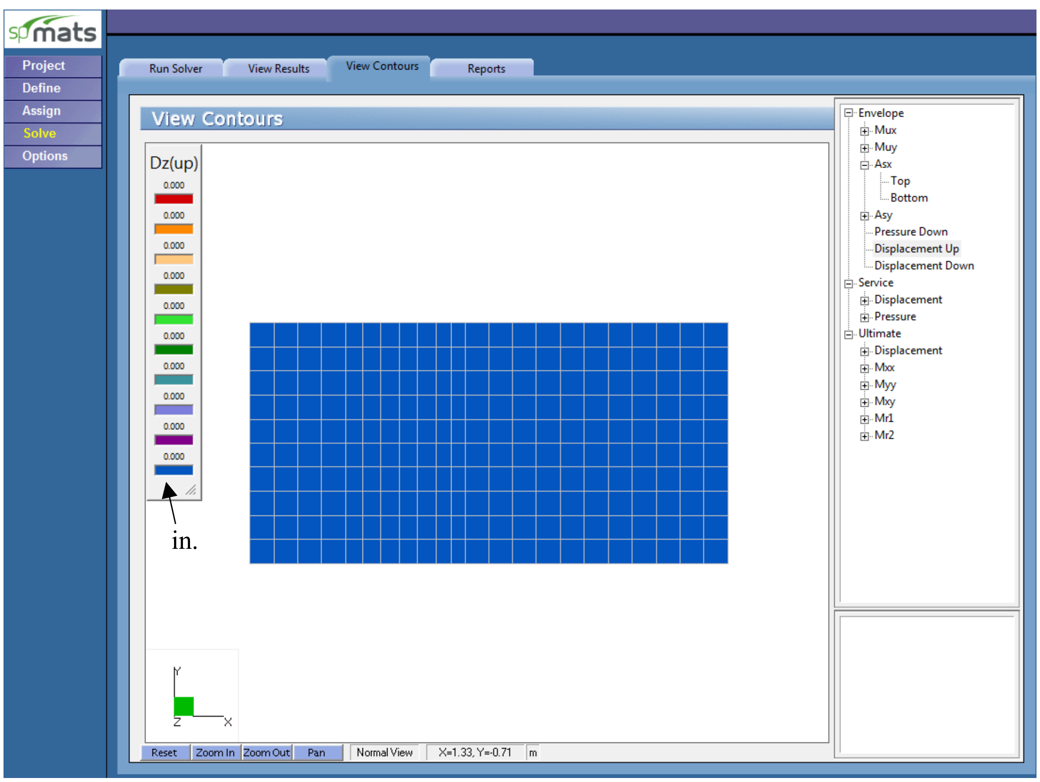


Figure 20 – Vertical (Up) Displacement Contour
(Note: figure indicates no uplift in the wall base)

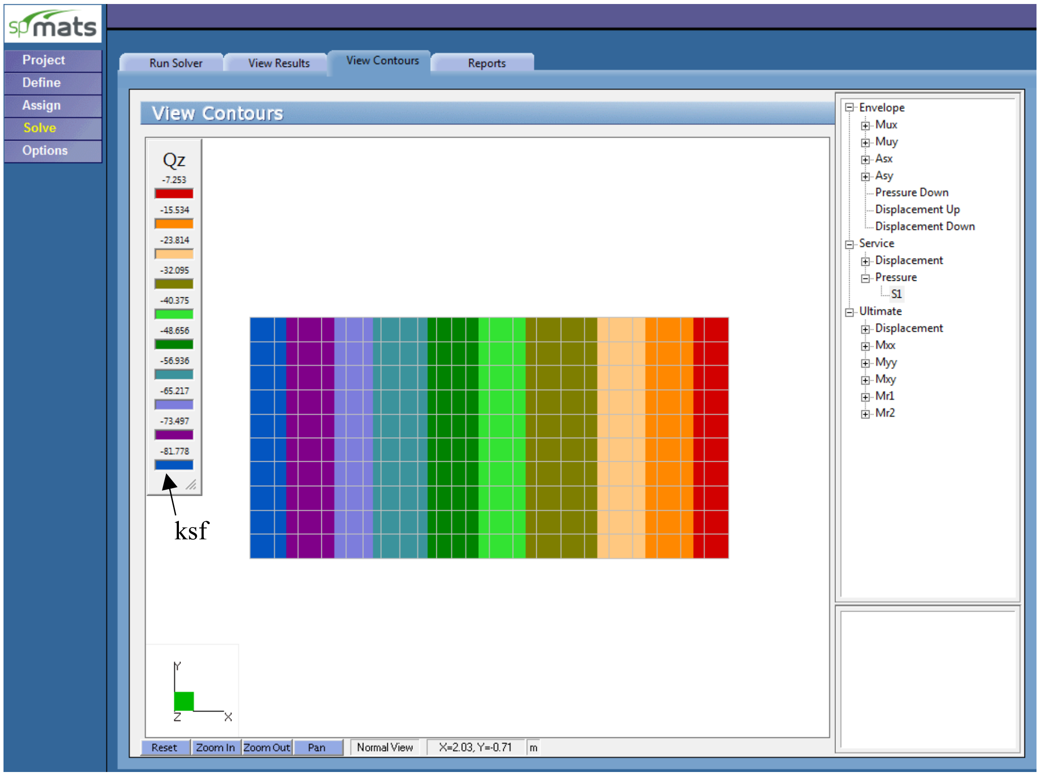


Figure 21 – Soil Bearing Pressure Contour

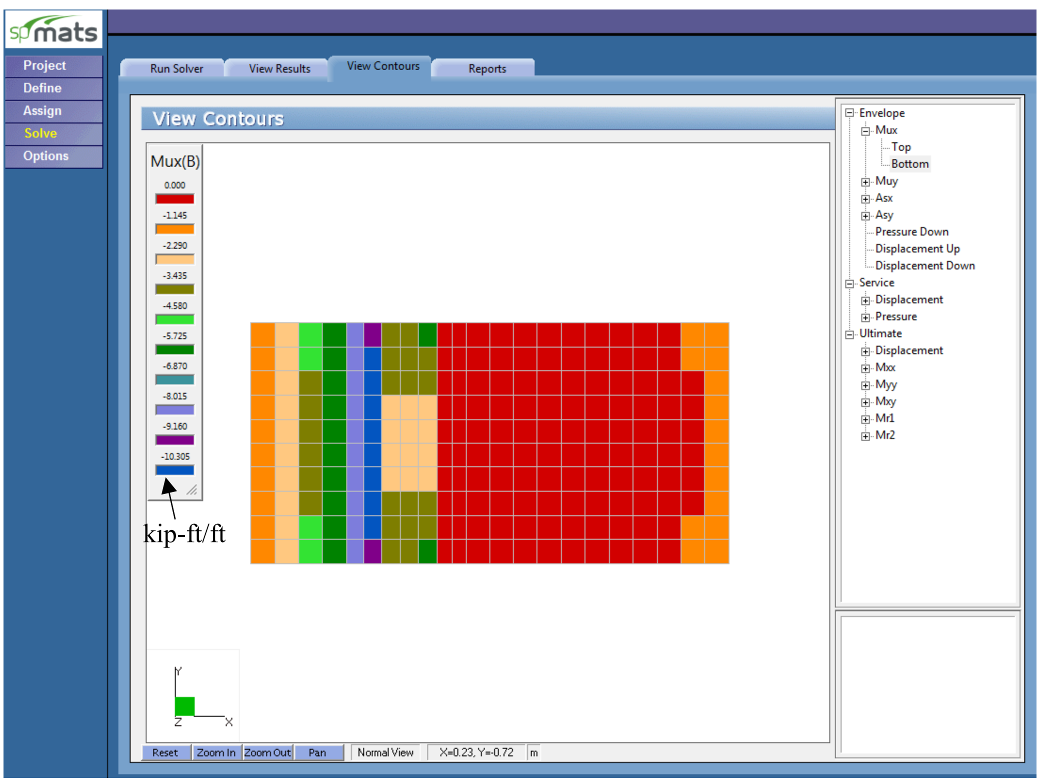


Figure 22 – Moment Contour along X-Axis (Max for Toe)

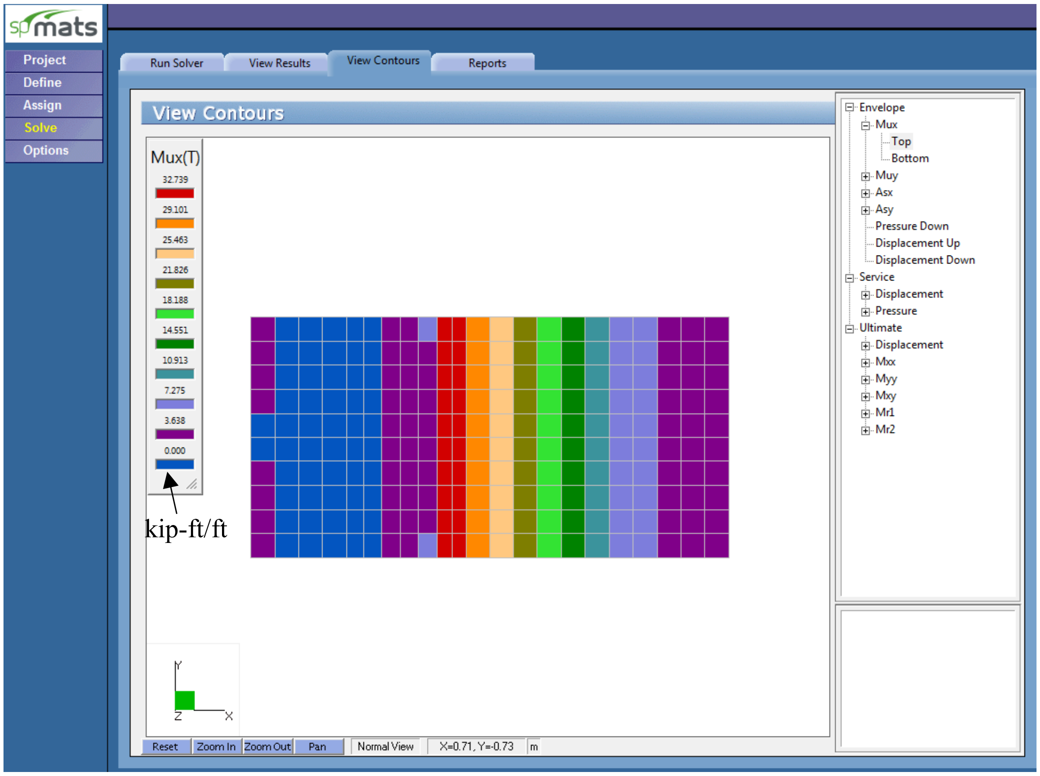


Figure 23 – Moment Contour along X-Axis (Max for Heel)

2.3. Cantilever Retaining Wall Foundation Required Reinforcement

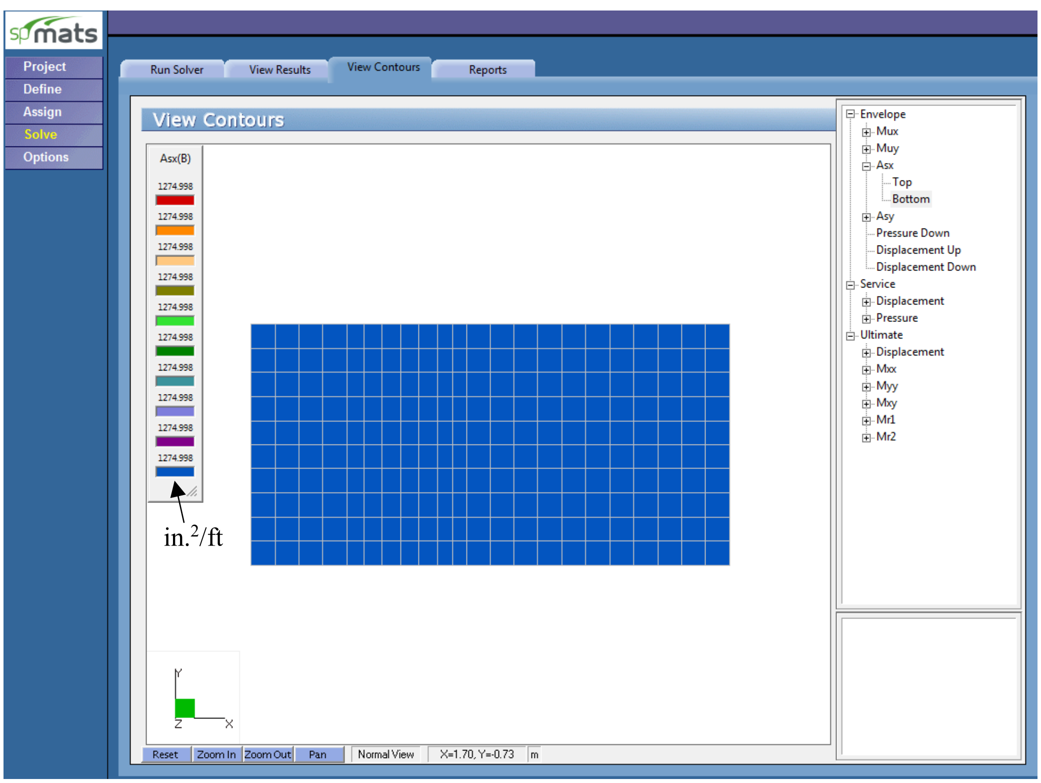


Figure 24 – Required Reinforcement Contour along X Direction (Bottom – Toe Design)
(Note minimum reinforcement governs)

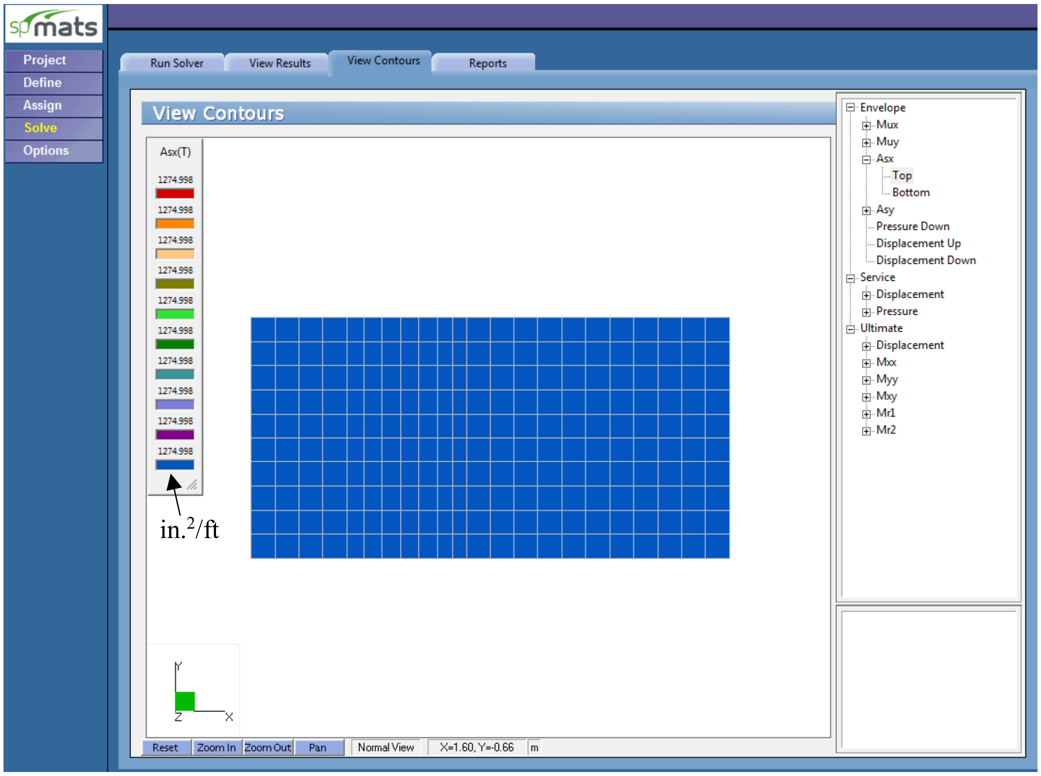


Figure 25 – Required Reinforcement Contour along X Direction (Top – Heel Design)
(Note minimum reinforcement governs)

2.4. Soil Reactions / Pressure

```
B3 - REACTIONS:
===============
Units --> Force (kN), Moment (kNm)
Service Load Combination: S1
   Sum of all forces and moments with respect to center of gravity (X, Y) = (0.99, 0.50) m

   Sum of Reactions       Fz           Mx           My
   ---------------- ------------ ------------ ------------
   Soil                 87.030       -0.000       24.496
   Springs                   -            -            -
   Piles                     -            -            -
   Restraints                -            -            -
   Slaved Nodes          0.000        0.000       -0.000
   ---------------- ------------ ------------ ------------
   Total Reactions      87.030       -0.000       24.496
   Total Loads         -87.030       -0.000      -24.496
```

Figure 26 – Soil Service Reactions

```
B4 - SOIL DISPLACEMENTS AND PRESSURES:
======================================
Units --> Displacement (mm), Pressure (kN/m^2)
Flags --> [x] Indicates allowable pressure is exceeded.
Service Load Combination: S1
    Elem    Node  Disp, Dz  Pressure, Qz    Node  Disp, Dz  Pressure, Qz
   -----   ----- ---------- ------------   ----- ---------- ------------
     111     140      -2.11      -77.958     117      -2.11      -77.959
             139      -2.22      -81.777     116      -2.22      -81.778
     132     161      -0.20       -7.274     138      -0.20       -7.275
             160      -0.29      -10.860     137      -0.29      -10.861
```

Figure 27 – Soil Bearing Pressure

2.5. Cantilever Retaining Wall Foundation Model Statistics

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

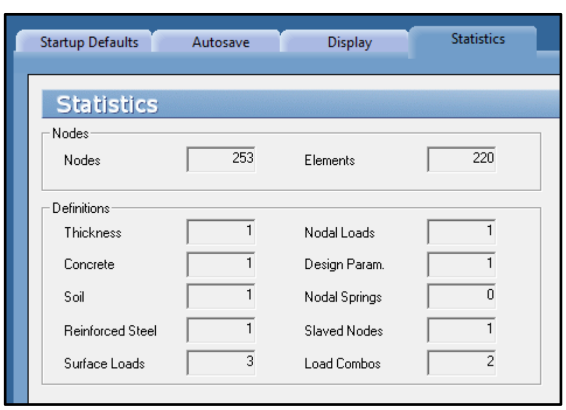


Figure 28 – Model Statistics

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. A detailed illustration of this approach can be found in "Rectangular Concrete Tanks Analysis and Design (ACI 350-06)" case study.

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.