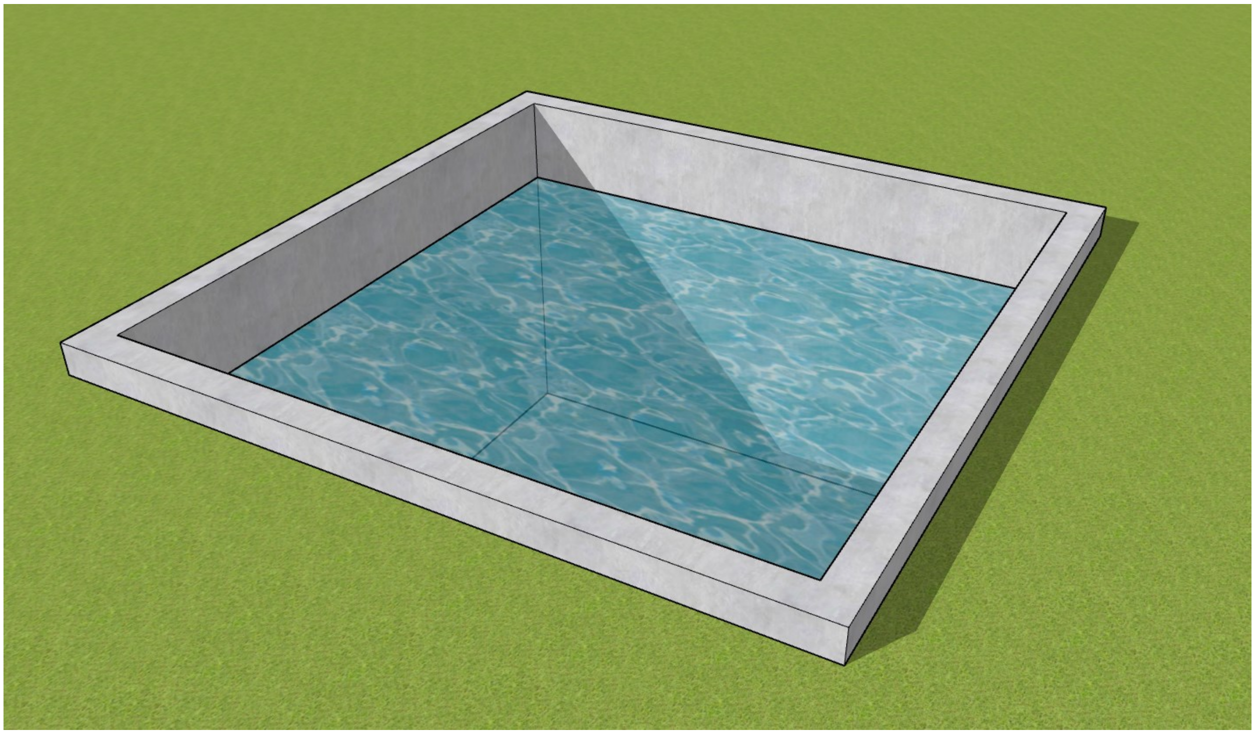
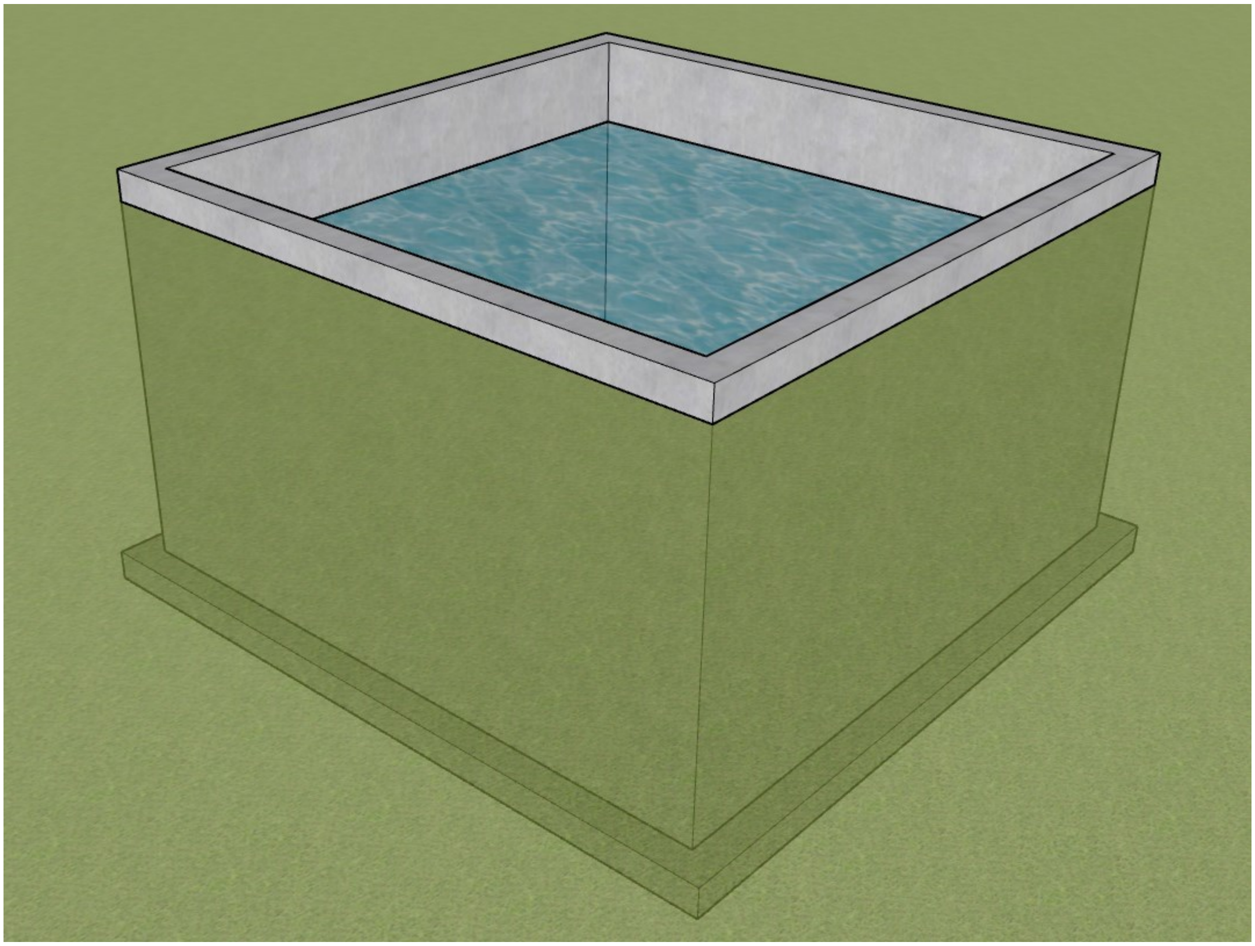
Liquid Containing Rectangular Concrete Tank Design





Liquid Containing Rectangular Concrete Tank Design

Reinforced concrete tanks are used widely to collect and contain liquids from wastewater stations, process facilities, agricultural and environmental plants. In some cases the treatment to remove contaminants or solids also subjects concrete to additional requirements beyond structural design including the proper selection of materials, detailing, erection and construction practices to achieve maximum liquid tightness. Agricultural process byproduct requires a rigorous management agenda for controlling pollution from surface runoff that may be contaminated by chemicals in fertilizer, pesticides, animal slurry, crop residues, food, milk, blood, or irrigation water. In many cases, chemical and temperature exposure has to be considered in the analysis and design of reinforced concrete tanks. This case study focuses on the design of a wastewater collection rectangular tank (pit) using the engineering software programs spWall and spMats. The tank under study is a 13 ft high partially buried open top fixed at the base to a 12" reinforced concrete base mat. The following figure and design data section and will serve as input for detailed analysis and design. ACI 350 requirements are not evaluated in detail in this case study.

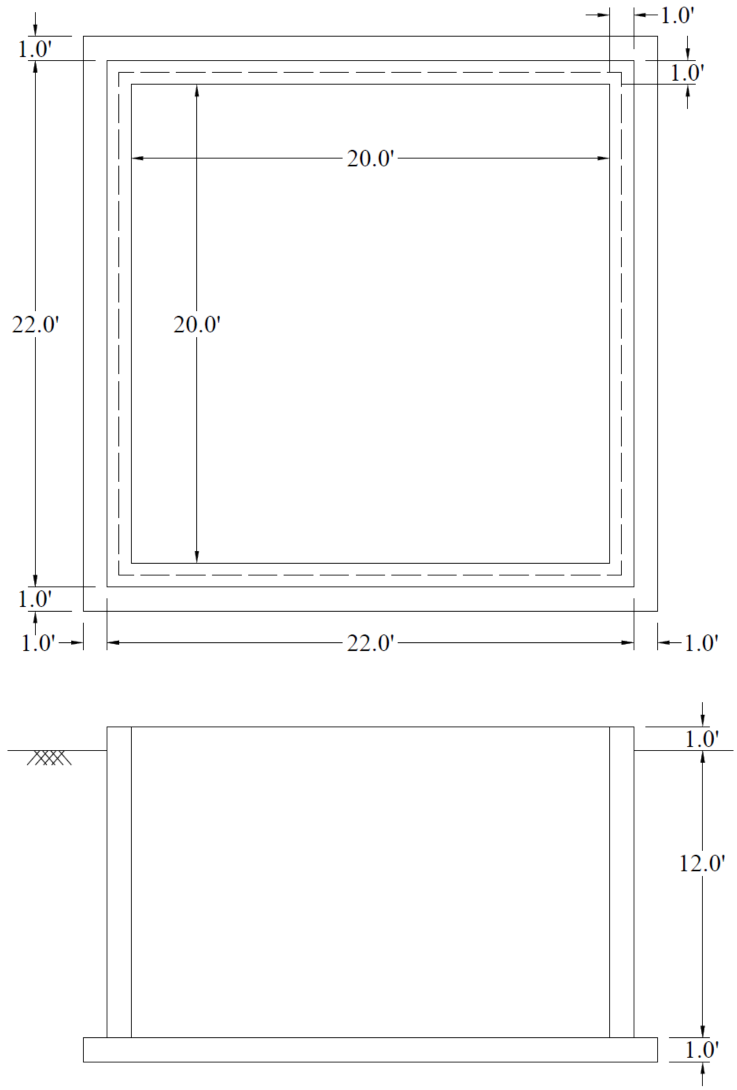


Figure 1 – Rectangular Concrete Tank Plan and Elevation

Code

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

Code Requirements for Environmental Engineering Concrete Structures and Commentary (ACI 350R-06)

Reference

spWall Engineering Software Program Manual v5.01, StucturePoint LLC., 2016

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

Design Data

Tank Wall Materials

f_c' = 4,000 psi

f_y = 60,000 psi

Tank Mat Foundation Materials

f_c' = 4,000 psi

f_y = 60,000 psi

Tank Wall Dimensions

Width = 22 ft

Height = 13 ft

Thickness = 12 in.

Tanks Mat Foundation Dimensions

Width = 24 ft

Length = 24 ft

Thickness = 12 in.

Applied Tank Loads

In addition to wall and mat selfweights, the following figure shows all the loads applied to the tank:

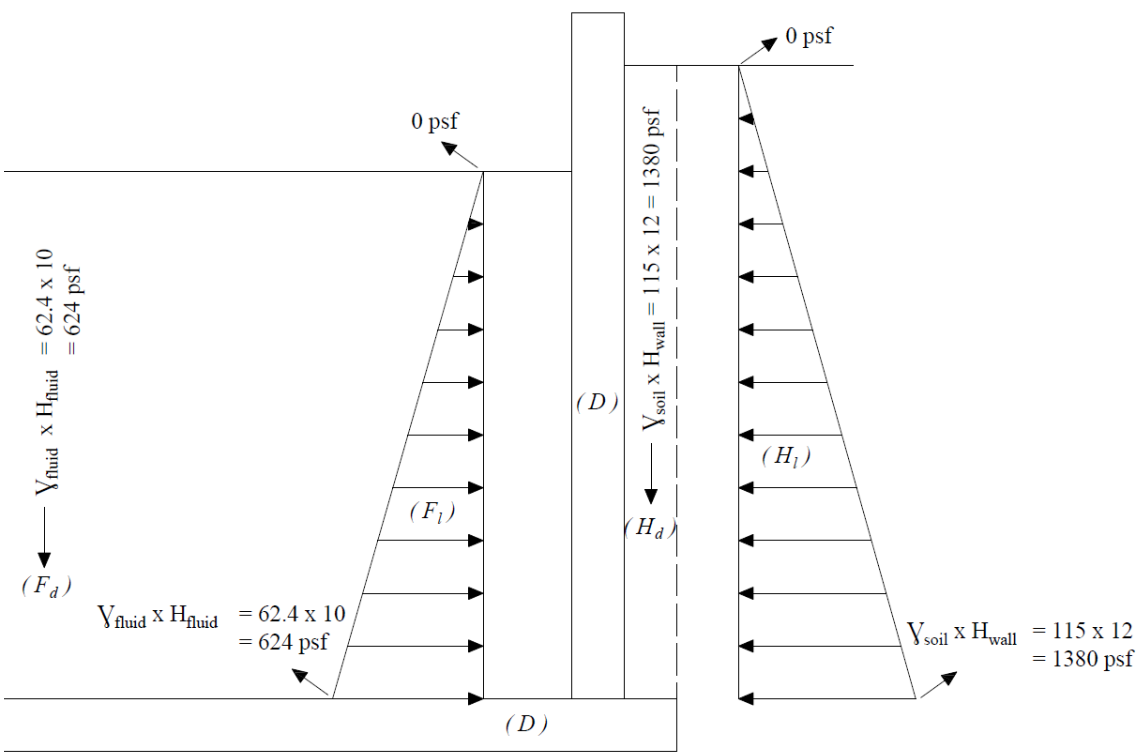
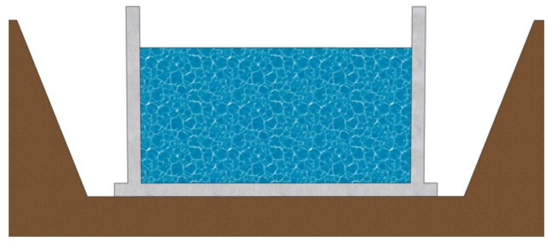
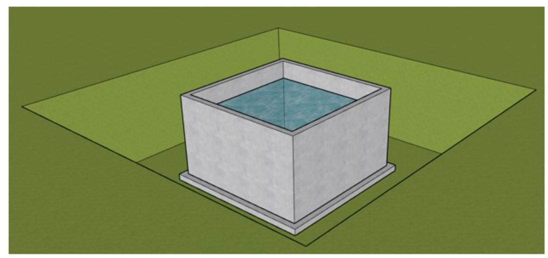
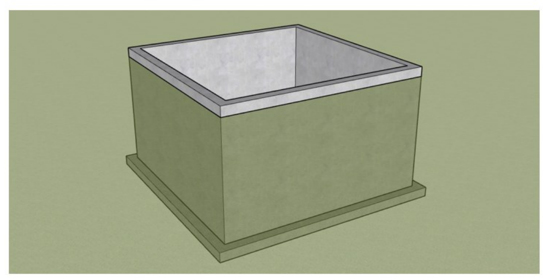
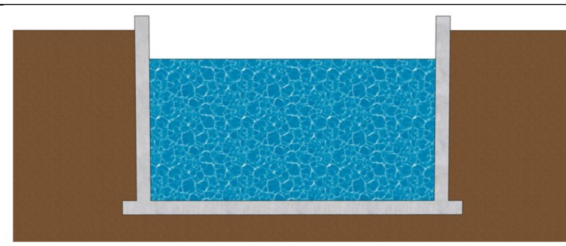
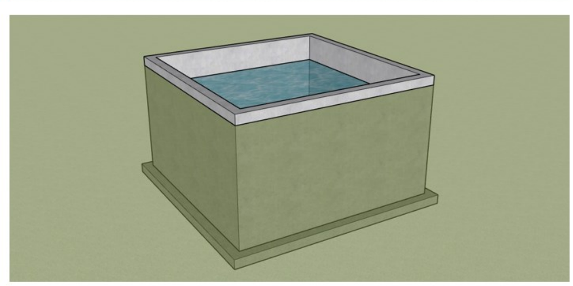


Figure 2 – Applied Loads (*l* and *d* indicated lateral and down respectively)

Load Combinations

Table 1 – Wastewater Tank Ultimate Load Combination	
Test Phase – Tank full without backfill $\text{Test}_1 = 1.4 \times (D + F_d) + 0.9 \times F_l$ $\text{Test}_2 = 0.9 \times (D + F_d) + 1.6 \times F_l$ $\text{Test}_3 = 1.2 \times (D + F_d) + 1.6 \times F_l$	 
Maintenance Phase – Tank empty with backfill $\text{Maintenance}_1 = 0.9 \times (D + H_d) + 1.6 \times H_l$ $\text{Maintenance}_2 = 1.2 \times (D + H_d) + 1.6 \times H_l$	 
Operation Phase – Tank full with backfill $\text{Operation}_1 = 1.2 \times (D + F_d) + 0.9 \times H_d + 1.6 \times F_l + 0.9 \times H_l$ $\text{Operation}_2 = 1.2 \times (D + H_d) + 0.9 \times F_d + 1.6 \times H_l + 0.9 \times F_l$	 

Contents

1. Wastewater Rectangular Concrete Tank 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 rectangular wastewater tank walls in this case study.

2. Tank Wall Model Input

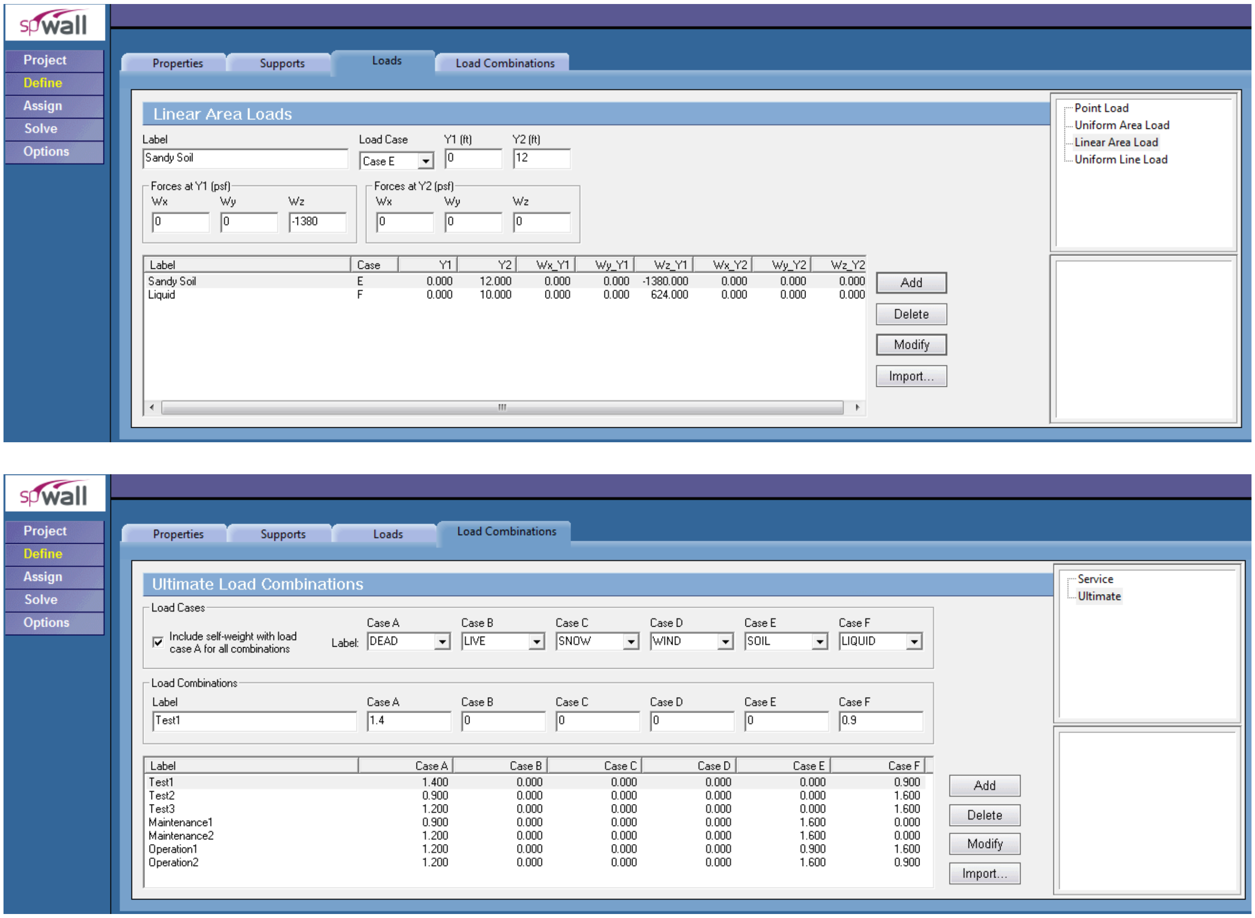
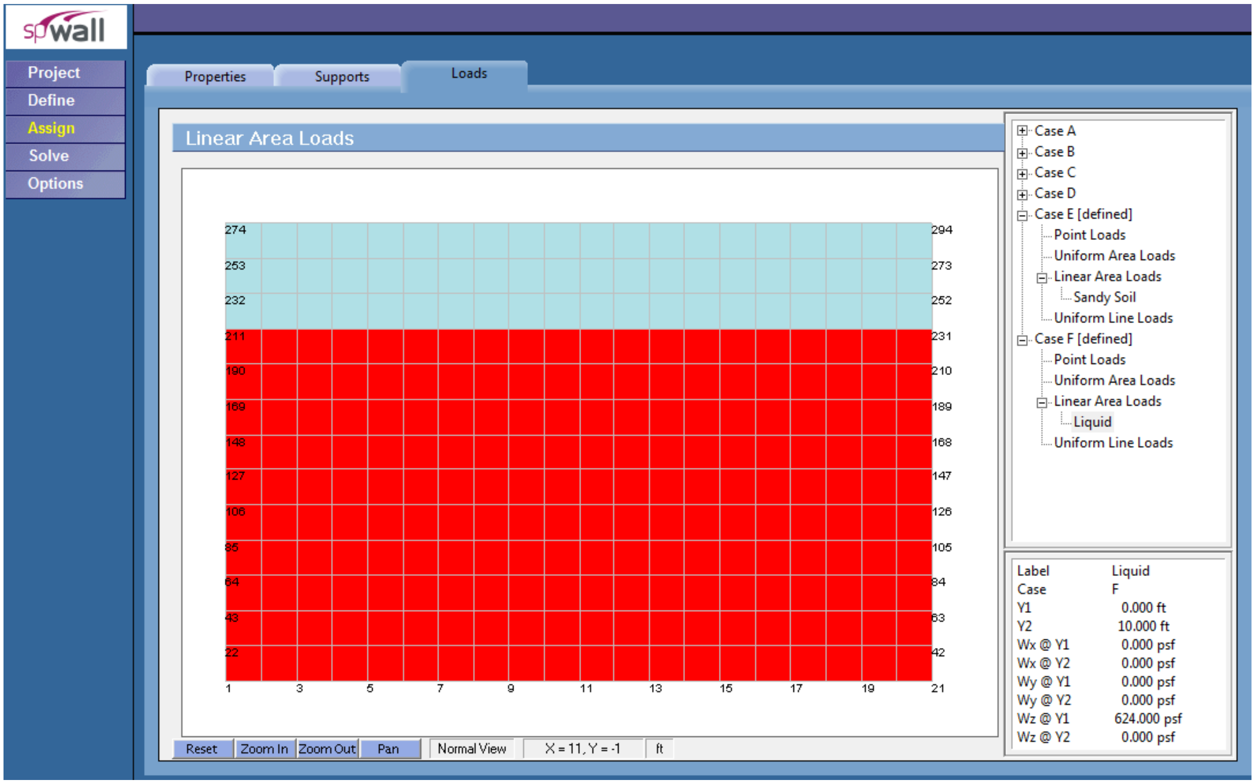


Figure 3 –Defining Tank Wall Loads and Load Combinations



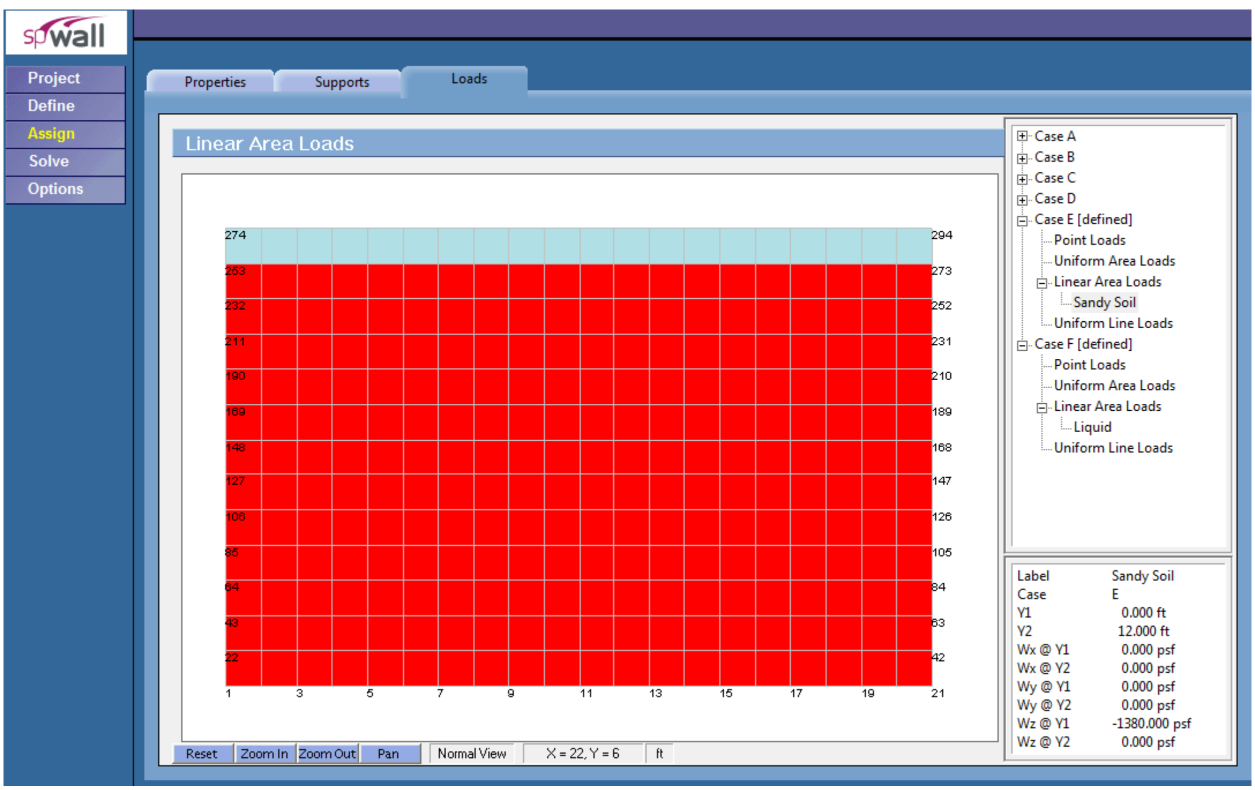


Figure 4 – Assigning Liquid and Soil Loads

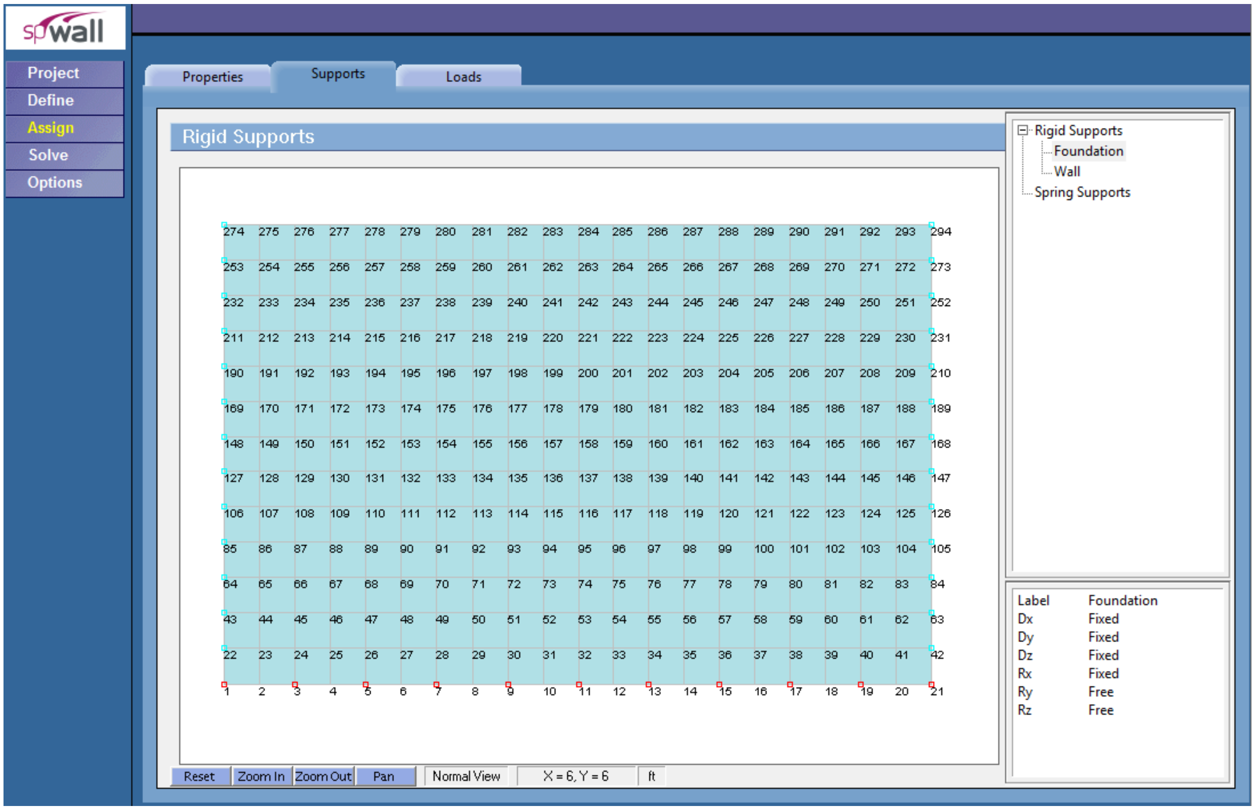


Figure 5 – Assigning Horizontal Wall Restraints

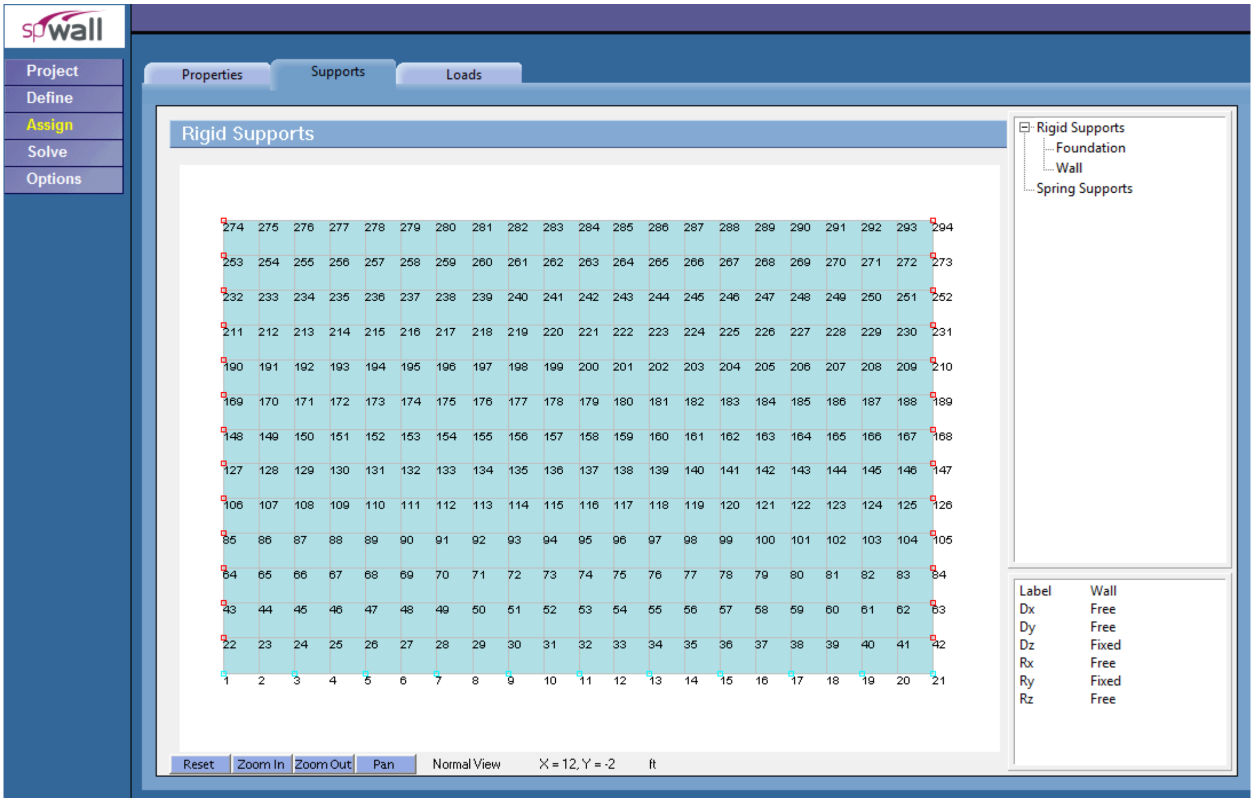


Figure 6 – Assigning Vertical Wall Restraints

3. Tank Wall Result Contours

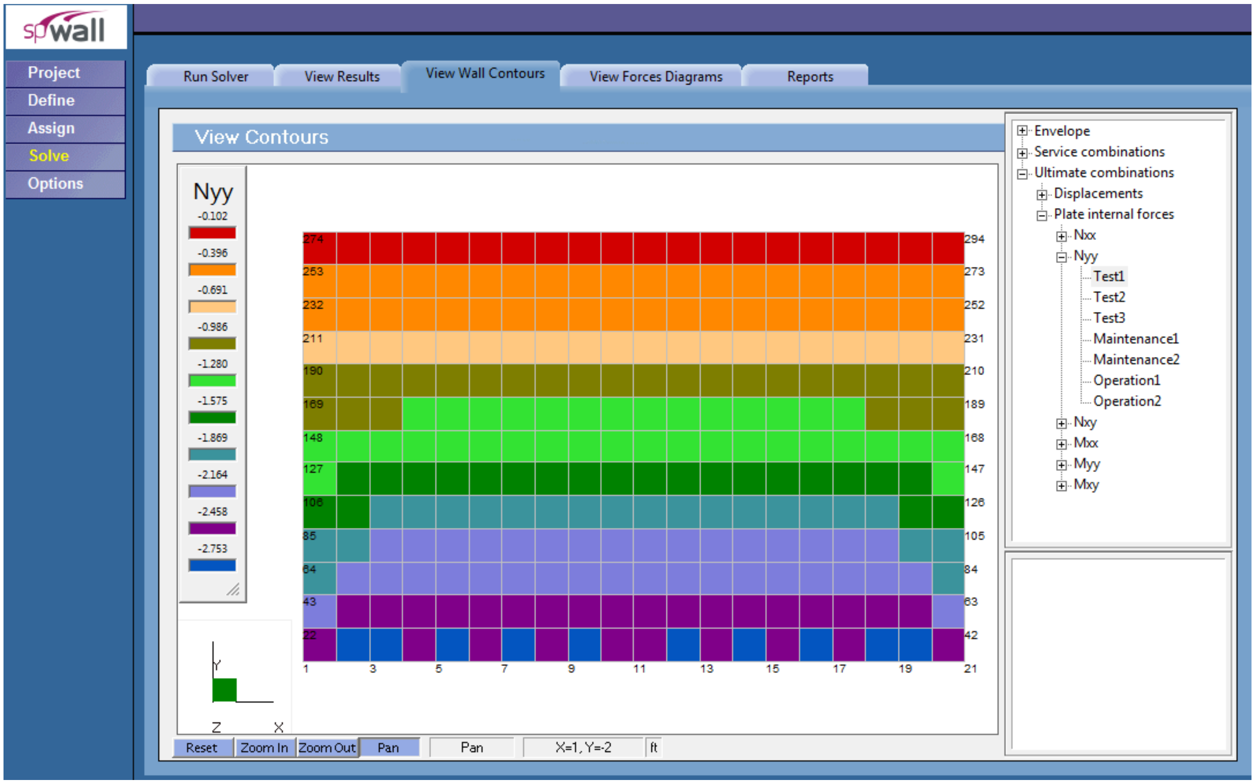


Figure 7 – Tank Wall Factored Axial Force Contour

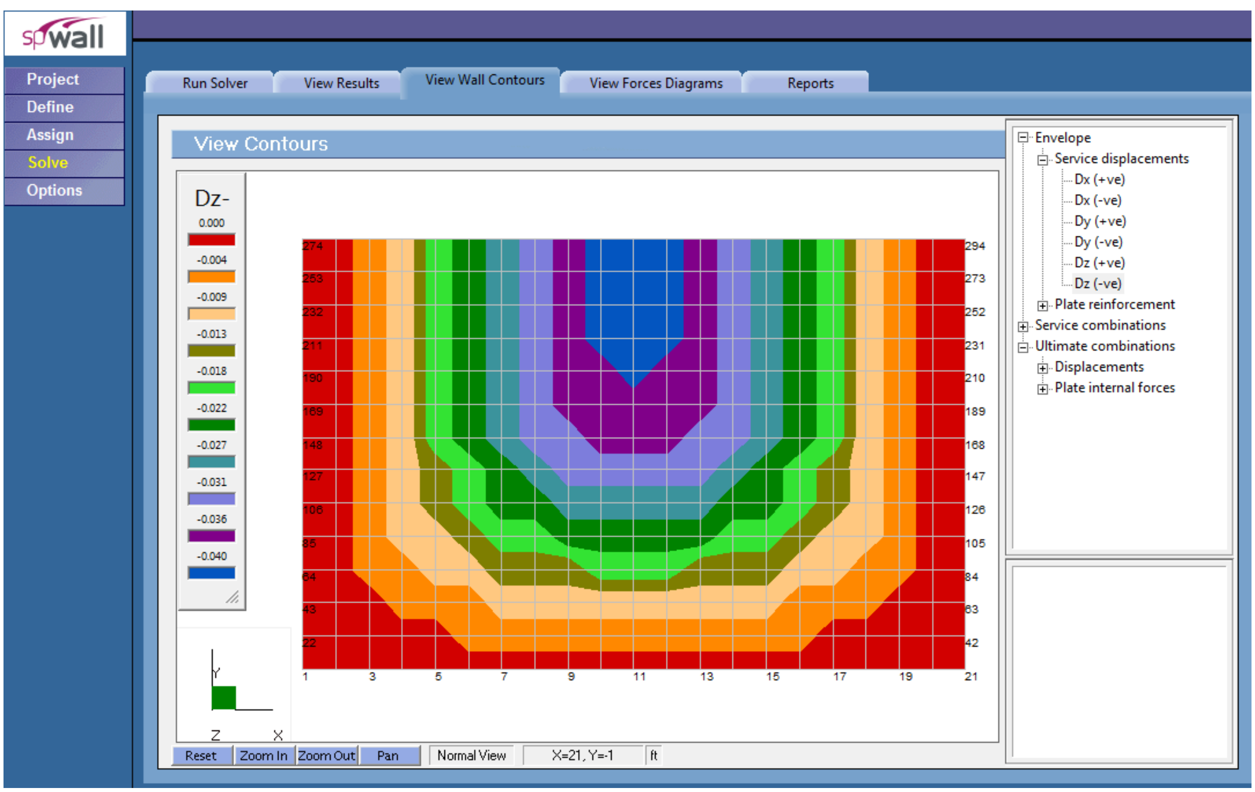


Figure 8 – Lateral Displacement Contour (Out-of-Plane)

4. Tank Wall Cross-Sectional Forces

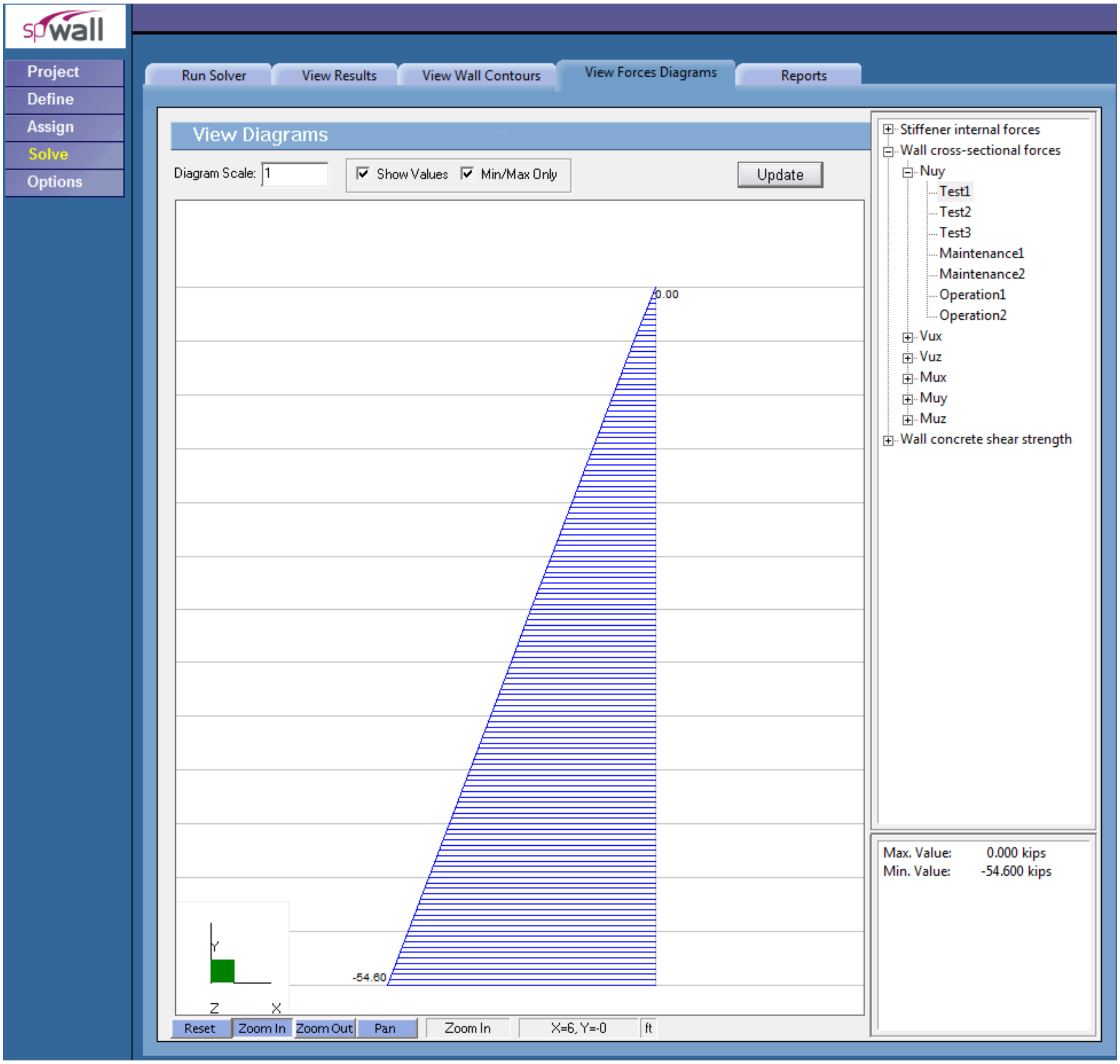


Figure 9 – Axial Load Diagram

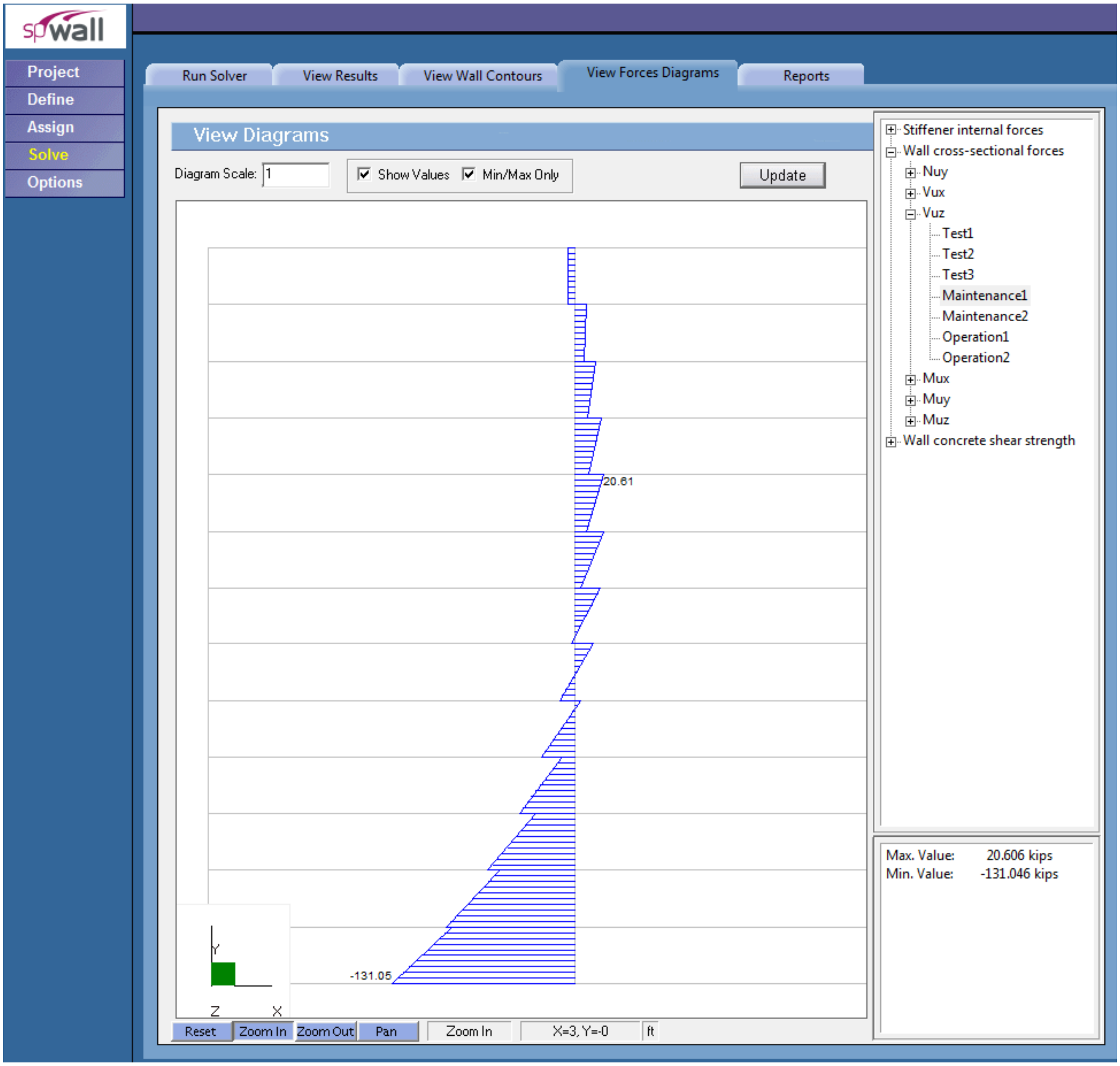


Figure 10 – Tank Wall Out-of-Plane Shear Diagram

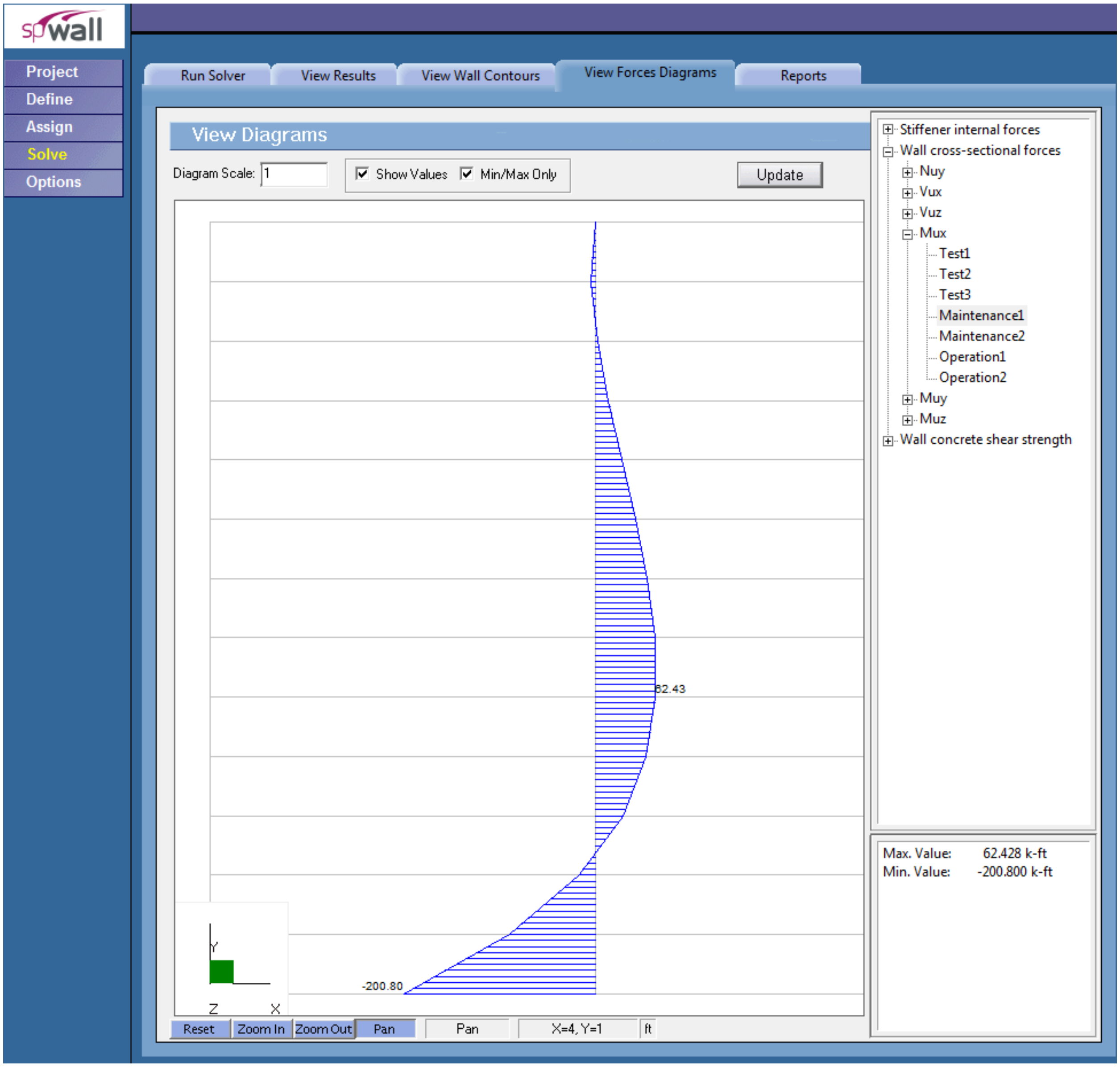


Figure 11 – Tank Wall Bending Moment Diagram

5. Maximum Tank Wall Displacement

```
Service combinations | Displacements | S2
=========================================

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

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


   Node     Dx          Dy          Dz
  ----- ---------- ---------- ----------
    169 -3.17e-005 -2.64e-004  4.99e-017
    170 -2.87e-005 -2.66e-004  4.82e-004
    171 -2.56e-005 -2.67e-004  1.68e-003
    172 -2.23e-005 -2.68e-004  3.28e-003
    173 -1.90e-005 -2.67e-004  5.05e-003
    174 -1.57e-005 -2.67e-004  6.78e-003
    175 -1.24e-005 -2.66e-004  8.36e-003
    176 -9.19e-006 -2.66e-004  9.68e-003
    177 -6.08e-006 -2.65e-004  1.07e-002
    178 -3.02e-006 -2.65e-004  1.13e-002
    179 -1.39e-018 -2.65e-004  1.15e-002
    180  3.02e-006 -2.65e-004  1.13e-002
    181  6.08e-006 -2.65e-004  1.07e-002
    182  9.19e-006 -2.66e-004  9.68e-003
    183  1.24e-005 -2.66e-004  8.36e-003
    184  1.57e-005 -2.67e-004  6.78e-003
    185  1.90e-005 -2.67e-004  5.05e-003
    186  2.23e-005 -2.68e-004  3.28e-003
    187  2.56e-005 -2.67e-004  1.68e-003
    188  2.87e-005 -2.66e-004  4.82e-004
    189  3.17e-005 -2.64e-004  4.99e-017
```

Figure 12 – Displacement at Critical Section (Service Combinations)

```
Ultimate combinations | Displacements | Maintenance1
=====================================================

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

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


   Node     Dx          Dy          Dz
  ----- ---------- ---------- ----------
    274 -1.40e-005 -2.73e-004  3.71e-016
    275 -1.29e-005 -2.74e-004 -6.71e-003
    276 -1.25e-005 -2.76e-004 -2.63e-002
    277 -1.19e-005 -2.77e-004 -5.50e-002
    278 -1.11e-005 -2.78e-004 -8.87e-002
    279 -9.90e-006 -2.78e-004 -1.24e-001
    280 -8.37e-006 -2.78e-004 -1.56e-001
    281 -6.55e-006 -2.78e-004 -1.85e-001
    282 -4.50e-006 -2.77e-004 -2.06e-001
    283 -2.29e-006 -2.77e-004 -2.20e-001
    284 -2.68e-018 -2.77e-004 -2.24e-001
    285  2.29e-006 -2.77e-004 -2.20e-001
    286  4.50e-006 -2.77e-004 -2.06e-001
    287  6.55e-006 -2.78e-004 -1.85e-001
    288  8.37e-006 -2.78e-004 -1.56e-001
    289  9.90e-006 -2.78e-004 -1.24e-001
    290  1.11e-005 -2.78e-004 -8.87e-002
    291  1.19e-005 -2.77e-004 -5.50e-002
    292  1.25e-005 -2.76e-004 -2.63e-002
    293  1.29e-005 -2.74e-004 -6.71e-003
    294  1.40e-005 -2.73e-004  3.71e-016
```

Figure 13 – Displacement at Critical Section (Ultimate Combinations)

6. Tank Wall Cross-Sectional Forces at Fixed Base

```
Ultimate combinations | Wall cross-sectional forces | Maintenance1
==================================================================

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

  Units:
  ======
  Y-coordinate, X-centroid: ft
  Force (Vux, Nuy, Vuz): kips, Moment (Mux, Muy, Muz): k-ft

  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       10.000  2.0048e-015 -3.5100e+001  1.1618e-013 -1.3105e+002 -2.0080e+002  4.8033e-012
```

Figure 14 – Cross-Sectional Forces

7. Tank Wall Reactions At Fixed Based

The following wall reactions will be serve as the input to the mat foundation model and will be used as the part of the primary load cases in spMats. The reactions along the vertical wall edge have an equal and opposite force from the opposite tank wall. A small in plane shear is generated causing a negligible axial stress in the walls.

Service combinations | Reactions | Self-Weight Wall Reactions

Coordinate System: Global

Units:
Force (Fx, Fy, Fz): kips, Moment (Mx, My, Mz): k-ft

Node	Fx	Fy	Fz	Mx	My	Mz
1	1.0111e+000	1.9074e+000	0.0000e+000	0.0000e+000	0.0000e+000	-4.8572e-017
3	-1.2704e-001	4.0306e+000	0.0000e+000	0.0000e+000	0.0000e+000	3.4694e-017
5	1.1218e-001	3.8948e+000	0.0000e+000	0.0000e+000	0.0000e+000	-6.0137e-017
7	9.5291e-002	3.8691e+000	0.0000e+000	0.0000e+000	0.0000e+000	5.2909e-017
9	4.8993e-002	3.8654e+000	0.0000e+000	0.0000e+000	0.0000e+000	-7.2280e-018
11	-2.3880e-016	3.8653e+000	0.0000e+000	0.0000e+000	0.0000e+000	7.4449e-017
13	-4.8993e-002	3.8654e+000	0.0000e+000	0.0000e+000	0.0000e+000	3.4984e-017
15	-9.5291e-002	3.8691e+000	0.0000e+000	0.0000e+000	0.0000e+000	-3.2382e-017
17	-1.1218e-001	3.8948e+000	0.0000e+000	0.0000e+000	0.0000e+000	5.4355e-017
19	1.2704e-001	4.0306e+000	0.0000e+000	0.0000e+000	0.0000e+000	-7.5750e-017
21	-1.0111e+000	1.9074e+000	0.0000e+000	0.0000e+000	0.0000e+000	2.8681e-016

Service combinations | Reactions | Liquid Wall Reactions

Coordinate System: Global

Units:
Force (Fx, Fy, Fz): kips, Moment (Mx, My, Mz): k-ft

Node	Fx	Fy	Fz	Mx	My	Mz
1	0.0000e+000	0.0000e+000	6.3602e-001	7.8133e-002	-3.7007e-017	0.0000e+000
3	0.0000e+000	0.0000e+000	-1.3682e+000	-1.6984e+000	2.9606e-016	0.0000e+000
5	0.0000e+000	0.0000e+000	-3.7369e+000	-4.3226e+000	1.4803e-015	0.0000e+000
7	0.0000e+000	0.0000e+000	-4.6974e+000	-6.2436e+000	1.4433e-015	0.0000e+000
9	0.0000e+000	0.0000e+000	-5.1883e+000	-7.3971e+000	6.7076e-016	0.0000e+000
11	0.0000e+000	0.0000e+000	-5.3274e+000	-7.7759e+000	1.0871e-015	0.0000e+000
13	0.0000e+000	0.0000e+000	-5.1883e+000	-7.3971e+000	-8.1416e-016	0.0000e+000
15	0.0000e+000	0.0000e+000	-4.6974e+000	-6.2436e+000	1.3693e-015	0.0000e+000
17	0.0000e+000	0.0000e+000	-3.7369e+000	-4.3226e+000	-7.7716e-016	0.0000e+000
19	0.0000e+000	0.0000e+000	-1.3682e+000	-1.6984e+000	4.0708e-016	0.0000e+000
21	0.0000e+000	0.0000e+000	6.3602e-001	7.8133e-002	-3.0295e-017	0.0000e+000

Service combinations | Reactions | Soil Wall Reactions

Coordinate System: Global

Units:
Force (Fx, Fy, Fz): kips, Moment (Mx, My, Mz): k-ft

Node	Fx	Fy	Fz	Mx	My	Mz
1	0.0000e+000	0.0000e+000	-1.6800e+000	-1.9370e-001	-7.4015e-017	0.0000e+000
3	0.0000e+000	0.0000e+000	2.6401e+000	4.1973e+000	1.4803e-016	0.0000e+000
5	0.0000e+000	0.0000e+000	8.7708e+000	1.1258e+001	-3.1086e-015	0.0000e+000
7	0.0000e+000	0.0000e+000	1.1524e+001	1.6729e+001	-3.4787e-015	0.0000e+000
9	0.0000e+000	0.0000e+000	1.2989e+001	2.0119e+001	2.5720e-015	0.0000e+000
11	0.0000e+000	0.0000e+000	1.3418e+001	2.1250e+001	3.7007e-017	0.0000e+000
13	0.0000e+000	0.0000e+000	1.2989e+001	2.0119e+001	-1.4063e-015	0.0000e+000
15	0.0000e+000	0.0000e+000	1.1524e+001	1.6729e+001	3.7748e-015	0.0000e+000
17	0.0000e+000	0.0000e+000	8.7708e+000	1.1258e+001	-3.5527e-015	0.0000e+000
19	0.0000e+000	0.0000e+000	2.6401e+000	4.1973e+000	-7.4015e-016	0.0000e+000
21	0.0000e+000	0.0000e+000	-1.6800e+000	-1.9370e-001	-6.4311e-017	0.0000e+000

Figure 15 – Wall Reactions (Service Combinations)

8. Tank Wall Required Reinforcement

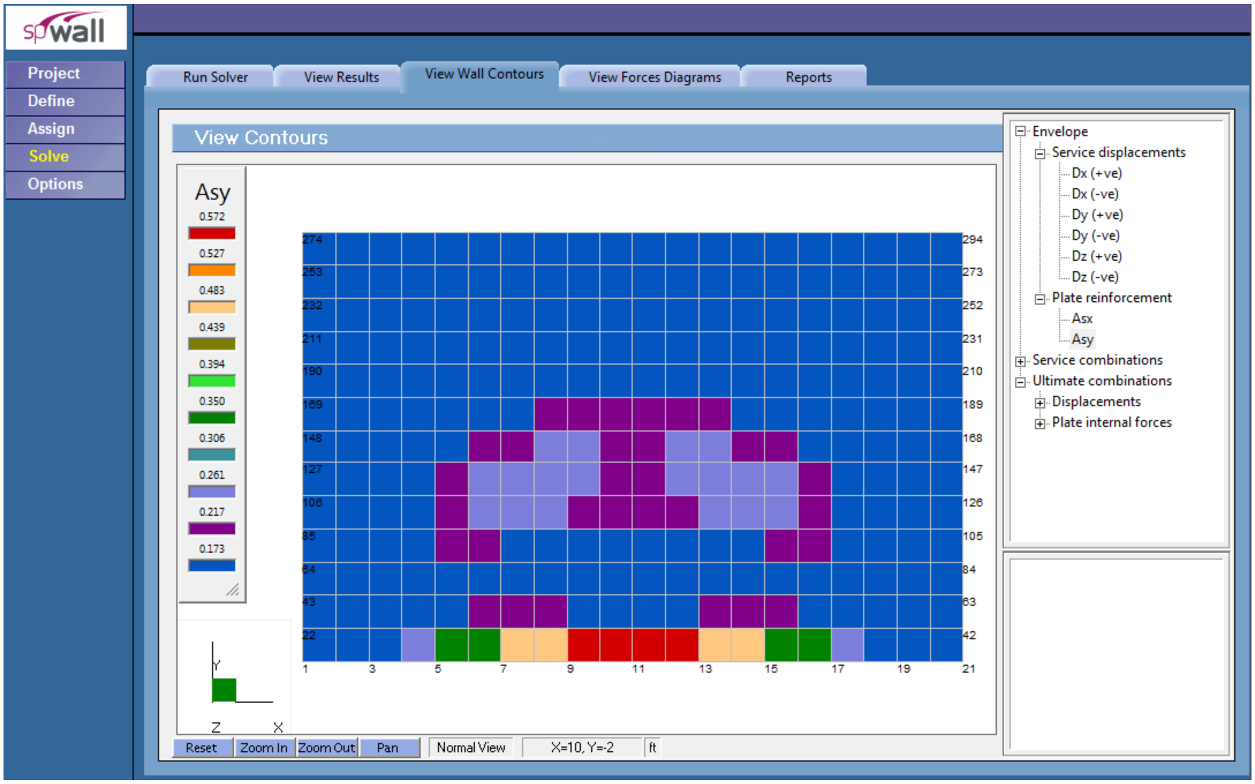


Figure 16 – Required Vertical Reinforcement

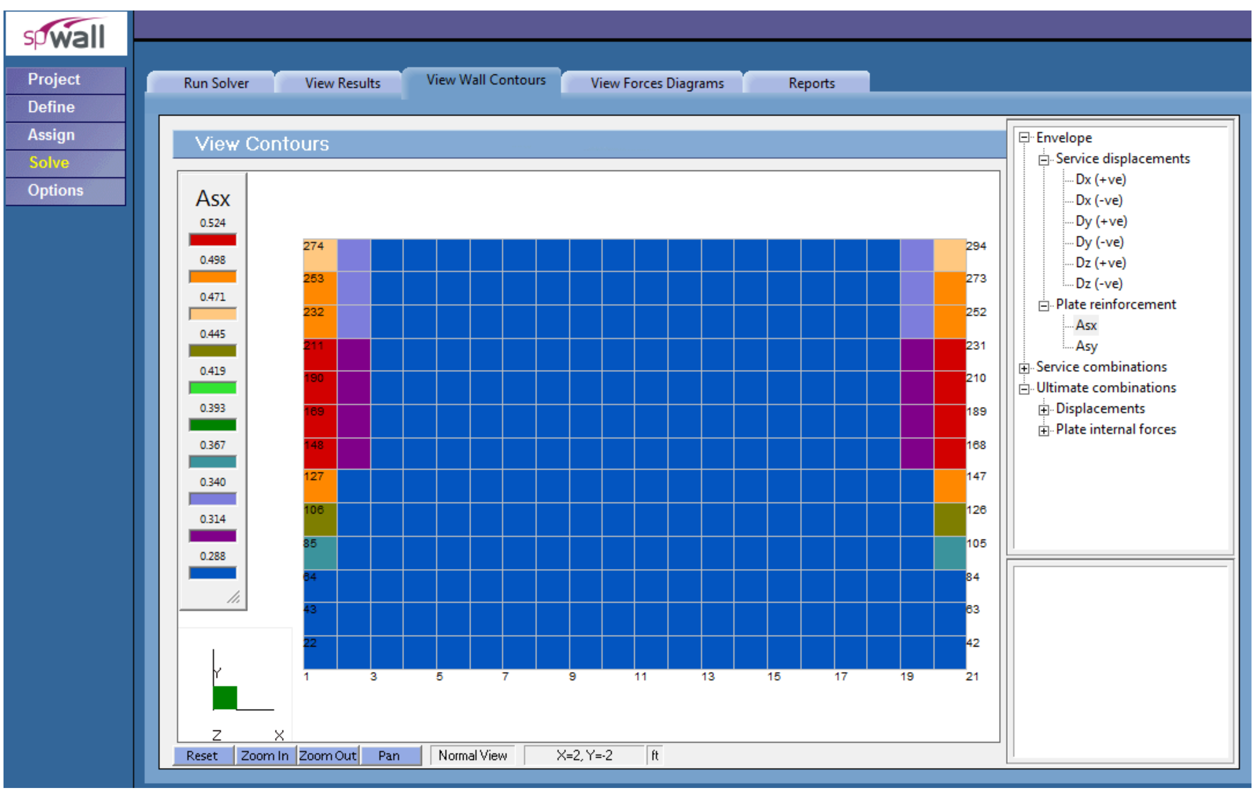


Figure 17 – Required Horizontal Reinforcement

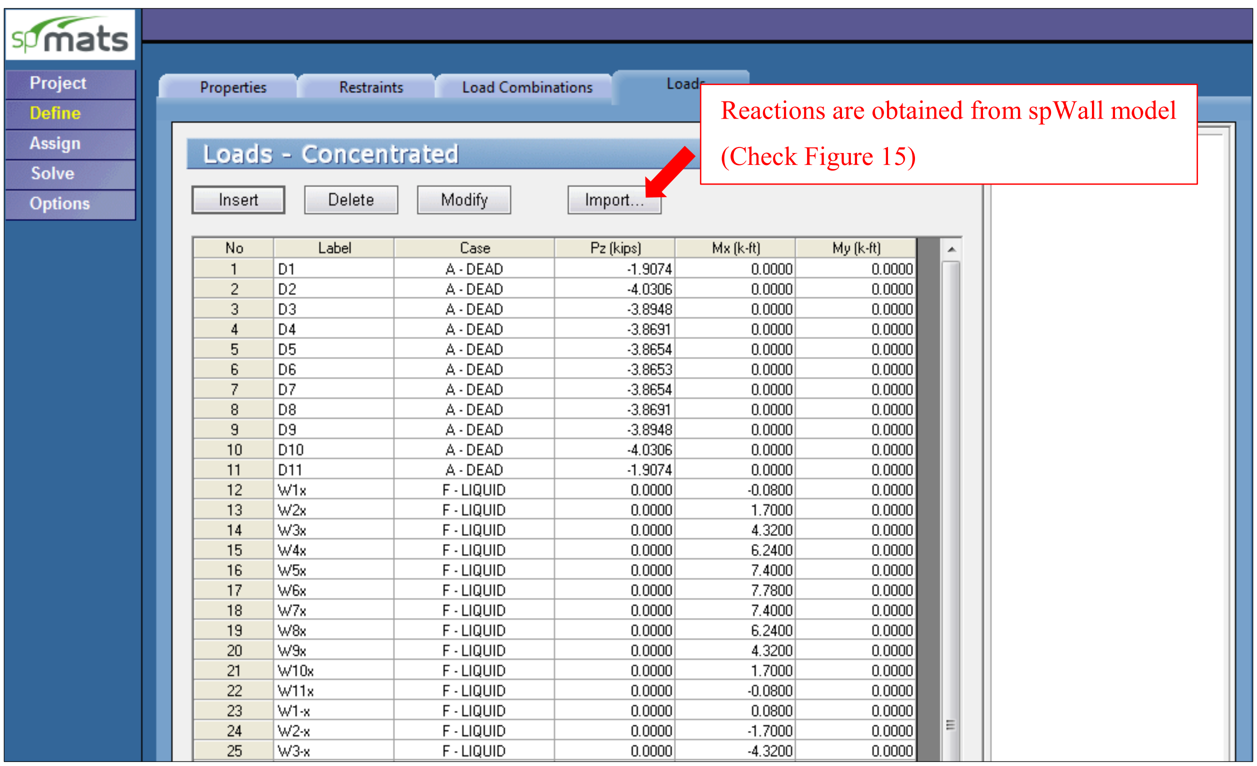
9. Tank Base Mat Analysis and Design – spMats Software

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 wastewater tank base mat in this case study.

10. Tank Base Mat Model Input



No	Label	Case	Pz (kips)	Mx (k-ft)	My (k-ft)
1	D1	A - DEAD	-1.9074	0.0000	0.0000
2	D2	A - DEAD	-4.0306	0.0000	0.0000
3	D3	A - DEAD	-3.8948	0.0000	0.0000
4	D4	A - DEAD	-3.8691	0.0000	0.0000
5	D5	A - DEAD	-3.8654	0.0000	0.0000
6	D6	A - DEAD	-3.8653	0.0000	0.0000
7	D7	A - DEAD	-3.8654	0.0000	0.0000
8	D8	A - DEAD	-3.8691	0.0000	0.0000
9	D9	A - DEAD	-3.8948	0.0000	0.0000
10	D10	A - DEAD	-4.0306	0.0000	0.0000
11	D11	A - DEAD	-1.9074	0.0000	0.0000
12	W1x	F - LIQUID	0.0000	-0.0800	0.0000
13	W2x	F - LIQUID	0.0000	1.7000	0.0000
14	W3x	F - LIQUID	0.0000	4.3200	0.0000
15	W4x	F - LIQUID	0.0000	6.2400	0.0000
16	W5x	F - LIQUID	0.0000	7.4000	0.0000
17	W6x	F - LIQUID	0.0000	7.7800	0.0000
18	W7x	F - LIQUID	0.0000	7.4000	0.0000
19	W8x	F - LIQUID	0.0000	6.2400	0.0000
20	W9x	F - LIQUID	0.0000	4.3200	0.0000
21	W10x	F - LIQUID	0.0000	1.7000	0.0000
22	W11x	F - LIQUID	0.0000	-0.0800	0.0000
23	W1-x	F - LIQUID	0.0000	0.0800	0.0000
24	W2-x	F - LIQUID	0.0000	-1.7000	0.0000
25	W3-x	F - LIQUID	0.0000	-4.3200	0.0000

Figure 18 – Importing Wall Reactions from spWall Model to the spMats Model

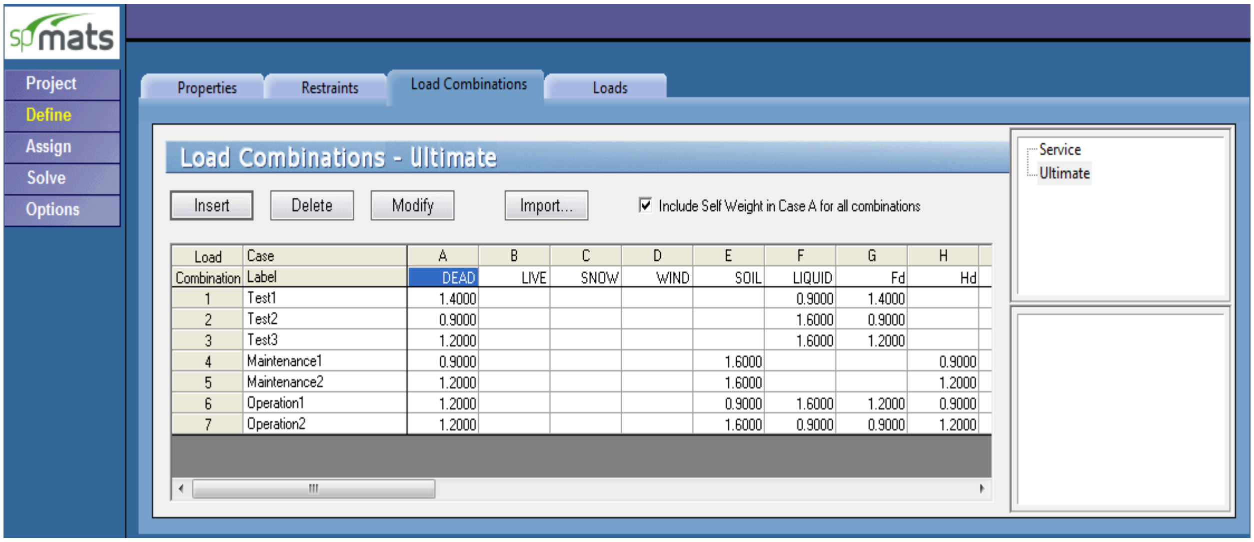


Figure 19 – Defining Load Combinations

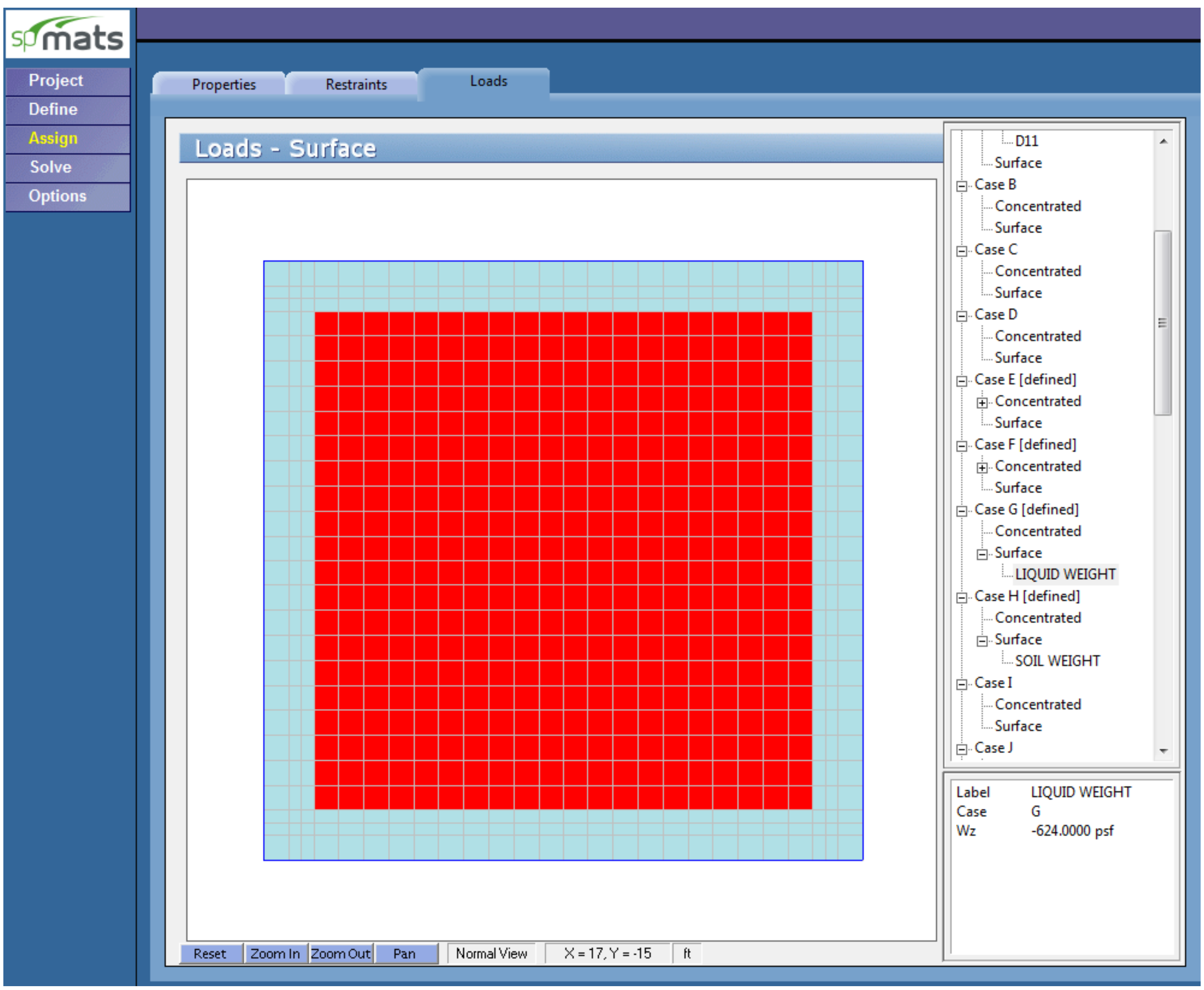


Figure 20 – Assigning Loads

11. Tank Base Mat Result Contours

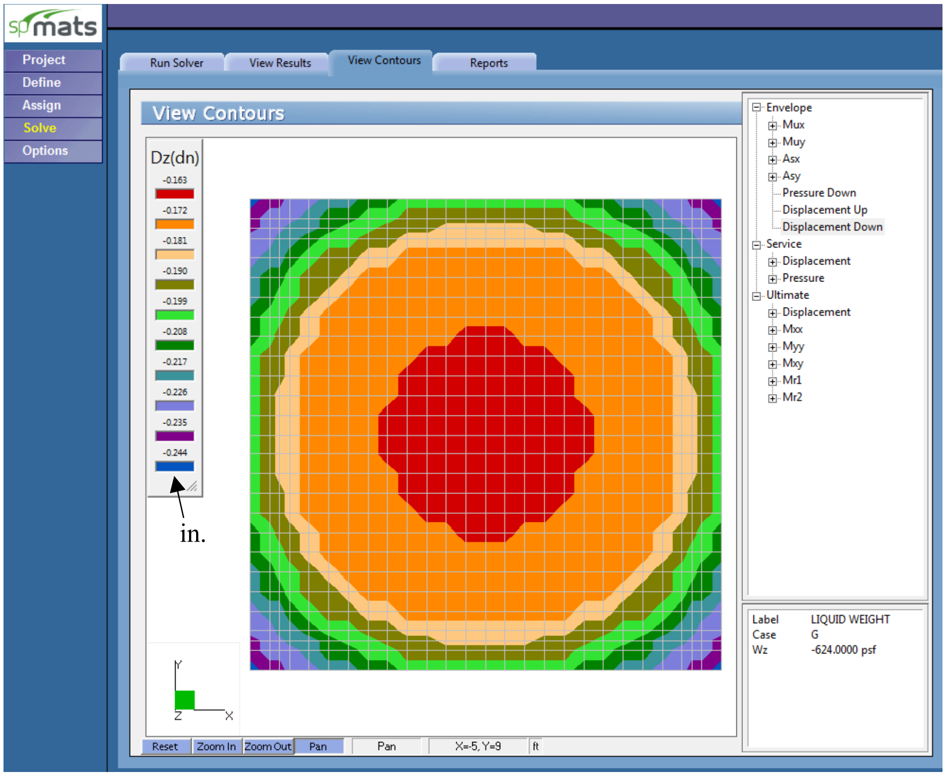


Figure 21 – Vertical (Down) Displacement Contour

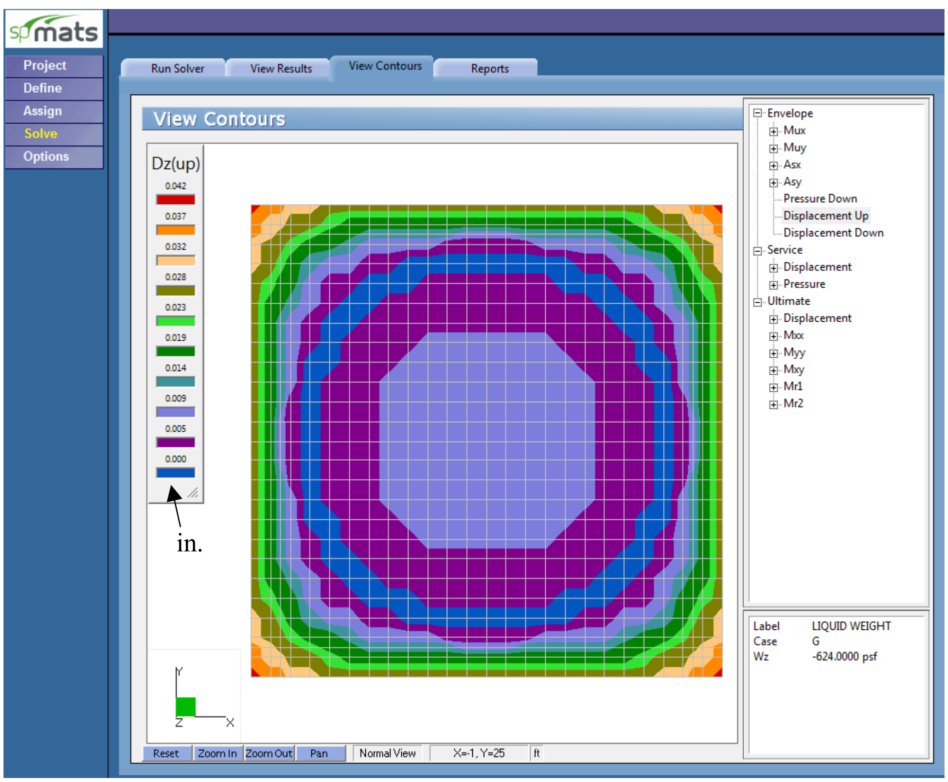


Figure 22 – Vertical (Up) Displacement Contour

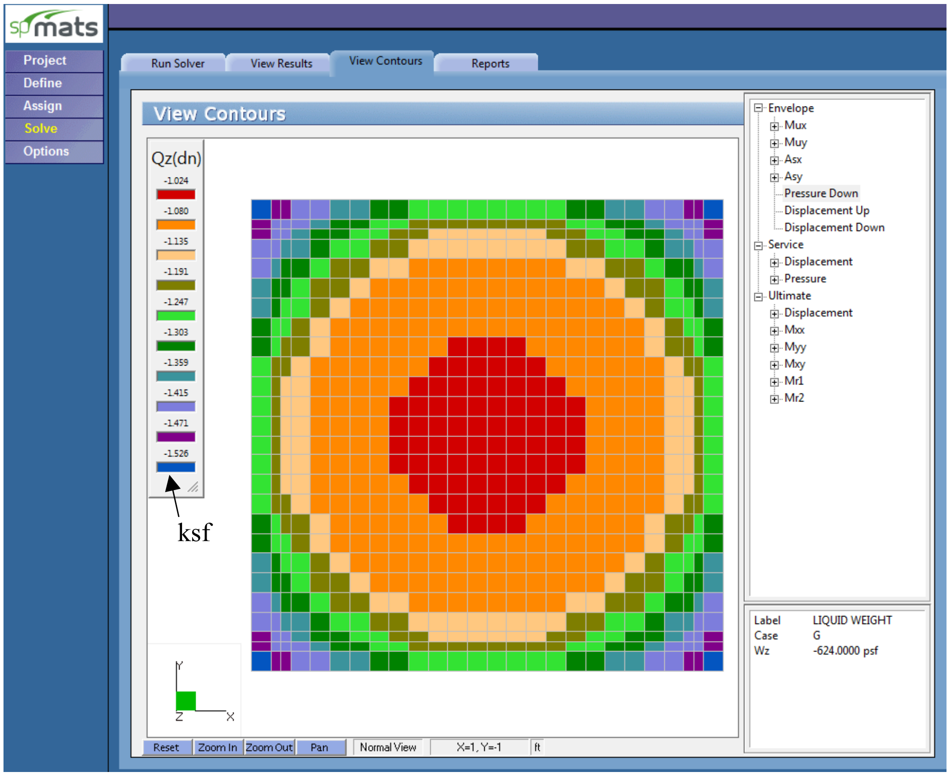


Figure 23 – Soil Pressure Envelope Contour

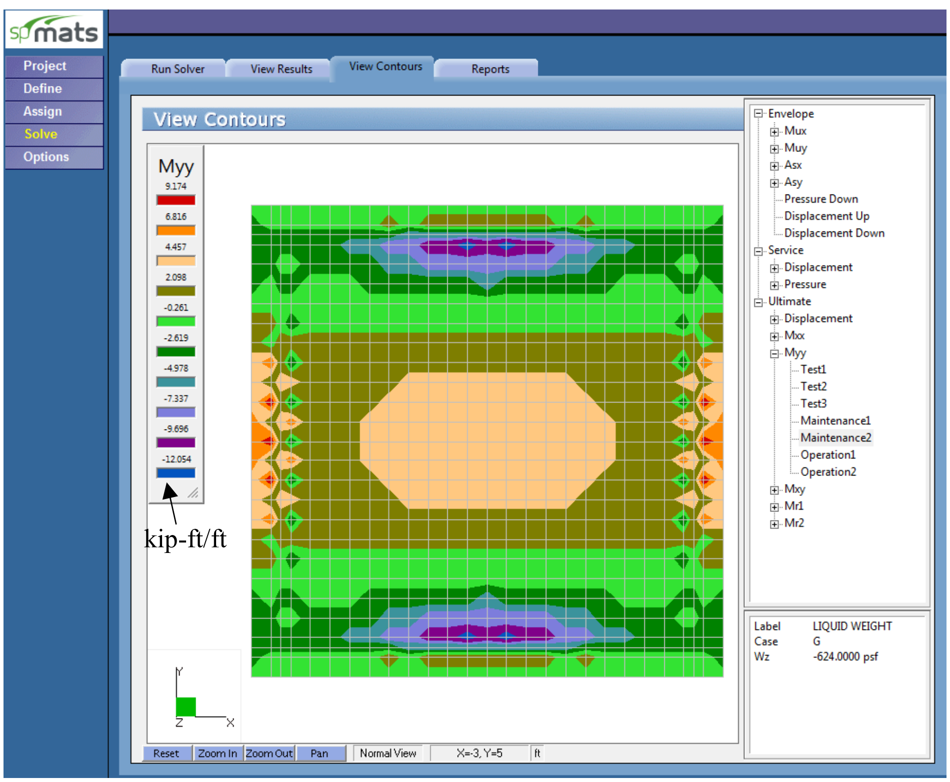


Figure 24 – Moment Contour along Y-Axis

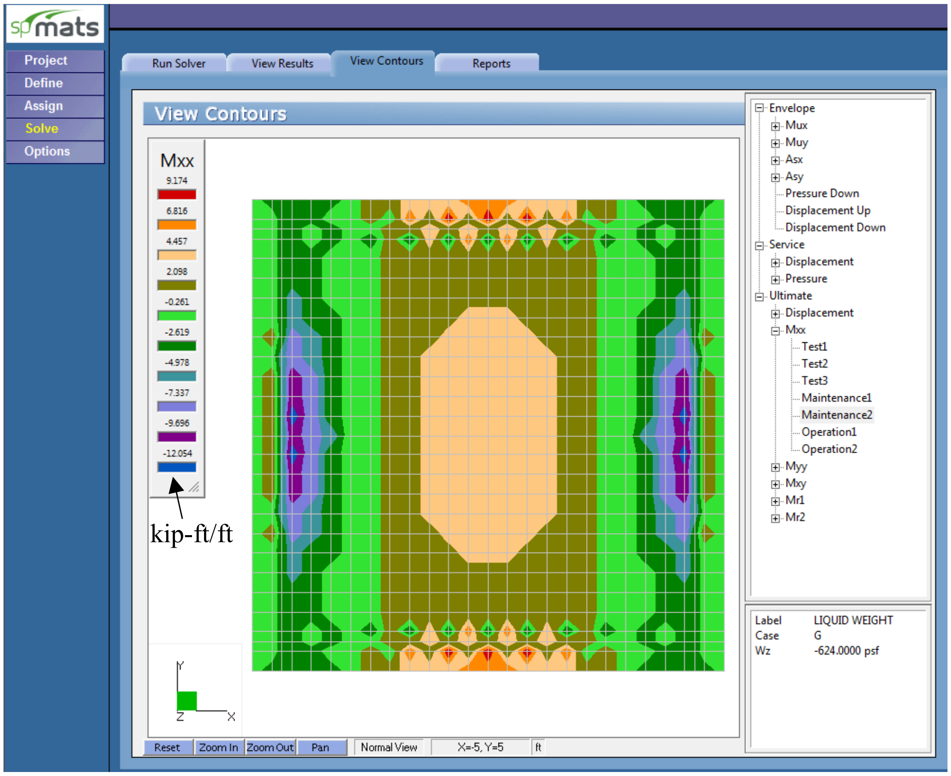


Figure 25 – Moment Contour along X-Axis

12. Tank Base Mat Required Reinforcement

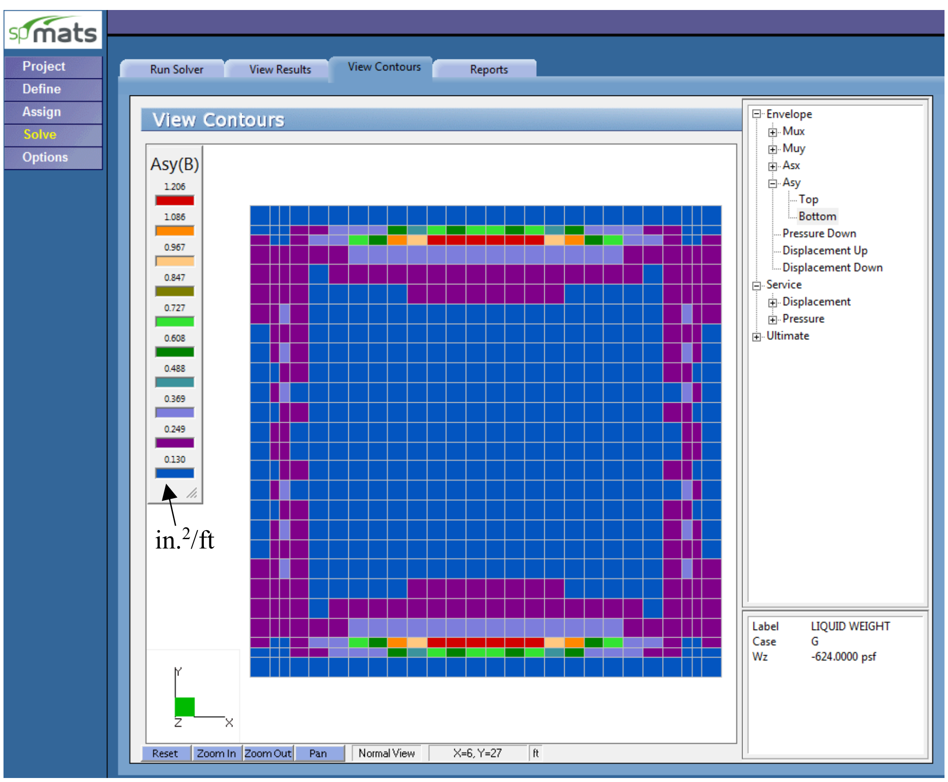


Figure 26 – Required Reinforcement Contour along Y Direction (Bottom)

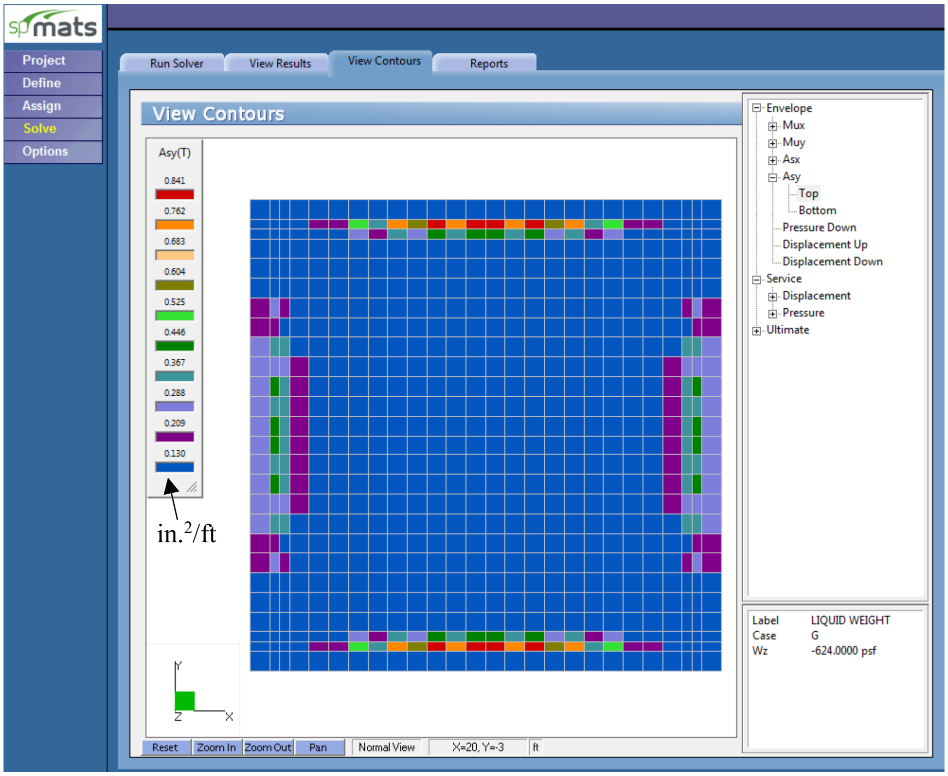


Figure 27 – Required Reinforcement Contour along Y Direction (Top)

13. Soil Reactions / Pressure

```
B3 - REACTIONS:
===============
Units --> Force (kip), Moment (kip-ft)
Service Load Combination: D+H+F
   Sum of all forces and moments with respect to center of gravity (X, Y) = (12.00, 12.00) ft

   Sum of Reactions        Fz           Mx           My
   ---------------- ------------ ------------ ------------
   Soil                 618.960        0.000       -0.000
   Springs                    -            -            -
   Piles                      -            -            -
   Restraints                 -            -            -
   Slaved Nodes               -            -            -
   ---------------- ------------ ------------ ------------
   Total Reactions      618.960        0.000       -0.000
   Total Loads         -618.960       -0.000       -0.000
```

Figure 28 – Soil Service Reactions

```
B4 - SOIL DISPLACEMENTS AND PRESSURES:
======================================
Units --> Displacement (in), Pressure (ksf)
Flags --> [x] Indicates allowable pressure is exceeded.
Service Load Combination: D+H+F
    Elem    Node   Disp, Dz   Pressure, Qz    Node   Disp, Dz   Pressure, Qz
   -----   -----  ----------  ------------   -----  ----------  ------------
       1      29     -0.1969        -1.231       2     -0.1997        -1.248
              28     -0.1997        -1.248       1     -0.2026        -1.266
       2      30     -0.1955        -1.222       3     -0.1982        -1.239
              29     -0.1969        -1.231       2     -0.1997        -1.248
       3      31     -0.1941        -1.213       4     -0.1967        -1.229
              30     -0.1955        -1.222       3     -0.1982        -1.239
       4      32     -0.1910        -1.194       5     -0.1935        -1.209
              31     -0.1941        -1.213       4     -0.1967        -1.229
       5      33     -0.1879        -1.175       6     -0.1901        -1.188
              32     -0.1910        -1.194       5     -0.1935        -1.209
       6      34     -0.1848        -1.155       7     -0.1866        -1.166
              33     -0.1879        -1.175       6     -0.1901        -1.188
       7      35     -0.1816        -1.135       8     -0.1832        -1.145
              34     -0.1848        -1.155       7     -0.1866        -1.166
       8      36     -0.1788        -1.117       9     -0.1800        -1.125
              35     -0.1816        -1.135       8     -0.1832        -1.145
       9      37     -0.1762        -1.101      10     -0.1771        -1.107
              36     -0.1788        -1.117       9     -0.1800        -1.125
      10      38     -0.1741        -1.088      11     -0.1748        -1.092
              37     -0.1762        -1.101      10     -0.1771        -1.107
```

Figure 29 – Soil Pressure

14. Tank Base Mat 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.

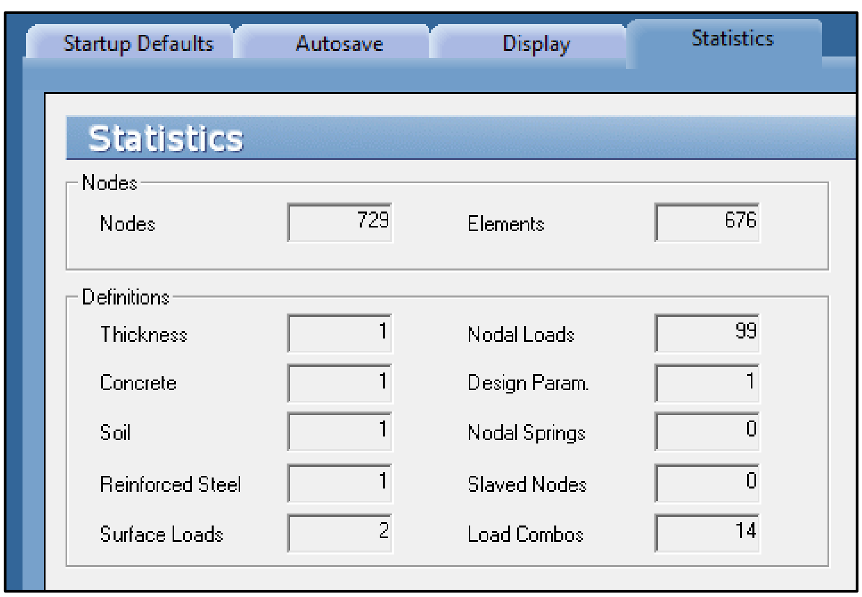


Figure 30 – Model Statistics

15. Tank Analysis Design Observation & Conclusions

The evaluation of the load combination requires a thorough evaluation of the construction, backfill, test, commissioning, maintenance, and repair stages required throughout the entire tank service life. The list used in the this case study is just a partial set chosen for illustration

Designer is advised to take the care required in exporting the wall reactions carefully to the base mat 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 tank. Additional loading considerations would be have to be added to adequately address this condition.