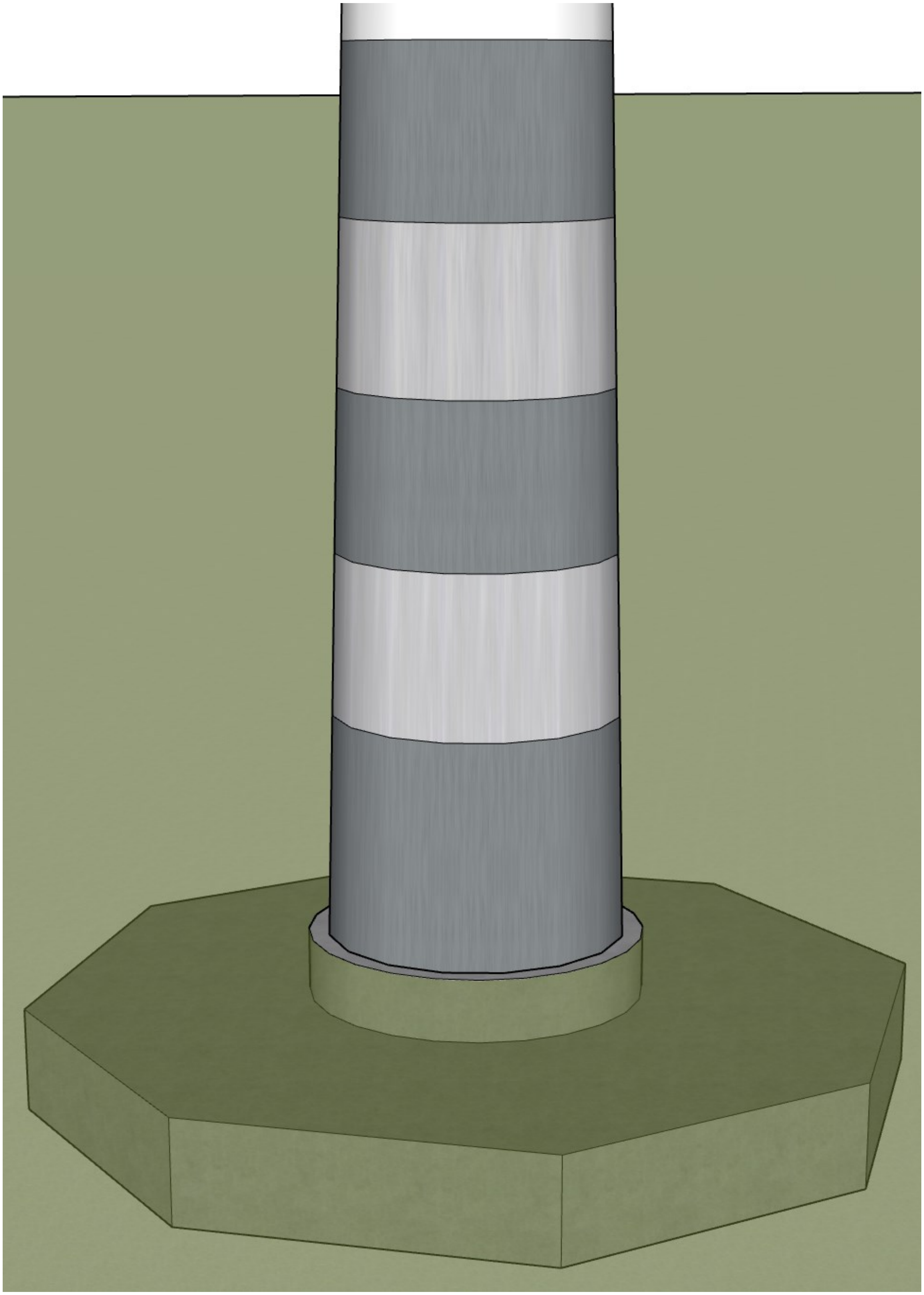
Short Wind Turbine Tower Reinforced Concrete Foundation Analysis and Design



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A wind turbine, or alternatively referred to as a wind energy converter, is a device that converts the wind's kinetic energy into electrical energy.

Wind turbines are manufactured in a wide range of vertical and horizontal axis. The smallest turbines are used for applications such as battery charging for auxiliary power for boats or caravans or to power traffic warning signs. Larger turbines can be used for making contributions to a domestic power supply while selling unused power back to the utility supplier via the electrical grid.

Arrays of large turbines, known as wind farms, are becoming an increasingly important source of intermittent renewable energy and are used by many countries as part of a strategy to reduce their reliance on fossil fuels. One assessment claimed that, as of 2009, wind had the "lowest relative greenhouse gas emissions, the least water consumption demands and the most favourable social impacts" compared to photovoltaic, hydro, geothermal, coal and gas.

Wind turbines with generating capacity from as little as 0.1 MW to as high as 4.0 MW are offered by vendors like Siemens, GE, Mitsubishi, EWT, Vestas, etc.

This case study focuses on the design of a typical wind turbine tower foundation using the engineering software program spMats. The tower under study is a 500kW turbine with a hub height of 150 ft, a 90 ft. blade length, and tapered tubular steel tower anchored at the base to the concrete mat foundation. All the information provided by the wind turbine provider are shown in the following figure and design data and will serve as input for the foundation analysis and design. Given the soil conditions at the site and the equipment availabilty from the contractor, a soil supported foundation was selected to resist the signifiant overturning moments generated at the tower base.

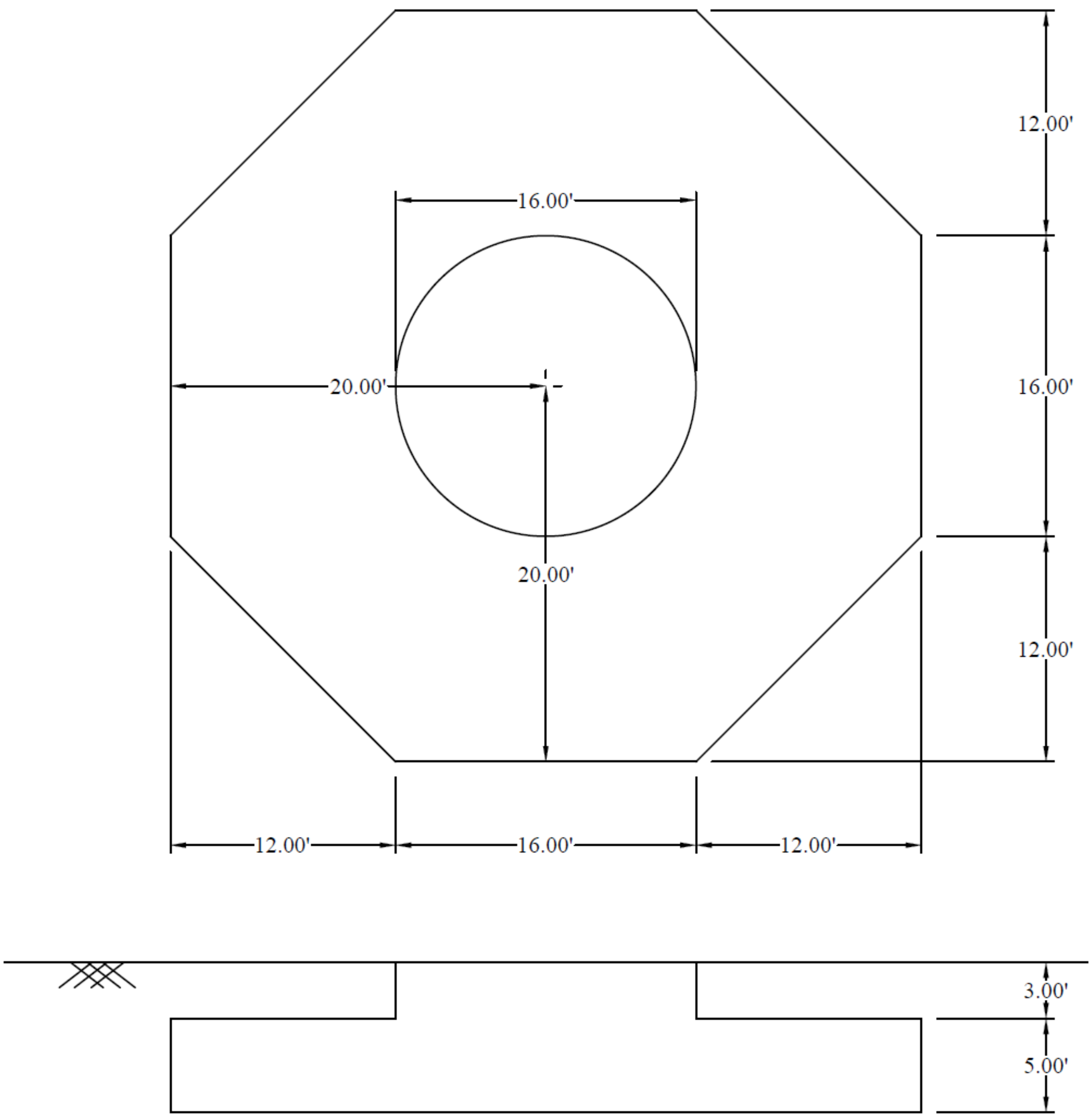


Figure 1 –Wind Turbine Tower Concrete Foundation Layout

Code

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

Reference

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

Design Data

Concrete Pier

Diameter = 16 ft

Height = 3 ft

Weight = 15.88 kips

Concrete Foundation

f_c' = 3,000 psi

f_y = 60,000 psi

Thickness = 18 in.

Clear Cover = 3 in.

Superimposed Soil Weight = 337.5 psf over the foundation cross-section

Foundation Loads

P_{DL} = 3.0 kips

P_{LL} = 1.0 kips-ft

$M_{x,wind}$ = 150 kips-ft

$M_{y,wind}$ = Not provided

Supporting Soil

Type = Rocky soil

Subgrade Modulus = 100 kcf

Allowable Pressure = 5.0 ksf

Contents

1. 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 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 and purposes, the following figures provide a sample of the input modules and results obtained from an spMats model created for the short wind turbine tower reinforced concrete foundation in this example.

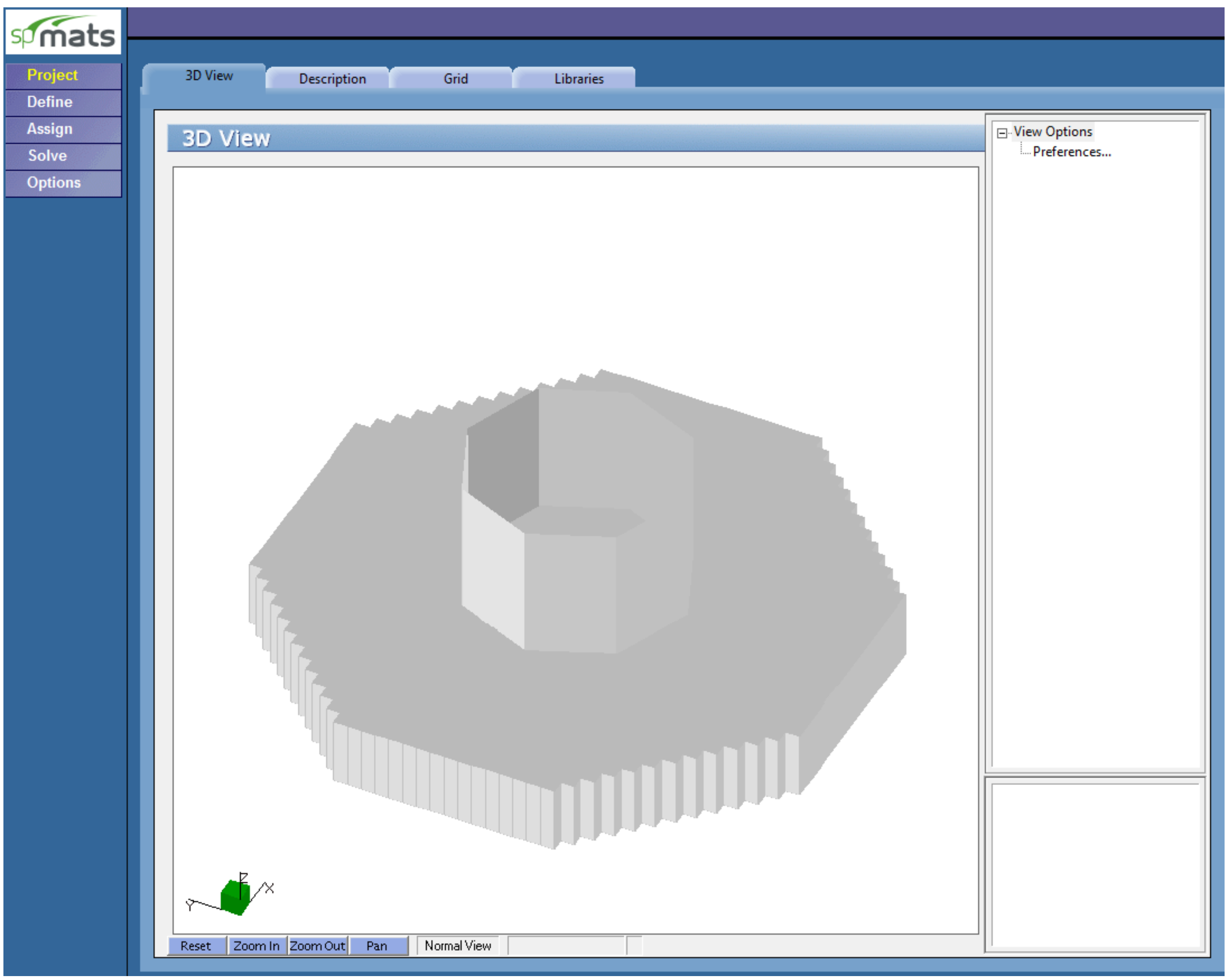


Figure 2 – Wind Turbine Tower Foundation Model 3D View

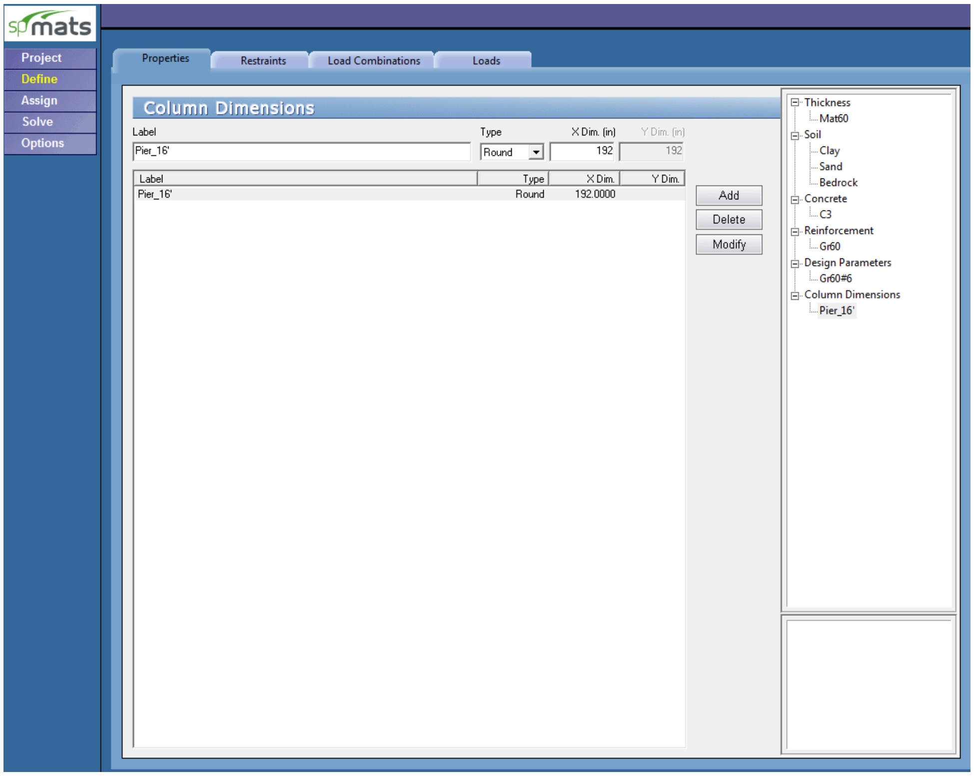


Figure 3 –Defining Column

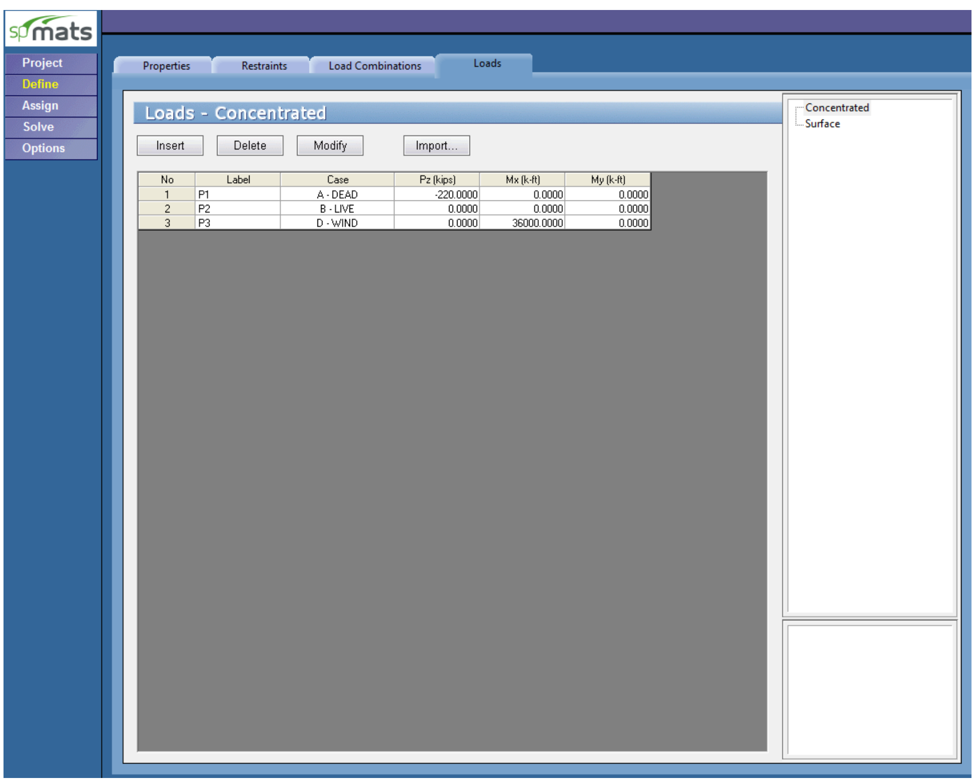


Figure 4 –Defining Load Cases

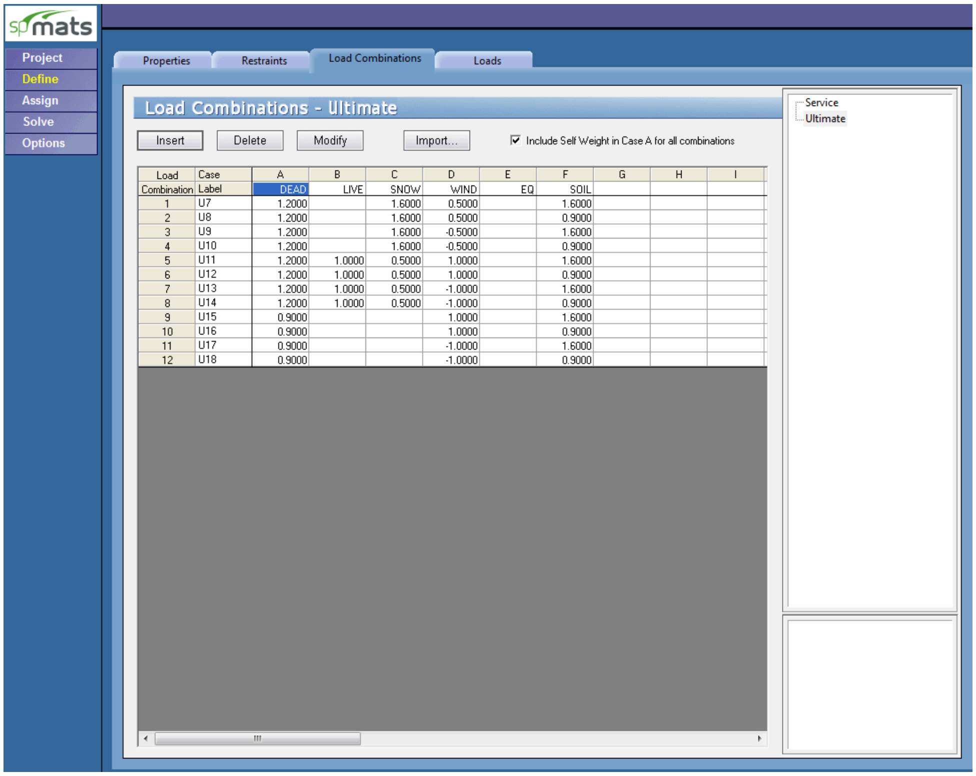


Figure 5 –Defining Load Combinations

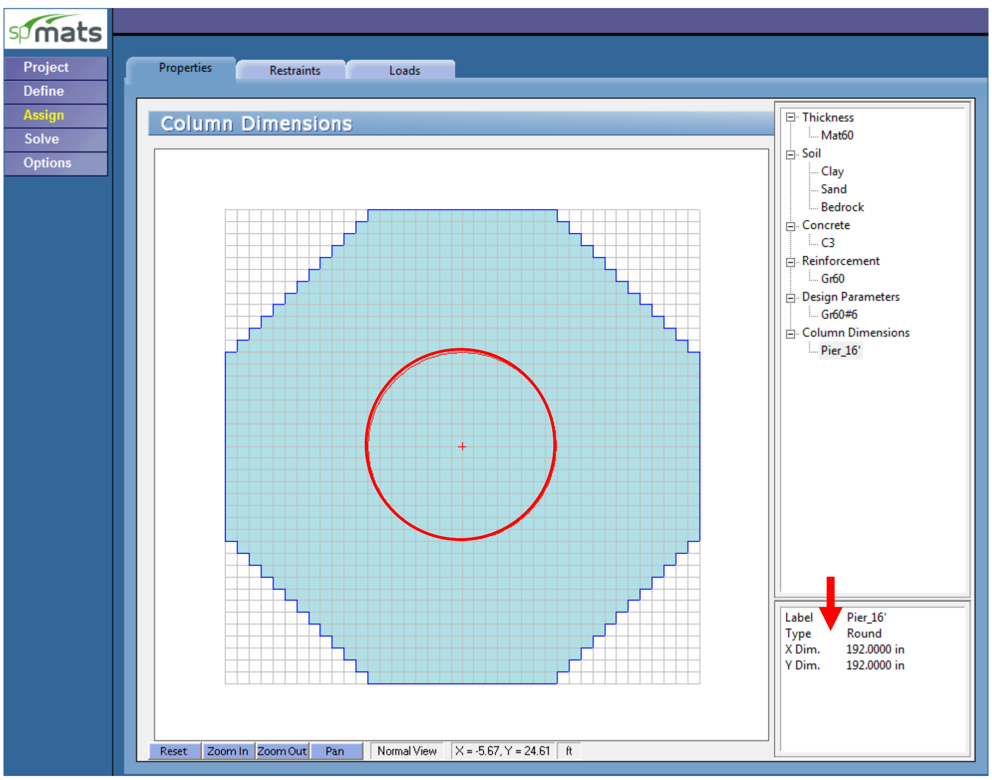


Figure 6 – Assigning Column For Base Pier

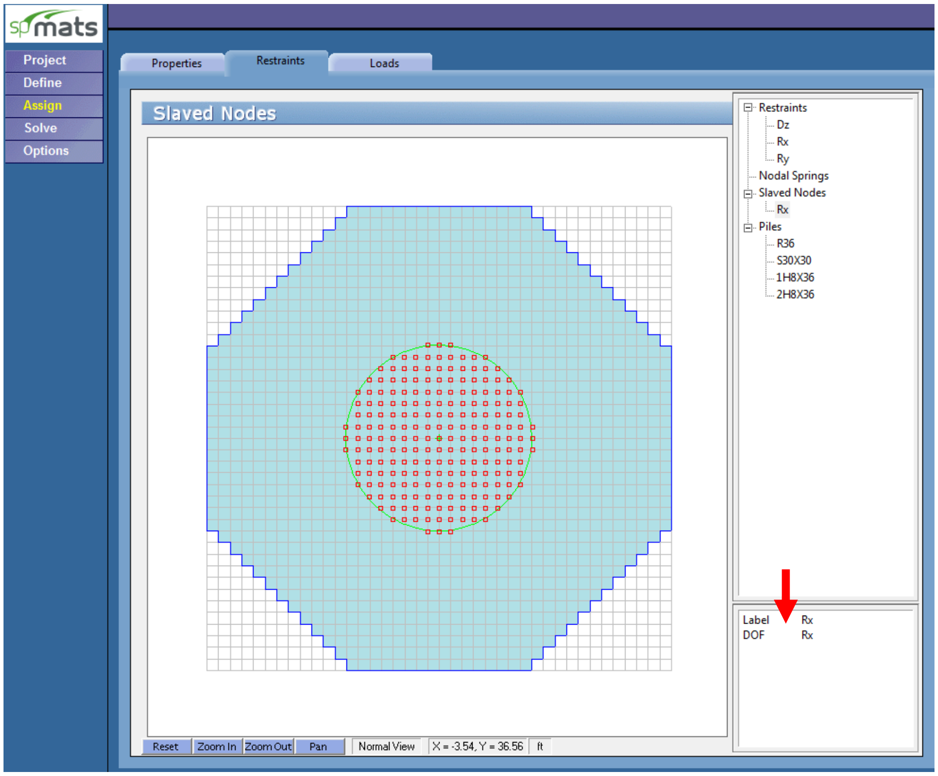


Figure 7 – Assigning Slaved Nodes Modeling Base Pier

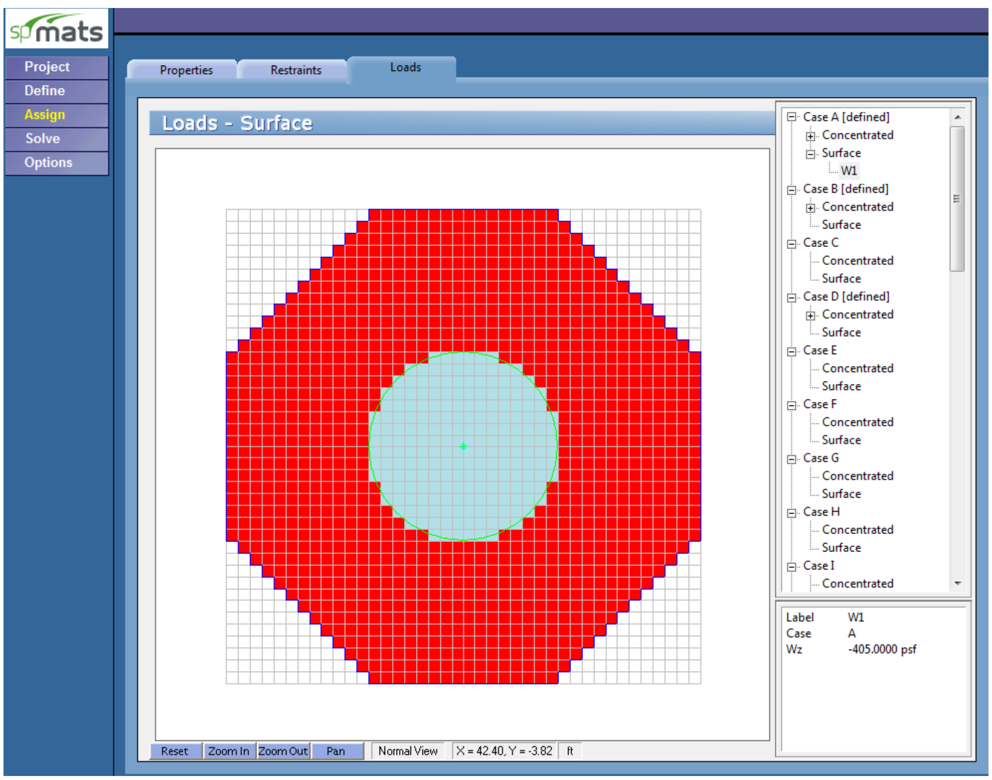


Figure 8 – Assigning Soil Surcharge Loads

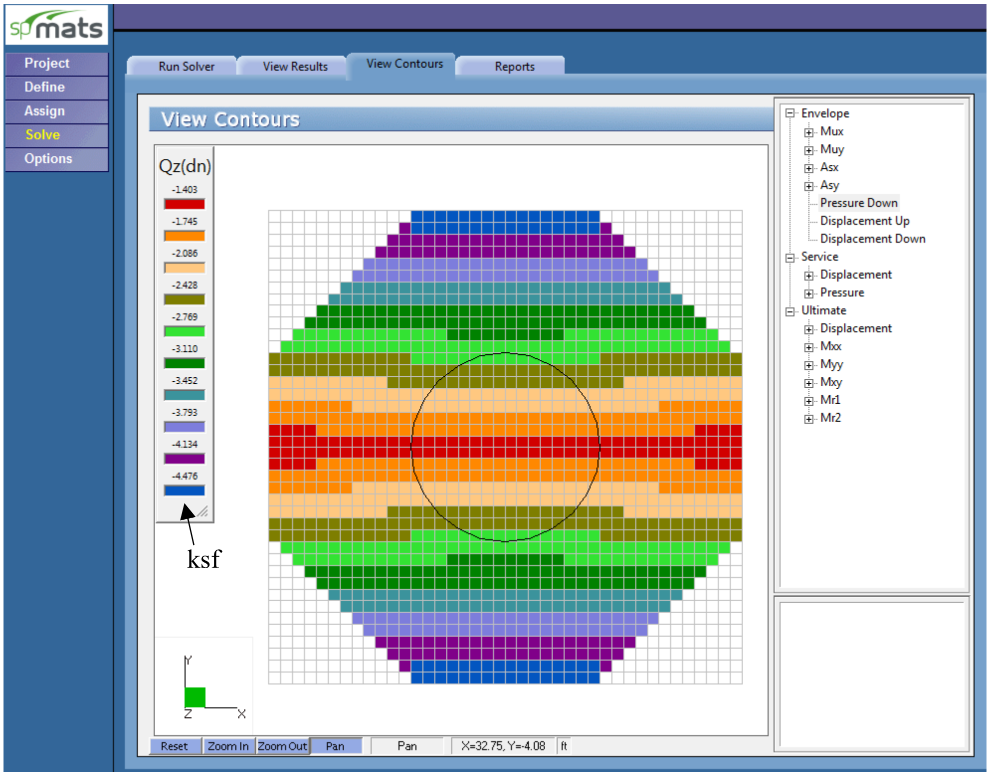


Figure 9 – Soil Pressure Contour

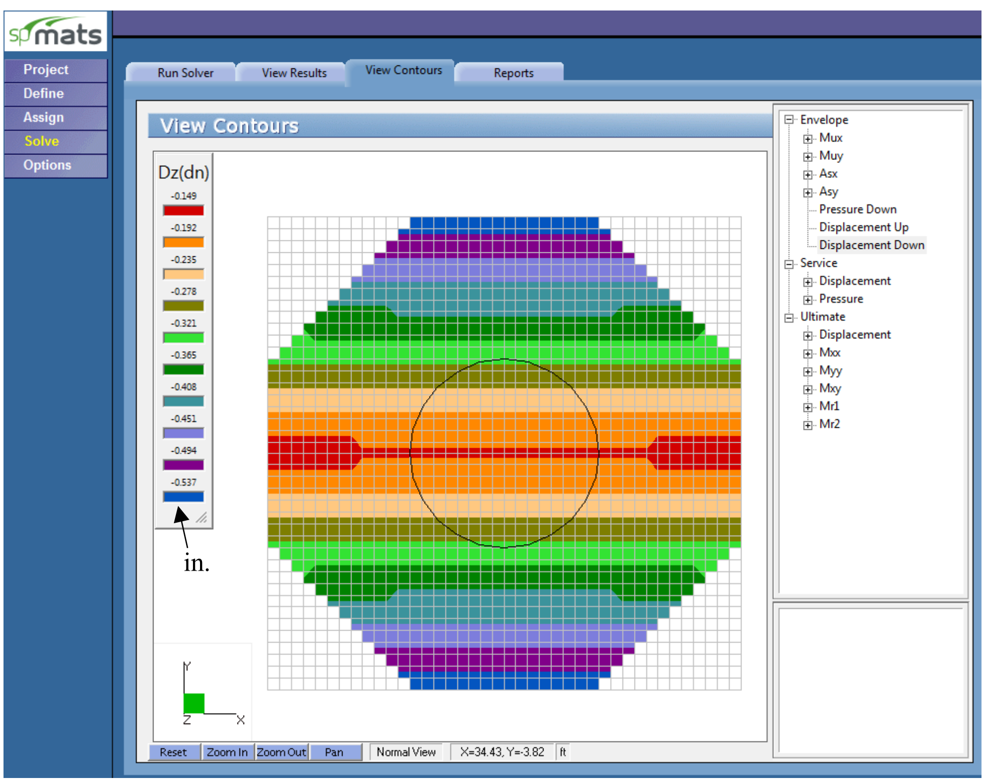


Figure 10 – Vertical Downward Displacement Contour

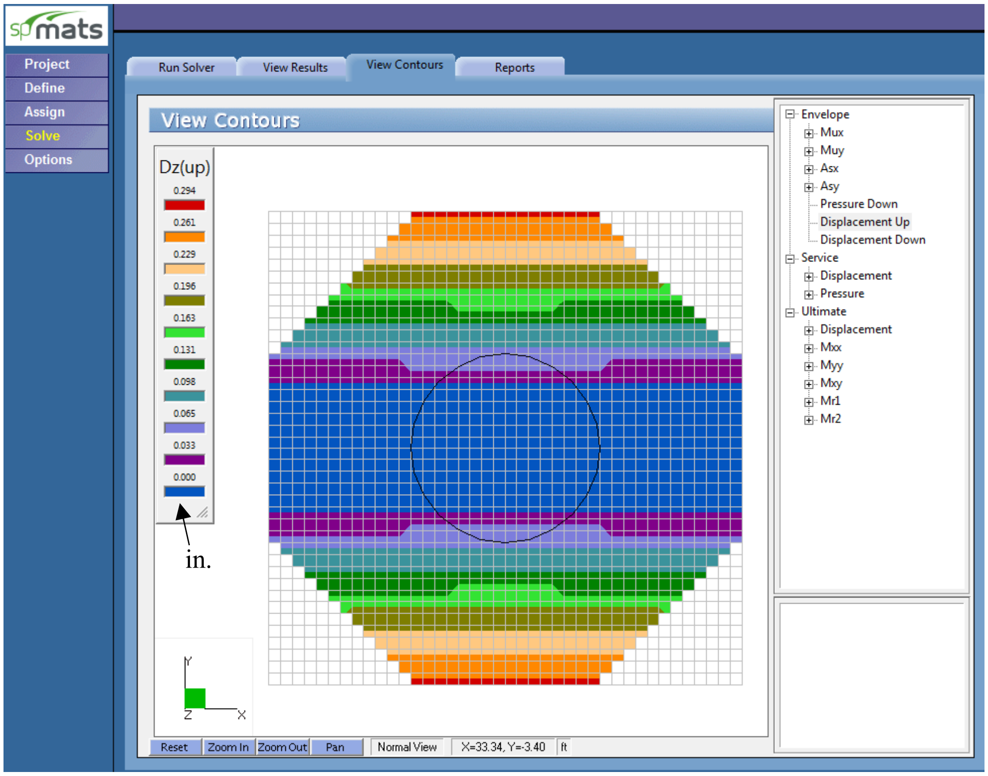


Figure 11 – Vertical Upward Displacement Contour

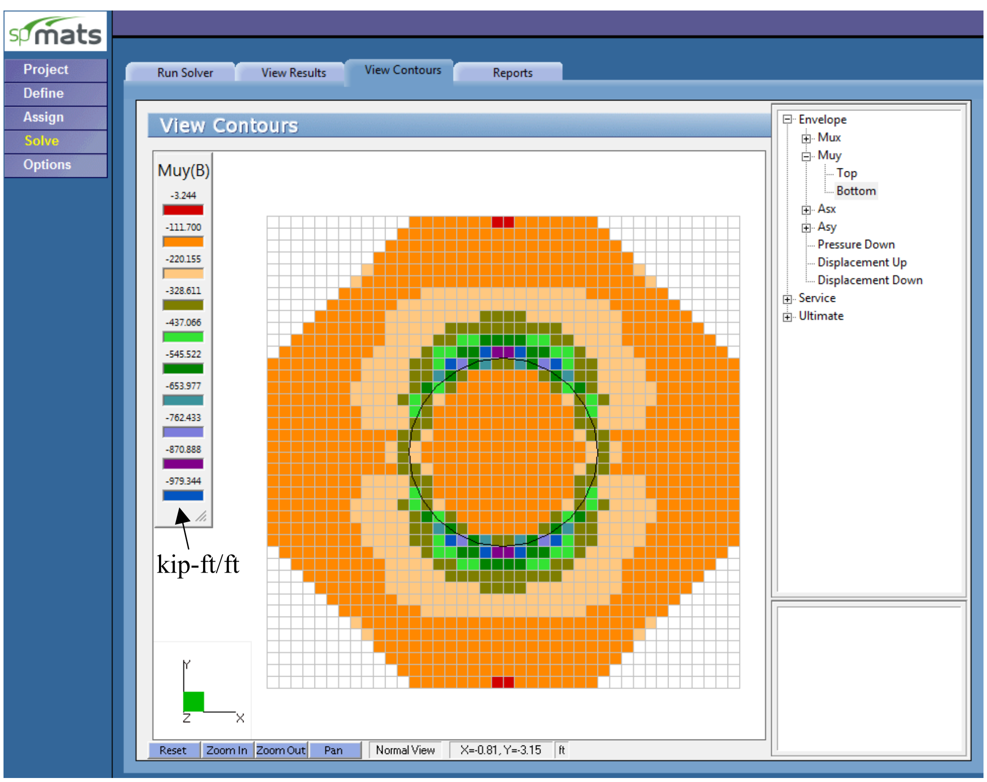


Figure 12 – Moment Contour along Y-Axis

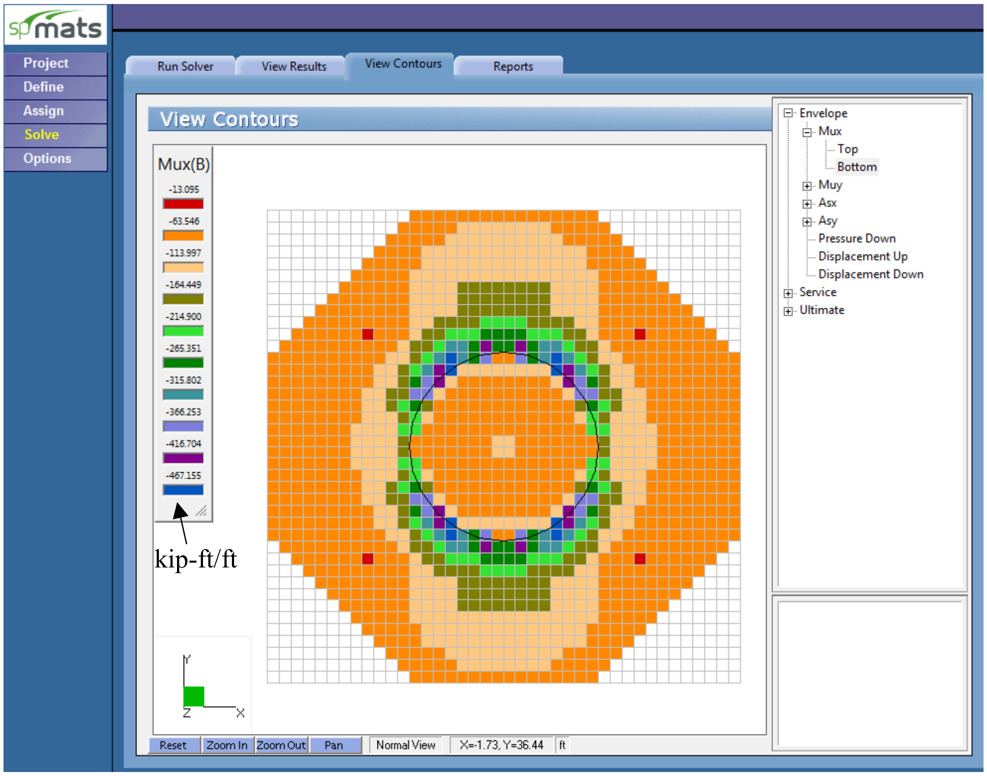


Figure 13 – Moment Contour along X-Axis

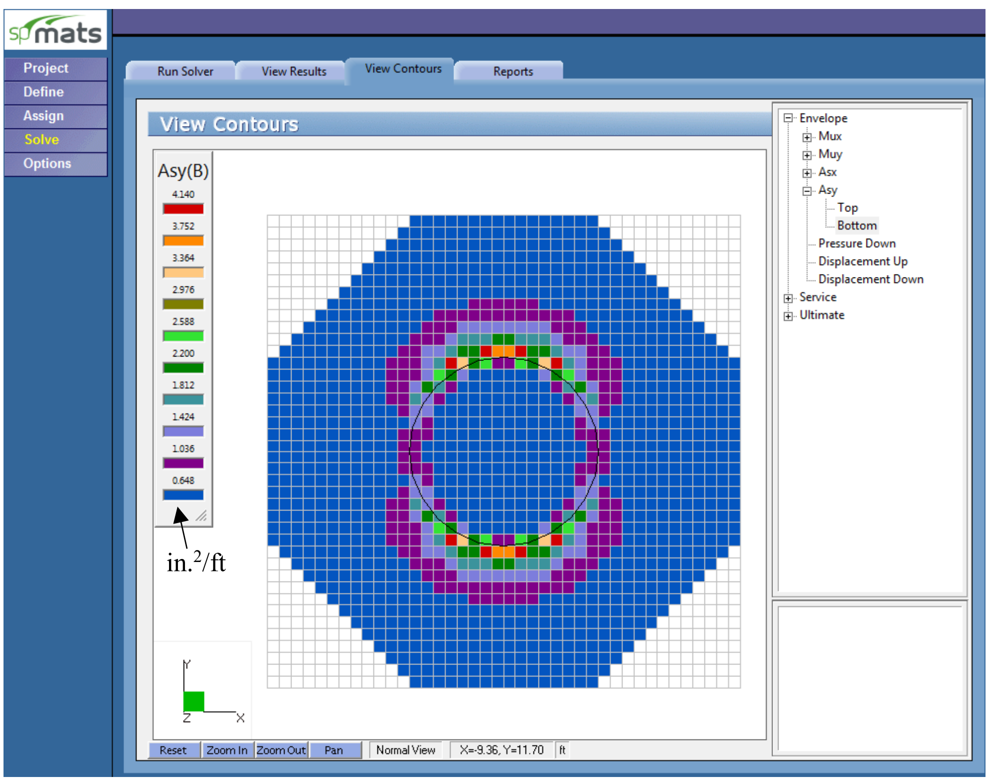


Figure 14 – Required Reinforcement Contour along Y Direction

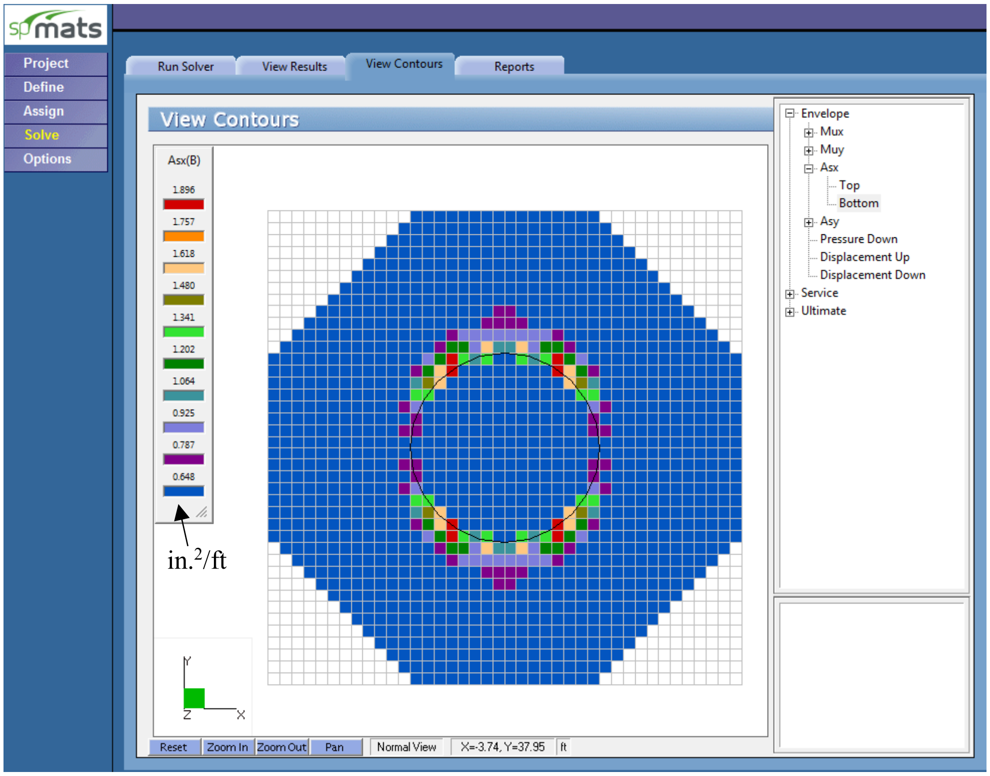


Figure 15 – Required Reinforcement Contour along X Direction

2. Two-way Punching Shear Check

```
B6 - Punching Shear Around Columns (Ultimate Load Combinations):
=================================================================
Units --> Applied Shear Force Vu (kips), Applied Moments Mux, Muy (k-ft)
          Factored Shear Stress vu (psi), Factored Shear Resistance Phi*vc (psi)
          Concrete Strength f'c (psi), distances X_Offset, Y_Offset (ft)
          Average depth (in), Dimensions Bx, By (ft)
          Area (in^2), Jxx, Jyy, Jxy (in^4)

Geometry of Resisting Area
--------------------------
      _________Column__________ Average  ___Dimensions____ _____Centroid____
 Node       Label      Location  Depth      Bx       By    X_Offset Y_Offset
----- -------------- --------- -------- -------- -------- -------- --------
  685 Pier_16'        Inner       56.63    20.72    20.72    -0.00    -0.00

Properties of Resisting Area
----------------------------
 Node  Column Label      Area         Jxx          Jyy          Jxy
----- -------------- ---------- ------------ ------------ ------------
  685 Pier_16'         44183.12  345895840.00 345895808.00         0.00

Ultimate Load Combination: U7
-----------------------------

  Factored Applied Forces:
  ------------------------
   Node  Column Label      Vu           Mux       Gamma_X      Muy        Gamma_Y
  ----- -------------- ---------- --------------- ------- --------------- -------
    685 Pier_16'          -264.00          7200.0   0.400            -0.0   0.400

  Factored Stress and Capacity:
  -----------------------------
                                                         _Critical Point__
   Node  Column Label      vu           f'c      Phi*vc   X_Offset Y_Offset Status
  ----- -------------- ----------- ---------- ----------- -------- -------- ------
    685 Pier_16'           -37.03    3000.00      164.32    -0.00   -10.36    Safe


B7 - Punching Shear Around Piles (Ultimate Load Combinations):
===============================================================
    * No piles assigned
```

Figure 16 – Two-Way Shear Results around the Column

3. Soil Reactions (Pressure)

```
B3 - REACTIONS:
===============
Units --> Force (kip), Moment (kip-ft)
Service Load Combination: S9
   Sum of all forces and moments with respect to center of gravity (X, Y) = (20.00, 20.00) ft

   Sum of Reactions       Fz           Mx           My
   ---------------- ------------ ------------ ------------
   Soil                 1623.400   -21600.000       -0.000
   Springs                     -            -            -
   Piles                       -            -            -
   Restraints                  -            -            -
   Slaved Nodes            0.000        0.000        0.000
   ---------------- ------------ ------------ ------------
   Total Reactions      1623.400   -21600.000       -0.000
   Total Loads         -1623.400    21600.000       -0.000
```

Figure 17 – Soil Service Reactions

```
B3 - REACTIONS:
===============
Units --> Force (kip), Moment (kip-ft)
Ultimate Load Combination: U7
   Sum of all forces and moments with respect to center of gravity (X, Y) = (20.00, 20.00) ft

   Sum of Reactions       Fz           Mx           My
   ---------------- ------------ ------------ ------------
   Soil                 1948.080   -18000.000       -0.000
   Springs                     -            -            -
   Piles                       -            -            -
   Restraints                  -            -            -
   Slaved Nodes            0.000        0.000        0.000
   ---------------- ------------ ------------ ------------
   Total Reactions      1948.080   -18000.000       -0.000
   Total Loads         -1948.080    18000.000       -0.000
```

Figure 18 – Soil Ultimate Reactions

Note: Positive and negative reaction values indicate compression and tension forces on soil, respectively.

4. 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.

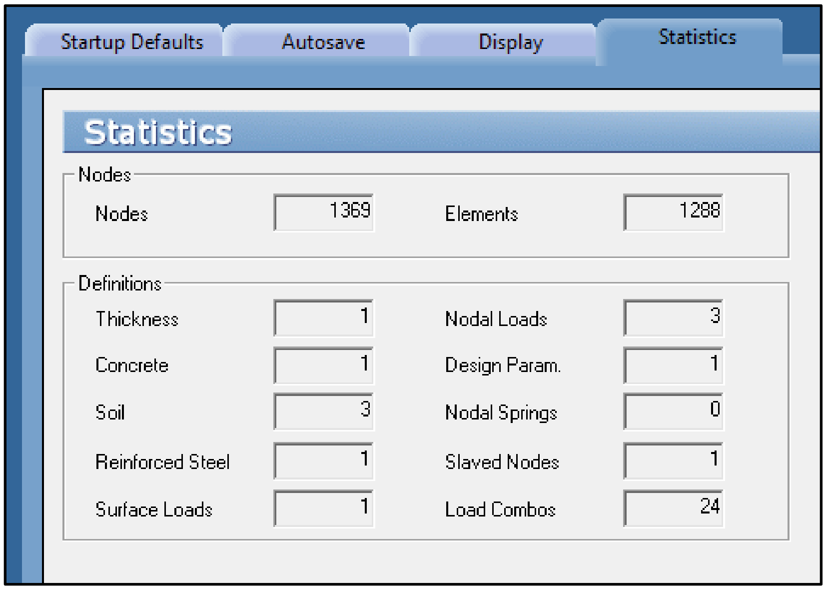


Figure 19 – Model Statistics

5. Concrete Pier and Pile Design - spColumn

spMats provides the options to export column and pile information from the foundation model to spColumn. Input (CTI) files are generated by spMats to include the section, materials, and the loads from the foundation model required by spColumn for strength design and investigation of piles and columns. Once the foundation model is completed and successfully executed, the following steps illustrate the design of a sample pile and column. This can be used as a supplementary check to confirm the adequacy of the turbine pier.

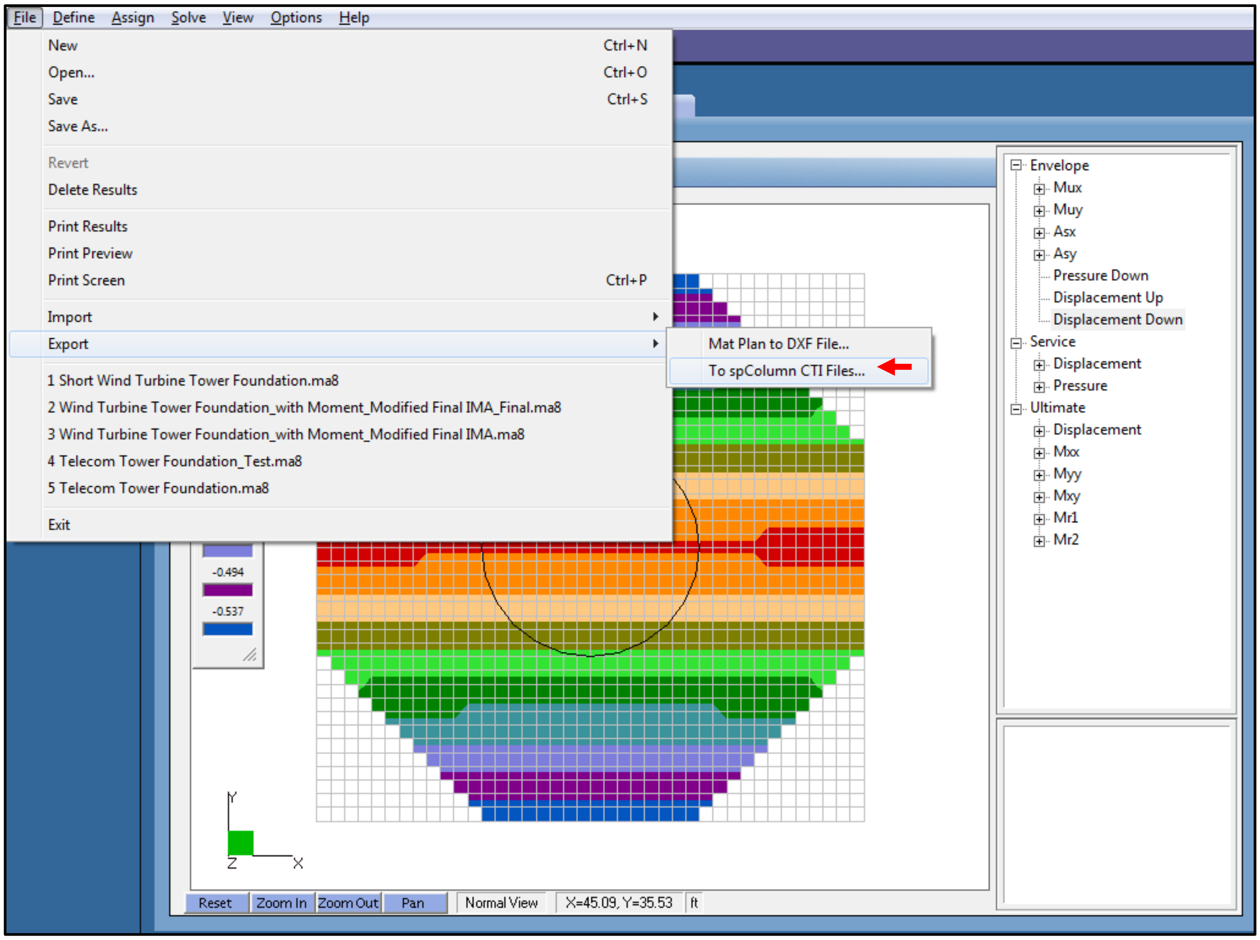


Figure 20 – Exporting Column Design CTI Files

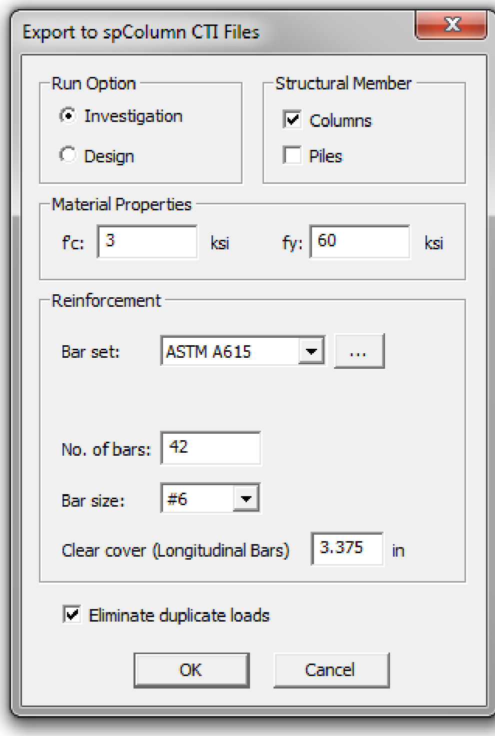
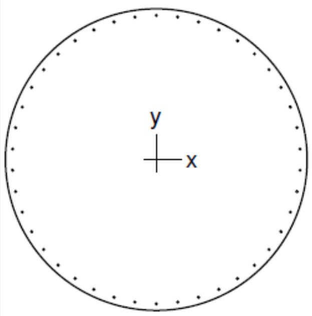


Figure 21 – Exporting Column Design CTI Files Dialog Box

After exporting spColumn input files, the pile and column design/investigation can proceed/modified to meet project specifications and criteria. In the following the wind turbine tower base pier design results are shown as an example.



192 in diam.

Code: ACI 318-14

Units: English

Run axis: Biaxial

Run option: Investigation

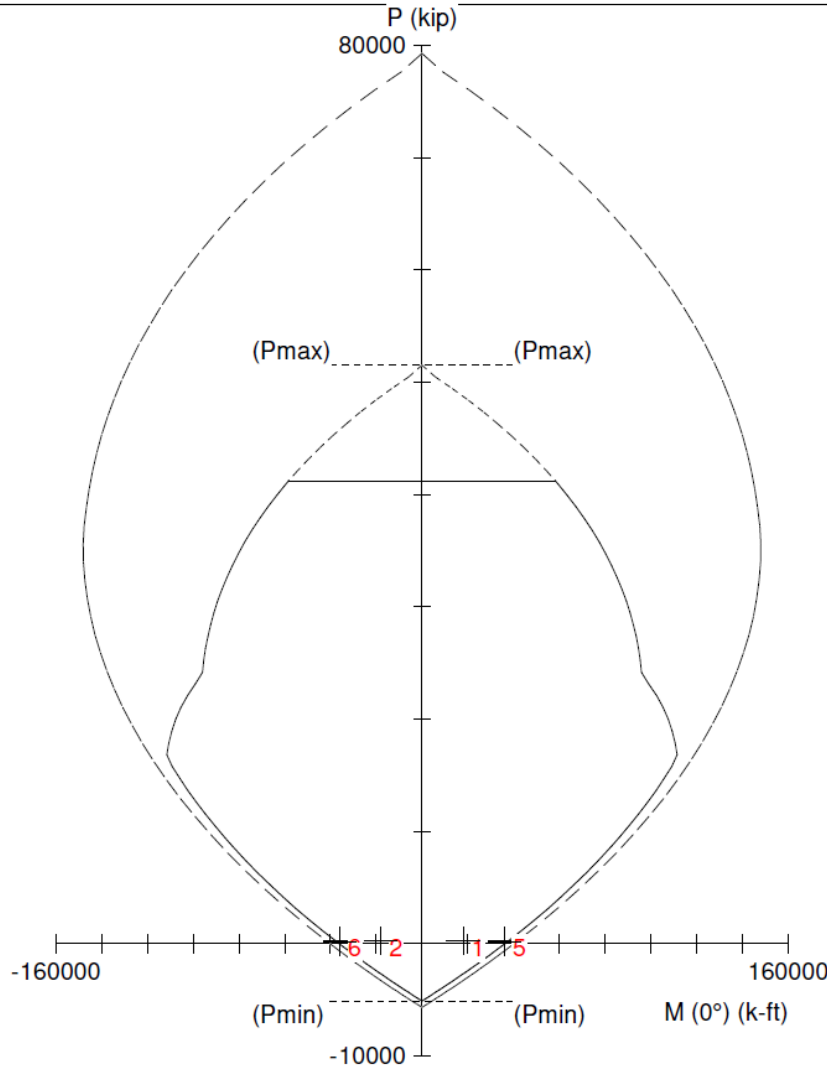
Slenderness: Not considered

Column type: Structural

Bars: ASTM A615

Date: 02/28/19

Time: 11:55:46



STRUCTUREPOINT - spColumn v6.50 (TM). Licensed to: StructurePoint. License ID:

File:

Project: Short Wind Turbine Tower Found

Column: C-685		Engineer: -	
f'c = 3 ksi	fy = 60 ksi	Ag = 28952.9 in^2	42 #14 bars
Ec = 3122 ksi	Es = 29000 ksi	As = 94.50 in^2	rho = 0.33%
fc = 2.55 ksi	e_yt = 0.00206897 in/in	Xo = 0.00 in	Ix = 6.67075e+007 in^4
e_u = 0.003 in/in		Yo = 0.00 in	Iy = 6.67075e+007 in^4
Beta1 = 0.85		Min clear spacing = 12.02 in	Clear cover = 3.38 in

Confinement: Tied

phi(a) = 0.8, phi(b) = 0.9, phi(c) = 0.65

Figure 22 – Wind Turbine Base Pier Design Capacity with Factored Load

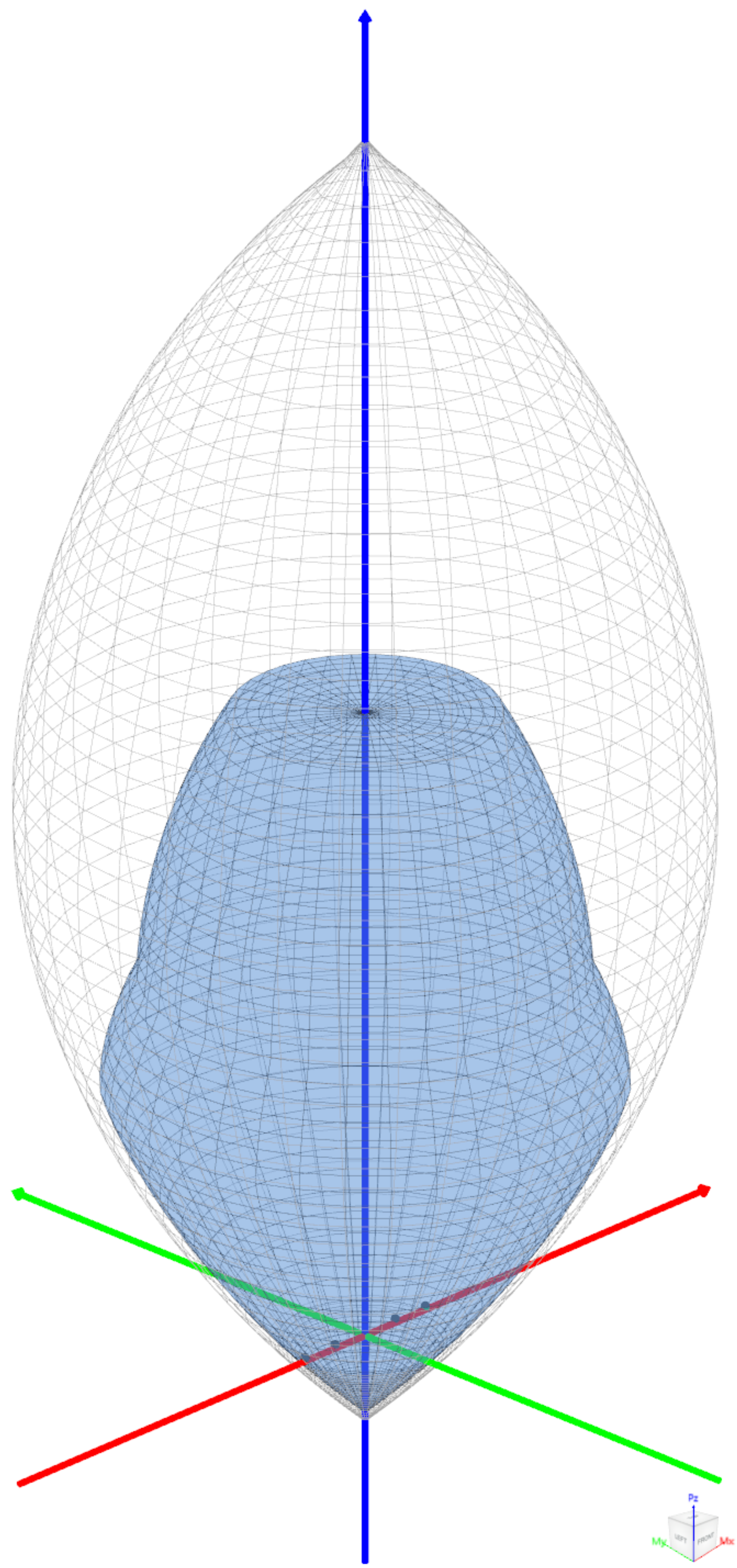


Figure 23 – Wind Turbine Tower Concrete Pier 3D Failure Surface

6. 2D/3D Viewer

2D/3D Viewer is an advanced module of the spColumn program. It enables the user to view and analyze 2D interaction diagrams and contours along with 3D failure surfaces in a multi viewport environment.

2D/3D Viewer is accessed from within spColumn. Once a successful run has been performed, you can open 2D/3D Viewer by selecting the **2D/3D Viewer** command from the **View** menu. Alternatively, 2D/3D Viewer can also be accessed by clicking the 2D/3D Viewer button in the program toolbar.

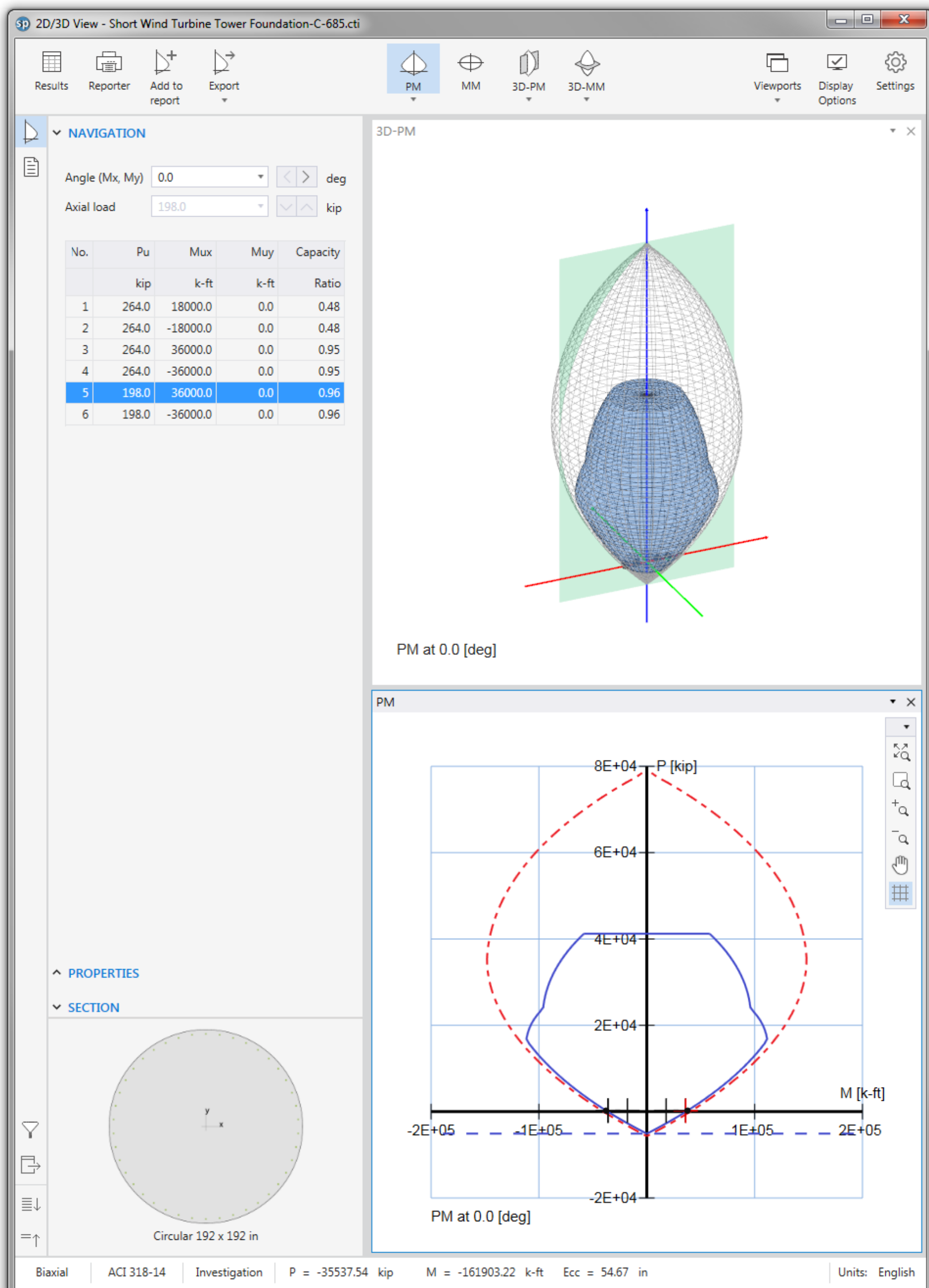


Figure 24 – 2D/3D View for Pier

7. Wind Turbine Tower Base Pier Reinforcement Optimization

The builder was provided two options for steel bar arrangement to increase field and construction flexibility. The impact of the two alternative reinforcement patterns is illustrated below.

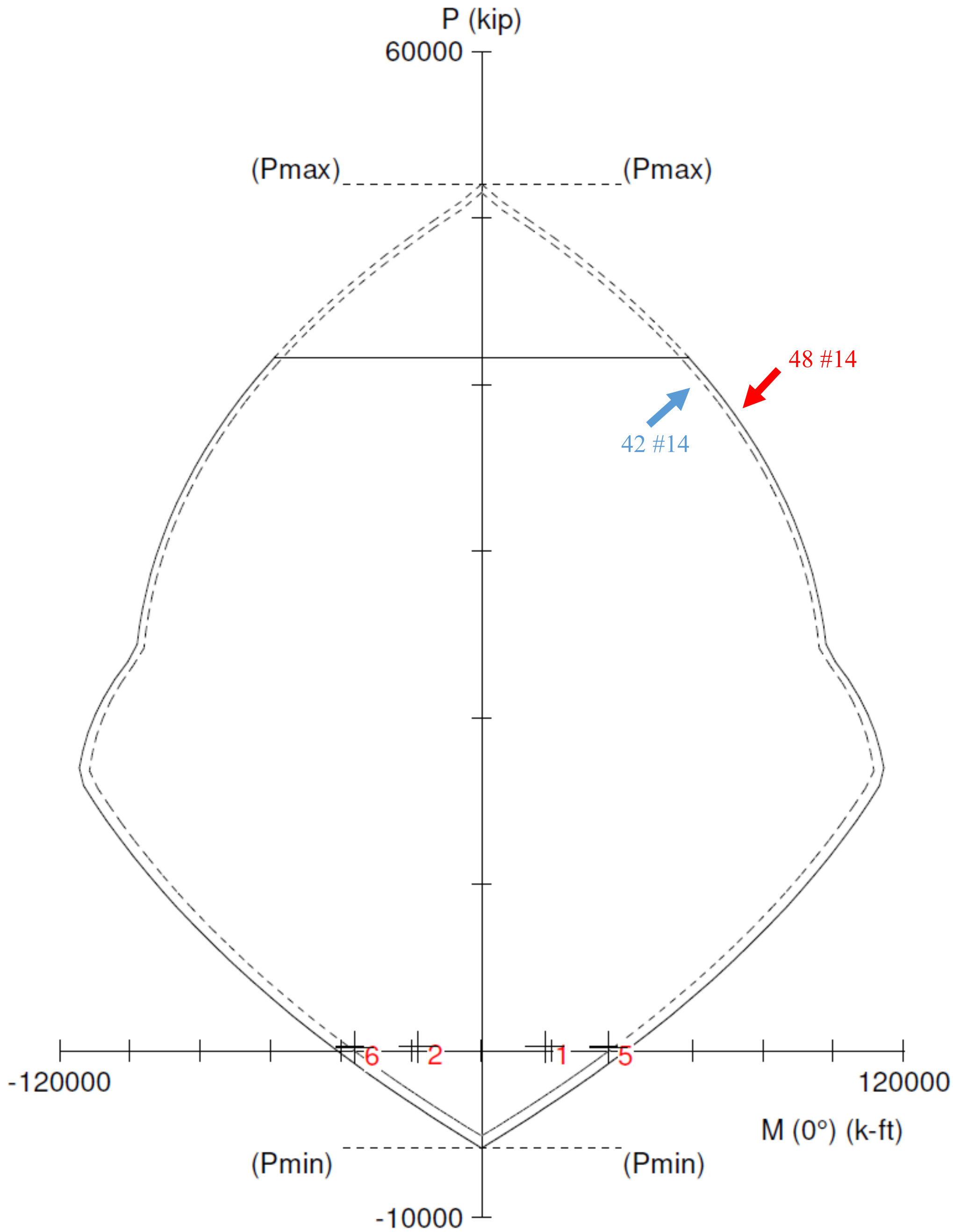


Figure 25 – Tower Base Reinforcement Comparison