# ANALYSIS AND DESIGN OF VERTICAL VESSEL FOUNDATION

***A thesis***

*Submitted by*


**JAGAJYOTI PANDA (109CE0168)**

**M.S.SRIKANTH (109CE0462)**


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## CERTIFICATE

This is to certify that this report entitled, "**Analysis and design of vertical vessel foundation**" submitted by **Jagajyoti Panda (109CE0168)** and **M.S.Srikanth (109CE0462)** in partial fulfillment of the requirement for the award of Bachelor of Technology Degree in Civil Engineering at National Institute of Technology, Rourkela is an authentic work carried out by them under my supervision.

To the best of my knowledge, the matter embodied in this report has not been submitted to any other university/institute for the award of any degree or diploma.

Date:

Prof. Pradip Sarkar
Department of Civil Engineering
(Research Guide)

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Jagajyoti Panda and M.S.Srikanth

## ABSTRACT

**KEYWORDS:** *vertical vessel, anchor bolts, octagonal footing, spectral acceleration, fundamental period, butt weld, dowel bars, soil stiffness, resonance.*

Vertical vessels are massive structures used in oil industries which store oil and different fluids. Due to the massiveness of the structure and pedestal considerations, an octagonal foundation is designed in place of a simple rectangular footing. The design includes analyzing of loads from superstructure, design of base plate and foundation bolt, design of pedestal and footing. The design of pile is not considered in the present study. The main objective of the study is to evaluate the manual method of design procedure. The same footing is modeled in different commercial finite element software. Performance of the designed foundation as obtained from the finite element analysis is then compared with that obtained from manual calculations. Maximum moment obtained from the software for the given support forces are found to be higher than those calculated manually according to Process Industry Practices guideline. Therefore, the design process outlined in PIP underestimates the bending moment demand as per the present study. However the present study is based on one typical case study. There is a provision for repeating this study taking into consideration a large number of foundations with varying parameters to arrive at a more comprehensive conclusion.

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# NOTATIONS

| | |
|---|---|
| $d_0$ | Diameter of anchor bolt |
| BCD | Bolt circle diameter |
| $D_{ped}$ | Diameter of pedestal |
| $h_{ef}$ | Depth of embedment |
| $M_{ped}$ | Overturning moment at the base of the pedestal |
| $F_u$ | Max. tension in reinforcing bar |
| $\alpha$ | Strength reduction factor in rebar |
| $h_{foot}$ | Depth of footing |
| $A_{foot}$ | Area of footing |
| SR | Stability Ratio |
| $A_{st}$ | Area of steel reinforcement |
| DCD | Dowel circle diameter |
| SBC | Safe bearing capacity |
| $E_s$ | Elastic modulus of steel $=2 \times 10^5$ MPa |
| $E_c$ | Modulus of elasticity of concrete |
| $f_{yd}$ | Design yield strength |
| $f_y$ | Yield strength of structural steel |
| $f_{ck}$ | 28 day characteristic strength of concrete |
| $V_b$ | Basic wind speed |

| | |
|---|---|
| $r_c$ | Radius of gyration |
| I | Moment of Inertia |
| $I_{eff}$ | Effective moment of inertia |
| M | Bending moment acting on a section at service load |
| $M_u$ | Ultimate moment of resistance |
| T | Tension |
| $C_t$ | Coefficient depending upon slenderness ratio |
| k | Slenderness ratio |
| $V_{cr}$ | Critical velocity |
| $V_d$ | Design wind speed |
| $X_U$ | Depth of neutral axis |
| $b_{edge\ anchor}$ | Edge distance of anchor bolt |
| $M_{ped}$ | Overturning moment at the base of pedestal |
| $n_d$ | Number of dowels |
| $h_{foot}$ | Depth of the footing |

# CHAPTER 1
# INTRODUCTION

## 1.1 BACKGROUND

Vertical vessels find their application usually in oil and gas industries. They contain a number of trays which are designed for mixing between a rising gas and a falling liquid. The vessel is similar to a horizontal drum that comprises of two dished heads, one at the top and one at the bottom. It is supported by a skirt which is welded to the bottom head. Skirt is a cylindrical steel shell which rests on the reinforced concrete foundation.

It is due to the massive structure and large capacities of the vessels for which octagonal foundations are preferred. The monopoles are also designed with octagonal foundations underneath. The design includes analyzing of loads from superstructure, design of base plate and foundation bolt, design of pedestal and footing. The design of pile is kept outside the scope of the study.

## 1.2 OBJECTIVES

Prior to defining the specific objectives of the present study, a detailed literature review was taken up. This is discussed in detail in the next chapter. The main objectives of the present study have been presented as follows.

1. Analyze and Design vertical vessel foundation using manual calculation available in literature.
2. Model and analyse the foundation using FEM
3. Evaluate the Manual Method of designing vessel foundation

## 1.3 SCOPE OF WORK

1. The design includes following items:
    - Analysis of loading on the foundation.
    - Design of foundation bolt.
    - Design of pedestal and footing.

2. The foundation is designed as a soil supported one i.e. as a shallow foundation.

3. Design of pile is kept outside the scope of the study

## 1.4 ORGANISATION OF THESIS

Chapter 1 has presented the background, objective and scope of the present study.

Chapter 2 starts with a description of various load cases and different design considerations to be taken into account for foundation design.

Chapter 3 deals with the analysis of the vessel superstructure.

Chapter 4 discusses the manual calculation of design of anchor bolts, pedestal and the footing using the available literatures.

Chapter 5 shows the design results of the octagonal footing by manual calculation and with the help of finite element software.

Finally chapter 6 presents summary, significant conclusions from this study and future scope of research in the area.

# CHAPTER 2

# LITERATURE REVIEW

## 2.1 GENERAL

In this section a general study on the different type of loads and load combinations is carried out using the STE03350 - Vertical Vessel Foundation Design guide and various other literatures available. The most relevant literature available on the study of different load cases has been reviewed and presented in this Chapter.

## 2.2 IDENTIFICATION OF LOAD CASES

Different loads are taken into account while analyzing the superstructure i.e. the various vertical loads, the horizontal wind loads and the eccentric loads.

### 2.2.1 VERTICAL LOADS

- Structure dead load- It is the sum of weights of the pedestal, footing and the overburden soil.
- Erection dead load- It is the fabricated weight of the vessel taken from the certified vessel drawing.
- Empty dead load- It is the load coming from the trays, insulations, piping, attachments taken from the drawings.
- Test dead load- It is the load coming from the empty weight of the vessel and that of the test fluid (usually water) required for hydrostatic test.
- Operating dead load- It is the weight of the empty vessel plus the weight of the operating fluid during service conditions.

### 2.2.2 HORIZONTAL LOADS

- Wind load- It is the wind pressure acting on the surface of the vessel, piping and other attachments of the vessel.

- Seismic load- The horizontal earthquake load is applied 100 % in one direction and 30 % on the orthogonal direction.

### 2.2.3 LIVE LOADS

Live loads are taken into account as per STE03350 - Vertical Vessel Foundation Design guidelines. Live loads would not typically control the design of the foundation.

### 2.2.4 ECCENTRIC LOADS

Eccentric vessel loads must be taken into account which is caused by large pipes and boilers.

## 2.3 OTHER DESIGN CONSIDERATIONS

- To check stability of structure against stability and overturning.
- To check soil bearing pressures not exceeding the ultimate bearing capacity of the soil.
- Anchor bolt design to be carried out.

# CHAPTER 3

# ANALYSIS OF STEEL SUPERSTRUCTURE

## 3.1 WIND LOAD ANALYSIS

Calculation of static wind load is based on IS 875 Part 3: 1987 considering the vessel as general structure with mean probable design life of 50 years.

Risk factor (k1) = 1

As vessel is to be located on a level ground, k3 = 1

and considering vessel site to be located on sea coast terrain, category 1 is considered for the wind load calculation.

Since the vessel is 21.6m high, the size class structure is considered as class B.

Assuming the highest average wind speed in the site is

V max = 20 km/hr

= 6.556 m/s

Basic wind speed as per Fig 1. IS 875 Part 3 is $V_b$= 39 m/s

Wind load on the vessel will be increased due to the presence of platform, ladder and other fittings (5 % increase in the wind load)

For computing wind loads and design of the chimney, the total height of the vessel is divided into 3 parts.

<u>Part 1 (21.6m – 20m)</u>

Diameter of the vessel d1 = 1.3m

Considering $k_2$ factor in this height range

Lateral wind load $P_1 = \int_{20}^{h} 0.6\left[\text{k1}\ \left[1.13\ +\ \left\{(\text{h}-20)\times\frac{1.13-1.10}{30-20}\right\}\right]\text{k3 Vb}\ \right]^2$

= 0.243×10 kN

Moment due to the wind force at the base and part1

$$M_1 = \int_{30}^{h} 0.6\left[k1\ \left[1.13\ +\ \left\{(h-30)\times\frac{1.13-1.13}{50-20}\right\}\right] k3\ Vb\ \right]^2 d(h\text{-}20)d_h$$

$= 19.5$ kNm

Shell thickness of the vessel $T_1 = 0.4$m

Section modulus $Z_1 = \pi d^2 T/4$

$= 0.5\ m^3$

Bending stress at the extreme fiber of the shell at 30m level $f_{mo1} = 1.05\ M_1 / Z_1$

$= 18$ Mpa

Max tensile stress = 40 MPa

$f_{t1} < f_{allow,T}$ (hence okay)

<u>Part 2 ( 20m – 12m)</u>

It is located at a height of 12m to 20m from the ground.

Considering K2 factor in this height range,

$$P_{2a} = \int_{12}^{20} 0.6\left[k1\ \left[1.10\ +\ \left\{(h-20)\times\frac{1.13-1.10}{30-20}\right\}\right] k3\ Vb\ \right]^2 d\times dh$$

$= 11.23$ kN

$P_2 = 11.23 + 2.43$

$= 13.66$ kN

Moment due to the wind force at the base of part-2 (at 16m)

$$M_{2a} = \int_{20}^{21.6} 0.6\left[k1\ \left[1.10\ +\ \left\{(h-20)\times\frac{1.13-1.10}{30-20}\right\}\right] k3\ Vb\ \right]^2 d\times(h\text{-}12)\times dh$$

$= 20.31$ kNm

$M_{2b} = \int_{12}^{20} 0.6\left[k1\ \left[1.10 + \left\{(h-20)\times\frac{1.13-1.10}{30-20}\right\}\right] k3\ Vb\right]^2 d\times(h-12)\times dh$

= 45.2 kNm

$M_2$ = 65.55 kNm

Section modulus at this level is 0.5 $m^3$

Bending stress at the extreme fiber of the vessel at 12m level is

$f_{mo2} = 1.05\ M_2 / Z_2$

= 137.65 KN/ $m^2$

Max tensile stress $f_{t3} = f_{mo3}$ = 28.9 Mpa < 212 Mpa

Part 3 ( 0m-12m)

Part 3 is located at a height of 0m to 12m from the ground.

d = 1.3m

considering $K_2$ factor, lateral wind force

$P_a = \int_{10}^{12} 0.6\left[k1\ \left[1.03 + \left\{(h-10)\times\frac{1.07-1.03}{15-10}\right\}\right] k3\ Vb\right]^2 d\times dh$

= 2.55 kN

$P_b = \int_{0}^{10} 0.6[k1 * 1.03 * k3 * Vb]^2 d * dh$

= 12.5 kN

Shear force due to wind force at the base

= 12.5 + 2.55 + 13.66

= 28.7 kN

Moment due to the wind force at the base of the part 3,

$M_a = \int_{20}^{21.6} 0.6\left[k1\ \left[1.10\ +\ \left\{(h-20) * \frac{1.13-1.10}{30-20}\right\}\right] k3\ Vb\ \right]^2 d \times (h-0) \times dh$

$= 47.9$ kNm

$M_b = \int_{12}^{20} 0.6\left[k1\ \left[1.10\ +\ \left\{(h-20) \times \frac{1.13-1.10}{30-20}\right\}\right] k3\ Vb\ \right]^2 d \times (h-0) \times dh$

$= 180$ kNm

$M_c = \int_{10}^{12} 0.6\left[k1\ \left[1.03\ +\ \left\{(h-10) \times \frac{1.07-1.03}{15-10}\right\}\right] k3\ Vb\ \right]^2 d \times (h-0) \times dh$

$= 28.13$ kNm

$M_d = \int_{0}^{12} 0.6\,[k1 \times 1.03 \times k3 \times Vb]^2 d \times (h-0) \times dh$

$= 90.62$ kNm

$M_3 = 346.65$ kNm

$Z = 0.5\ m^3$ ( at level of 0m )

Bending stress at the extreme fiber of the vessel at 0m level

$f_{mo3} = 1.05 \times 346.68 / 0.5$

$= 72.8$ MPa

Max tensile stress $f_{t3} = 72.8$ MPa $<$ 212 MPa

### 3.2 SEISMIC LOAD ANALYSIS

Maximum Spectral acceleration value corresponding to the above periods considering 2% damping and soft soil site,

$$Sa = 0.75 \times 9.81$$

Importance factor for Steel stack (I) = 1.5

Response Reduction factor ($R_f$) = 2

Zone factor = 0.10

Design Horizontal acceleration spectrum value (Ah) = (Z/2) × (Sa/9.81) / ($R_f$/I)

=0.281

Design base shear (Vb) = Ah × Wt = 43.2KN

Maximum Shear Stress at the base ($F_{sh\_eq}$) = $V_b/(\pi \times d \times T)$

= 0.264×10 MPa

<u>calculation of design moment</u>

Denominator = $\int_{20}^{21.6} \pi.d.T.\rho.h^2 dh$

$= \int_{12}^{20} \pi.d.T.\rho.h^2 dh$

$= \int_{0}^{12} \pi.d.T.\rho.h^2 dh$

$= 4.307 \times 10^5$ KN.m$^2$

1. Moment due to Seismic at the 20m level

   $M_{sesmic} = (\int_{20}^{21.6} (\pi.d.T.\text{density}) h^2.Vb.(h\text{-}20)dh)/\text{denominator}$

   =31.48KN

   Bending stress due to Seismic force at 20m level ($f_{smo}$)=M/Z

   =62.9MPa

   Increase of 33.33% in allowable stress is allowable stress is allowed for Earthquake load

   $F_{allow,seis} = 1.33 \times f_{allow} = 115.7$MPa (Therefore safe)

2. Moment due to Seismic at the 12m level

$M_{seismic} = \int_{20}^{21.6}(\pi.\mathrm{d}.\mathrm{T}.\mathrm{density})h^2$.Vb.(h-12).dh)/Denominator

$=\int_{12}^{20}(\pi.\mathrm{d}.\mathrm{T}.\mathrm{density})h^2$.Vb.(h-12).dh)/Denominator

=412.4MPa

Bending Stress due to seismic force at 12m level ($f_{smo}$) = M/Z

= 100.569MPa

Increase of 33.33% in allowable stress is allowable stress is allowed for Earthquake load

$F_{allow,seis} = 1.33 \times f_{allow}$ =115.7MPa (Therefore safe)

3. Moment due to Seismic at the 0m level

$M_{seismic} =(\int_{20}^{21.6}(\pi.\mathrm{d}.\mathrm{T}.\mathrm{density})h^2$.Vb.(h-0).dh)/Denominator

$=\int_{12}^{20}(\pi.\mathrm{d}.\mathrm{T}.\mathrm{density})h^2$.Vb.(h-0).dh)/Denominator

$=\int_{0}^{12}(\pi.\mathrm{d}.\mathrm{T}.\mathrm{density})h^2$.Vb.(h-0).dh)/Denominator

= 812.53 KN-m

Bending Stress due to seismic force at 0m level ($f_{smo}$)=M/Z

=5.254×10 MPa

Increase of 33.33% in allowable stress is allowable stress is allowed for Earthquake load=

$F_{allow,seis} = 1.33 \times f_{allow}$ =115.7MPa (Therefore safe)

## 3.3 FUNDAMENTAL PERIOD OF THE VESSEL

Fundamental period of vibration for this chimney is calculated as per IS 1893 Part 4 to check the vessel design against dynamic load.

Area of c/s at base of the vessel $A_{base} = \pi d_{base} . T_{sh}$

$= 0.163 \times 10\ m^2$

Radius of gyration at the base of the shell $r_c = (d_{base}/2) \times (1/2)^{1/2}$

$= 0.45m$

Slenderness ratio $k = ht / r_c$

$= 46.96$

Coefficient depending upon slenderness ratio $C_t = 1.8k$

$= 84.52$

Weight of superstructure = 128.23 KN/m

Weight of platform, ladder Wp = 0.2 Ws

= 25.6 KN

Total weight of vessel ($W_t$) = Ws + Wp

= 153.94 KN

Modulus of elasticity ($E_s$) = $2 \times 10^5\ N/m^2$

The fundamental period for vibration $T_n = C_t\ (Wt.Ht/\ Es.A_{base}\ g)^{1/2}$

$= 2.72$ s

### 3.4 CHECK FOR RESONANCE

Fundamental period of vibration for the vessel $T_n = 2.72$ s

Fundamental frequency of vibration $f = 1/\ T_n$

$= 3.68 \times 10^{-1}$Hz

Critical velocity $V_{cr} = 5 \times d \times f$

= 2.3897 m/s

Basic wind speed $V_b = 39$ m/s

Design wind speed $V_d = k1 \times k2 \times k3 \times V_b$

= 43.68 m/s

Velocity range for resonance :

V resonance_UL = 0.8 $V_d$ = 34.944 m/s

V resonance_LL = 0.33 $V_d$ =14.414 m/s

As critical velocity doesn’t lie within this range of resonance limit,the vessel need not be checked for the resonance.

# CHAPTER 4

# MANUAL CALCULATION

## 4.1 GENERAL

Using the available literature, the foundation is analyzed and designed manually. The assumptions, procedure and logic have been discussed in this Chapter.

## 4.2 MATERIAL PROPERTIES

Yield stress of the structural steel: $f_y = 415MPa$

Modulus of elasticity of the material of the material of structural shell: $E_s = 2\times10^5 MPa$

Mass density of the structural steel: 78.5 $kN/m^3$

Assume Imposed load and wt. of Platform, access ladder = 20% of the self-weight of the chimney shell

a. Max. permissible stress in tension
   $F_{allow\_tension} = 0.6fy = 250MPa$ (IS 800-2007)
   Considering efficiency of Butt weld: 0.85
   Allowable tensile stress: $f_{allow.T} = 0.85\times250 = 212MPa$

b. Max. permissible stress in shear
   $F_{allowable\_Shear} = 0.4fy = 160MPa$

c. Max. permissible stress in compression is a function of
   $h_{level}$ = Effective Height for consideration of buckling
   D = Mean diameter of the vessel at the level of considerable height
   T = Thickness at the level consideration

### 4.2.1 SUPERSTRUCTURE DATA

Table 1: Details of the superstructure

| | |
|---|---|
| OUTER DIAMETER | 1.7 m |
| THICKNESS | 0.4 m |
| HEIGHT | 21.6m |
| MATERIAL | STEEL |
| ERECTION WEIGHT | 470 KN |
| EMPTY WEIGHT | 350 KN |
| OPERATIONAL WEIGHT | 790 KN |
| WIND LOAD | 48 KN |

### 4.3 BOLT AND PEDESTAL DESIGN

Diameter of bolt = 45 mm

ACI 318 requires anchors that will be torqued should have a minimum edge distance of $6d_0$

$b_{\text{edge anchor}} = 6\times d_0$

$= 6\times 45$

$= 0.27\text{m}$

Bolt circle diameter (BCD) = Diameter of vessel + (0.12×2)

$= 1.7 + 0.24$

$= 1.94\text{m}$

Concrete pedestal supporting the vertical vessel shall be sized according to the following:

It should be greater than $d_1$ and $d_2$ where

$d_1 = \text{BCD} + 7 \text{ in}$

$d_2$ = BCD + $8d_0$

$d_1$ and $d_2$ come out to be 2.12m and 2.3m. We have assumed the dimension of pedestal to be 2.48m which satisfies both the conditions being greater than $d_1$ and $d_2$.

$D_{ped}$ reqd = 2.48m > 1.5m

(hence foundation is octagonal in shape)

Min. embedment depth $h_{ef} = 12d_0$

$= 12\times0.045$

= 0.54m

Let us assume $h_{ef}$ as 1m

According to ACI 318, min. embedment depth above ground level $h_{proj\text{-}ped}$ = 0.3m

Depth of pedestal larger should be larger than $h_{ef} + h_{proj\text{-}ped} =$ 1.3m

Depth of pedestal considered h pedestal = 1.6m

Unit weight of reinforced cement concrete = 25 $KN/m^3$

Weight of pedestal = $25\times5.092\times1.6\times1$

= 204 KN

Total weight of the pedestal and the vessel =414 KN

Total overturning moment at pedestal base $M_{ped}$ = M base + F×h

= 866.8 KN

Ultimate overturning moment = 1.6 $M_{ped}$

= $1.6\times866.8$

= 1386.88 kNm

Dowels should be provided when the height of pedestal exceeds 1.5m.

Assuming no of dowels $n_d$ = 40

Dowel circle diameter DCD = $d_{ped}$ – 6in

= $0.248\times10$ – 6in

$= 2.32m$

Total downward force = $F_y + W_{ped}$

$= 210 + 204$

$= 414$ KN

Max tension in reinforcing bar $F_u = [4Mu_{ped} / n \times DCD - 0.9(F_y + W_{ped})/n]$

$= 5.046 \times 10$ KN

Strength reduction factor for reinforcing bar $\alpha = 0.9$

Therefore the area reqd for each of the dowels $A_{s\ reqd} = F_u / \alpha \times f_{ys}$

$= 50.46 \times 10^3 / 0.9 \times 415$

$= 135.10\ mm^2$

Dowel size to be used = 16mm

$A_s$ provided $= \pi \times 16^2 / 4$

$= 201.062\ mm^2$

Spacing between dowel bars $= \pi \times DCD / n$

$= \pi \times 2.32 / 40$

$= 0.182m$

The pedestal shall have a reinforcing grid of 16mm diameter @ 180 mm c/c each way to prevent potential concrete cracking.

Provide tie 12mm tie set (2 tie per set) @ 300 mm c/c

Considering the bolts are of ductile steel, strength reduction factor for the anchor = 0.75 (for tension)

As Indian code doesn’t have specific requirement for design of anchor bolts, ACI 318:2005 is followed for the anchor bolt design.

Diameter of bolt (assumed) $d_0 = 45mm$

Yield strength of the bolt $f_{y\_bolt} = 400$ MPa

Tensile strength of bolt $f_t = 0.6 \times 400$

= 240 MPa

Tension capacity of each bolt $R_t = 0.8\times\pi\times d_0{}^2\times f_t / 4$

= 305.362 KN

BCD = 1.94m

Let number of bolts required (support moment increased by 50 % from stability consideration) be $n_b$

$n_b$ reqd = $[4M_{base}\times1.25\times1.5/(R_t\times \text{BCD})] - [0.7 P_{base}/ R_t]$

= $[4\times790\times1.25\times1.5/ (305.362\times1.94)] – [0.7 P_{base} / R_t]$

= 9.52

We have provided 18 bolts. (okay)

## 4.4 FOOTING DESIGN

Footing having least dimension across sides that is equal to greater than 2m shall be octagonal in shape. Assuming a trial depth of the footing $h_{foot}$ = 0.4m

Total overturning moment at the footing base = $M_{base} + V_{base} \times h_{footing}$

= 790 + 48 ×(1.6+0.4)

= 886 kNm

Taking allowable gross soil bearing pressure = 150 kN/$m^2$

Diameter D = $2.6[M_{footing} /SBC]^{1/3}$

= $2.6 [886/150]^{1/3}$

= 4.7 m

Providing a trial diameter $d_{footing}$ = 6m

Side of foundation = 2.485 m

Area of footing $A_{foot}$ = 8×0.5×3×2.485

= 2.982×10 $m^2$

Footing weight $W_{foot} = A_{foot} \times h_{foot} \times 25$

$= 29.82 \times 0.4 \times 25$

$= 298.2$ KN

Unit weight of wet soil = 18 KN / $m^3$

Weight of the soil = $(A_{foot} - A_{ped})(h_{ped} - h_{proj\text{-}ped}) \times 18$

$= 578.448$ KN

Weight of the pedestal = 204 KN

Total weight of vessel, pedestal, soil and footing W = P base + W soil + W ped + W foot

$= 210 + 578.448 + 204 + 298.2$

$= 1290.648$ KN

Water table is 0.5m below the ground level

Depth of footing from the ground = 2m

Depth of water at the footing base = 2 – 0.5 – 0.3

= 1.2 m

Unit weight of water = 10 KN / $m^3$

Upward water pressure below the footing = $10 \times 1.2$

= 12 KN / $m^2$

Total upward force on the footing due to water $P_{water} = 12 \times A_{foot}$

= 357.84 kN

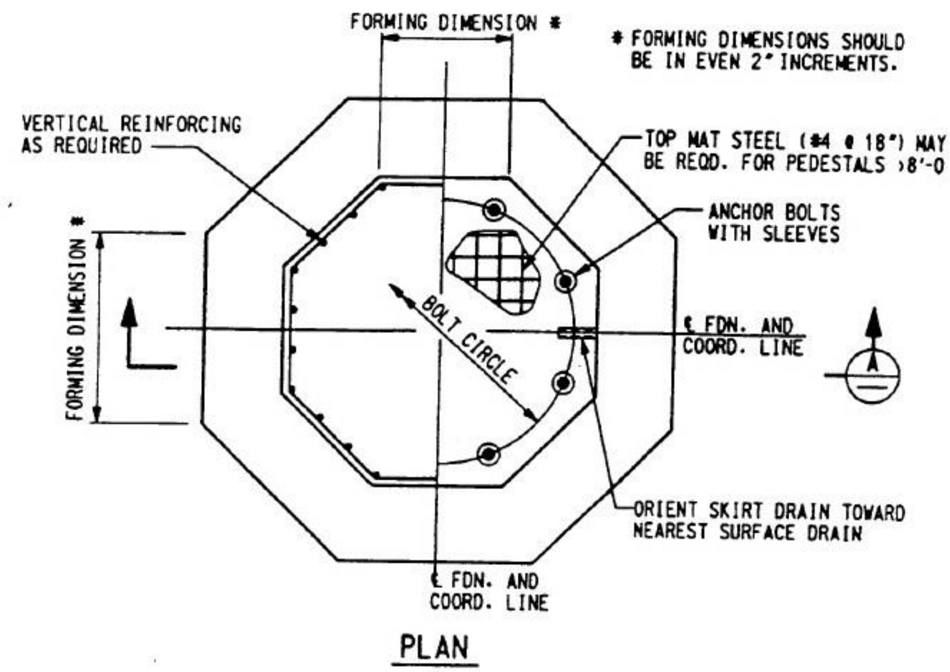



**Fig 1**: Plan of pedestal and foundation (ref. STE03350 - Vertical Vessel Foundation Design Guide)

## 4.5 CHECK FOR STABILITY

Net downward force giving stability to the structure $P_{down} = W - P_{water}$

$= 1290.648 - 357.84$

$= 932.808$ kN

Resultant loading eccentricity $e_{load} = M_{foot} / P_{down}$

$= 886 / 932.808$

$= 9.49\times10^{-1}$ m

Stability ratio (SR) = $d_{foot} /2 e_{load}$

$= 6 / 2\times0.949$

$= 3.161 > 1.5$ (safe)

## 4.6 CALCULATION OF SECTION MODULUS OF OCTAGONAL FOUNDATION

Section modulus is given by Z = I / y where 'I' is the moment of inertia about the centroidal axis and 'y' is the distance of extreme fiber from the neutral axis.

For a rectangle,this works out to be very simple and comes out to be $bd^2 / 6$

whereas for the case of octagonal foundation, calculation of Z becomes very difficult. We take the help of ratio of stability vs e/D for indirectly arriving at the section modulus.

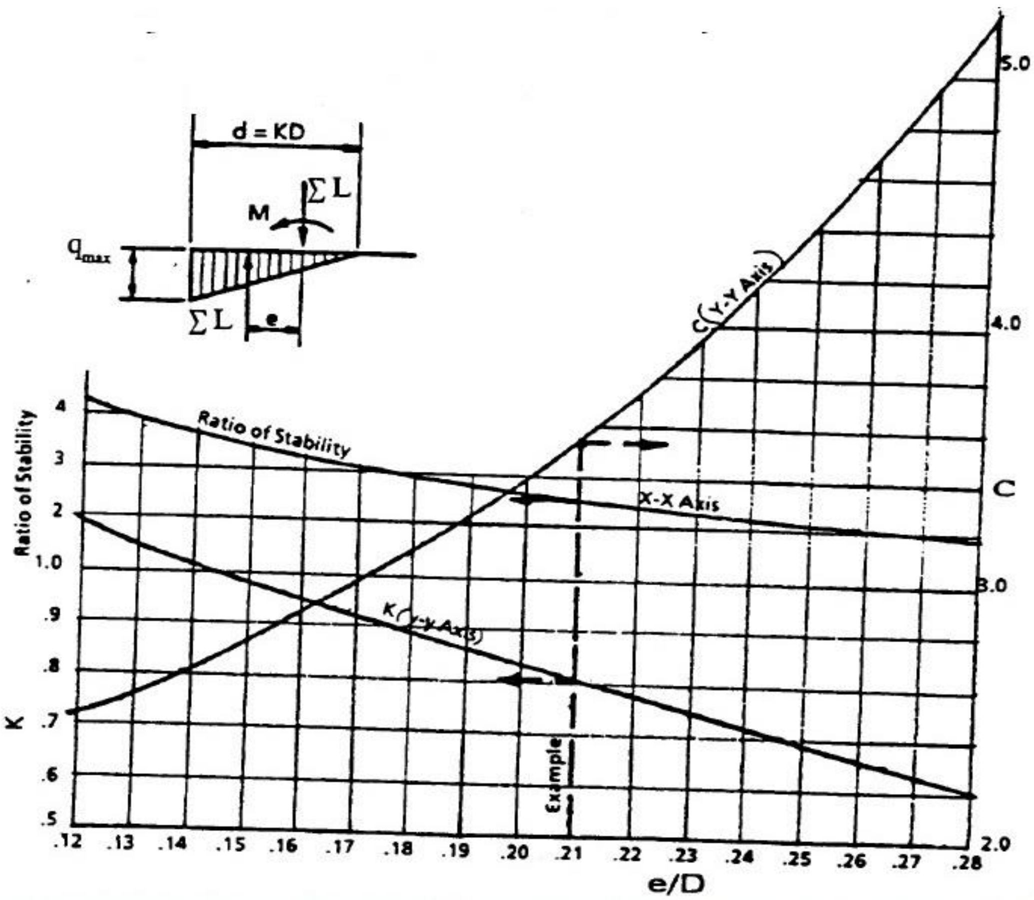



**Fig 2**. Graph for calculation of $L_{diag}$ of octagonal footing. ref. STE03350 - Vertical Vessel Foundation Design Guide

## 4.7 CHECK FOR SOIL BEARING

$e_{load} / d_{foot}$ = 0.949 / 6

= 0.158

Corresponding from chart $L_{diag} = 2.5$

Max compression, $f_{max} = L_{diag} \times P_{down} / A_{foot}$

$= 2.5 \times 932 / 29.82$

$= 78.135$ kN / m$^2$ < 150 kN / m$^2$ (safe)

## 4.8 REINFORCEMENT

$M_u = 1.6\ M_{foot}$

$= 1.6 \times 886$

$= 1417.6$ kNm

$P_u = 0.9\ W$

$= 0.9 \times 1290.65$

$= 1161.58$ kN

Resulting loading eccentricity $e_u = M_u / P_u$

$= 1.22$ m

$e_u / d_{foot} = 1.22 / 6$

$= 0.203$

From STE03350 - Vertical Vessel Foundation Designguide fig-b , foundation pressure for octagonal base (table 2)

For $e / d = 0.203$ we have $k = 0.4935$

$L = 4.503$

Neutral axis depth $X_u = k.d_{foot}$

$= 0.4935 \times 6$

$= 2.96$ m

Distance of extreme comp. end from neutral axis $X_{comp} = d_{foot} - X_u$

$= 6 - 2.96$

$= 3.04$ m

Corresponding footing pressure $f_u = L \times P_u / A_{foot}$

$= 4.503 \times 1161.58 / 29.82$

$= 1.75 \times 10^{-1}$ MPa

Equivalent square for pedestal cross-section $b_{eq} = (A_{ped})^{1/2}$

$= (5.092)^{1/2}$

$= 2.26$ m

Projection of the footing edge to the pedestal face $b_{proj} = (d\ foot - b\ eq) / 2$

$= 1.87$ m

Pressure at the face of the equivalent square pedestal $f_{ped\_face} = f\,u\,(X_{comp} - b_{proj}) / X_{comp}$

$= 6.8 \times 10^{-2}$ MPa

Considering the width of the footing = 1m

$M_u$ footing $= [f_{ped\_face} \times b_{foot} \times b_{proj}^{\ 2} / 2] + [0.5 \times (f_u - f_{ped\_face}) b_{proj} \times b_{foot} \times 2/3\ b_{proj}]$

$= 118.89 + 124.73$

$= 243.73$ kNm

Effective depth of the footing design $d_{foot\_eff} = h_{foot} - 50 - (0.5 \times 20)$

$= 340$ mm

R footing $= M_u / (b_{foot} \times d_{foot}^{\ 2})$

$= 2.11$ MPa

Material properties for footing f ys = 415 MPa

f ck = 20 MPa

Area reqd for tensile reinforcement $= 0.5\ f_{ck} / f_{ys}\ [\ 1 - (1 - 4.6\ Mu / f\ ck\ b_{foot}\ d_{foot}^{\ 2})^{1/2}\ ]$

$= 2312.95\ mm^2$

Spacing of reinforcement $= 1000 \times \pi/4 \times 20 \times 20 / 2312.95$

$= 135.82$ mm

Providing 8 Y20 bars @ 130 mm c/c each way at the bottom of the footing

## 4.9 ONE WAY SHEAR CHECK

Pressure at a distance 'd' from the face of the equivalent square pedestal:

$F_{beam\_shear} = F_u (X_{comp}-b_{proj}+d_{foot\_eff})/X_{comp}$

$=.087$MPa

Shear force at a distance 'd' from the face of the equivalent square pedestal for 1m width.

$Vu=f_{beam\_shear}(b_{proj}-d_{foot-eff}).b_{footing} + (f_u-f_{beam-shear})(b_{proj}-d_{foot-eff})/2$

$=200.43$ kN

Shear stress$=200.43\times10^3/(1000\times.340)$

$=.59$ MPa

Design shear strength of the concrete:

## 4.10 PUNCHING SHEAR CHECK

$f_{punch\_shear} = 1.4\ W_L / A_{foot}$

$= 1.4\times1290.48/ 29.82$

$= 0.0605$ MPa

Shear stress at a distance d/2 from the face of the equivalent square pedestal for width,

$V_{u\_punch} = f_{punch\_shear} ( A_{foot} -(b_{eq} + d_{foot\ eff})^2 )$

$= 1695.476$ kN

Shear stress $\tau_{punch} = V_{u\_punch}/ \{4(b_{eq} + d_{foot\ eff})\times d_{foot\ eff}\}$

$= 0.093$ MPa

Design shear strength of concrete $\tau_c = 0.25 (f_{ck})^{1/2}$

$= 1.11$ MPa

Allowable shear stress for punching shear $\tau = k_s \times 1.11$

$= 1.11$ MPa $> \tau_c$ (hence okay)

# CHAPTER 5

# FINITE ELEMENT ANALYSIS OF FOUNDATION

## 5.1 GENERAL

Finite Element (FE) analysis is carried out on the foundation designed based on manual method to evaluate the validity of the manual calculation method outlined in PIP design guideline. STAAD-Pro and STAAD foundation are used for reinforcement design whereas PLAXIS is used to check the soil stability. This chapter presents the results obtained from the FE analysis.

## 5.2 FE ANALYSIS based on STAAD Pro

The tables below show all modelling parameters and material properties for design in STAAD Pro.

Table 2: Modelling parameters for STAAD Pro

| | |
|---|---|
| Structure Type | Space Frame |
| No. of Nodes | 1353 |
| No. of Plates | 1995 |
| No. of Basic Load cases | 02 |
| No. of Combined load cases | 03 |
| Primary | Load case 1 DEAD LOAD |
| Primary | Load case 2 UPLIFT |

Table 3: Material Properties

| NAME | GRADE | E (MPa) | v | Density (kg/m$^3$) |
|---|---|---|---|---|
| STEEL | Fe 415 | $2\times10^5$ | 0.30 | $7.83\times10^3$ |
| CONCRETE | M20 | 24000 | 0.17 | $2.43\times10^3$ |

### 5.2.1 3-D VIEW OF THE PEDESTAL AND FOOTING

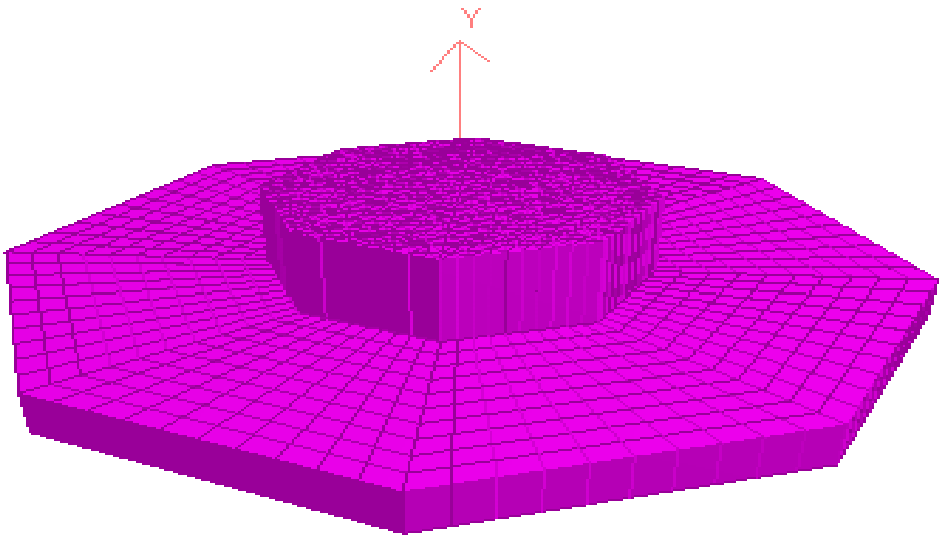



**Fig.3** STAAD model of the pedestal and footing

### 5.2.2 STAAD GENERATED MESH OF PEDESTAL AND FOOTING

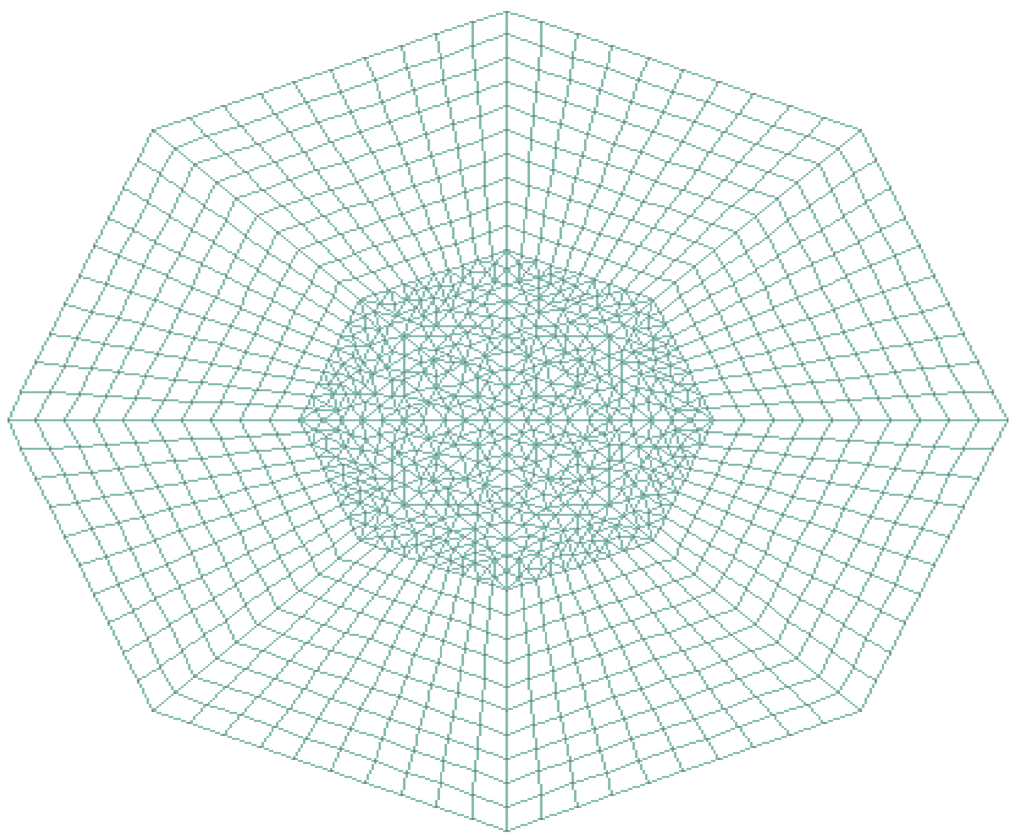


**Fig.4** Plate model

### 5.2.3 LOAD CASES DETAILS

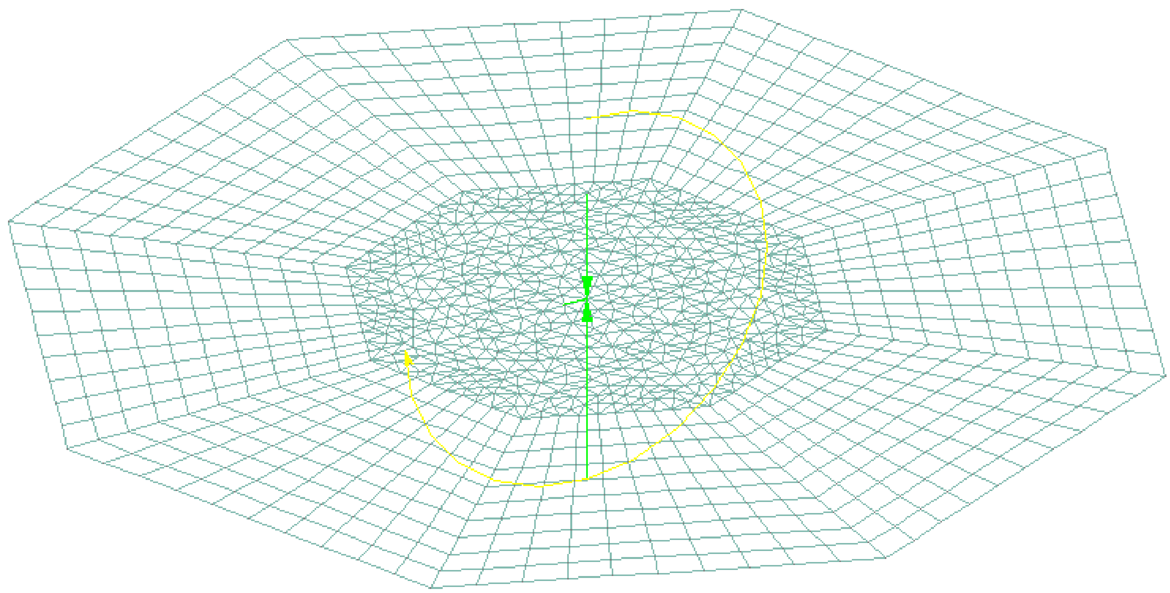


fig.5 Base force and Moment

### 5.2.4 STAAD PRO RESULTS

The tables below show the STAAD Pro output of the applied base shear and moment for the plates and nodes respectively.

Table 4 Plate contour

| | | | Shear | | Membrane | | | Bending Moment | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Plate | L/C | SQX (local) N/mm2 | SQY (local) N/mm2 | SX (local) N/mm2 | SY (local) N/mm2 | SXY (local) N/mm2 | Mx kNm/m | My kNm/m | Mxy kNm/m |
| Max Qx | 1873 | 3 GENERATE | **0.725** | 0.158 | 0.000 | 0.000 | 0.000 | -3583.975 | 208.495 | -998.630 |
| Min Qx | 1361 | 1 DEAD LOA | **-0.551** | -0.134 | 0.000 | 0.000 | 0.000 | 2400.733 | -127.579 | 665.754 |
| Max Qy | 1617 | 3 GENERATE | 0.300 | **0.469** | 0.000 | 0.000 | 0.000 | -238.985 | -1206.965 | -1683.029 |
| Min Qy | 1963 | 3 GENERATE | 0.132 | **-0.375** | 0.000 | 0.000 | 0.000 | -172.369 | -895.398 | 723.953 |
| Max Sx | 20 | 1 DEAD LOA | 0.000 | -0.000 | **0.000** | 0.000 | 0.000 | 0.005 | -0.001 | 0.000 |
| Min Sx | 20 | 1 DEAD LOA | 0.000 | -0.000 | **0.000** | 0.000 | 0.000 | 0.005 | -0.001 | 0.000 |
| Max Sy | 20 | 1 DEAD LOA | 0.000 | -0.000 | 0.000 | **0.000** | 0.000 | 0.005 | -0.001 | 0.000 |
| Min Sy | 20 | 1 DEAD LOA | 0.000 | -0.000 | 0.000 | **0.000** | 0.000 | 0.005 | -0.001 | 0.000 |
| Max Sx | 20 | 1 DEAD LOA | 0.000 | -0.000 | 0.000 | 0.000 | **0.000** | 0.005 | -0.001 | 0.000 |
| Min Sx | 20 | 1 DEAD LOA | 0.000 | -0.000 | 0.000 | 0.000 | **0.000** | 0.005 | -0.001 | 0.000 |
| Max Mx | 1361 | 3 GENERATE | -0.240 | 0.043 | 0.000 | 0.000 | 0.000 | **3502.511** | -289.958 | 998.630 |
| Min Mx | 1873 | 3 GENERATE | 0.725 | 0.158 | 0.000 | 0.000 | 0.000 | **-3583.975** | 208.495 | -998.630 |
| Max My | 1105 | 3 GENERATE | 0.185 | -0.267 | 0.000 | 0.000 | 0.000 | 157.522 | **1125.502** | 1683.029 |
| Min My | 1617 | 3 GENERATE | 0.300 | 0.469 | 0.000 | 0.000 | 0.000 | -238.985 | **-1206.965** | -1683.029 |
| Max Mx | 1232 | 3 GENERATE | -0.139 | -0.200 | 0.000 | 0.000 | 0.000 | 2604.907 | 607.688 | **1896.219** |
| Min Mx | 1744 | 3 GENERATE | 0.624 | 0.401 | 0.000 | 0.000 | 0.000 | -2686.370 | -689.152 | **-1896.219** |

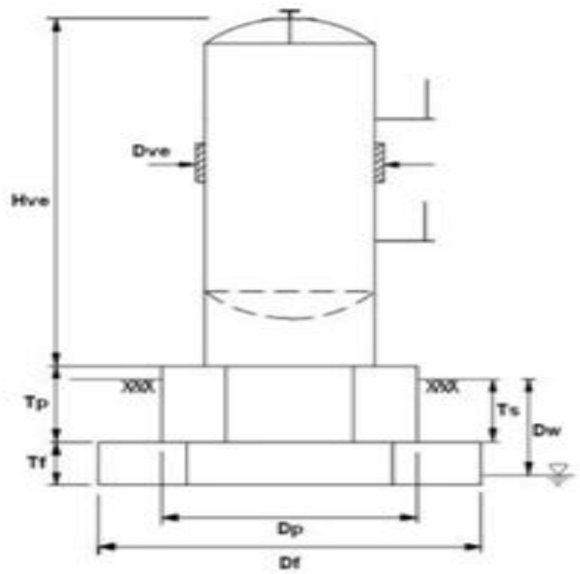
Table 5   Node Reaction Summary

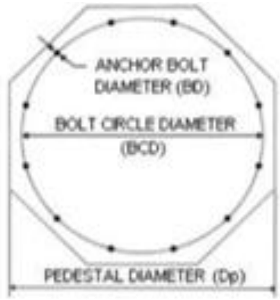
| | | | Horizontal | Vertical | Horizontal | Moment | | |
|---|---|---|---|---|---|---|---|---|
| | Node | L/C | Fx kN | Fy kN | Fz kN | Mx kNm | My kNm | Mz kNm |
| Max Fx | 1 | 1 DEAD LOA | **0.000** | 0.010 | 0.000 | 0.000 | 0.000 | 0.000 |
| Min Fx | 9 | 3 GENERATE | **-72.000** | -4.616 | 0.000 | 0.000 | 0.000 | 0.000 |
| Max Fy | 9 | 1 DEAD LOA | -48.000 | **4.371** | 0.000 | 0.000 | 0.000 | 0.000 |
| Min Fy | 9 | 2 UPLIFT | 0.000 | **-7.449** | 0.000 | 0.000 | 0.000 | 0.000 |
| Max Fz | 1 | 1 DEAD LOA | 0.000 | 0.010 | **0.000** | 0.000 | 0.000 | 0.000 |
| Min Fz | 1 | 1 DEAD LOA | 0.000 | 0.010 | **0.000** | 0.000 | 0.000 | 0.000 |
| Max Mx | 1 | 1 DEAD LOA | 0.000 | 0.010 | 0.000 | **0.000** | 0.000 | 0.000 |
| Min Mx | 1 | 1 DEAD LOA | 0.000 | 0.010 | 0.000 | **0.000** | 0.000 | 0.000 |
| Max My | 1 | 1 DEAD LOA | 0.000 | 0.010 | 0.000 | 0.000 | **0.000** | 0.000 |
| Min My | 1 | 1 DEAD LOA | 0.000 | 0.010 | 0.000 | 0.000 | **0.000** | 0.000 |
| Max Mz | 1 | 1 DEAD LOA | 0.000 | 0.010 | 0.000 | 0.000 | 0.000 | **0.000** |
| Min Mz | 1 | 1 DEAD LOA | 0.000 | 0.010 | 0.000 | 0.000 | 0.000 | **0.000** |

## 5.3 STAAD FOUNDATION

Input Parameters

Geometrical Description






**Anchor Bolt Data**

| | |
|---|---|
| Bolt Circle Diameter (BCD): | 1.940 m |
| Bolt Diameter (BD): | 0.045 m |
| Sleeve Diameter (SD): | 0.075 m |
| Number of Anchor Bolts ($N_b$): | 18 |
| Effective Embedment Depth ($h_{eff}$): | 1.000 m |

Fig.6 Modeling in STAAD Foundation

## 5.4 DESIGN

The following files depict the design of pedestal and footing in STAAD Foundation.

### Pedestal Design

| | |
|---|---|
| Minimum Pedestal Dimension: | 2.680 m |
| $D_p > D_{p\_min}$, | Hence O.K. |
| Critical Load Case for Pedestal Design : | 29 |
| Factored O.T.M. At Base Of Pedestal : | 1094.763 kNm |
| Nominal Axial Load (Empty/Operating) : | 188.999 kN |
| Dowel Circle Diameter ($D_c$): | 2.674 m |
| Number of Dowels ($N_d$): | 33 |

**Pedestal Dowel Calculation**

Tensile Force In Each Dowel Per PIP STC03350 4.5.4

$$F_u = 4 \times \frac{(M_{uped})}{N_d \times DC} - 0.9 \times \frac{[(P) + D_p]}{N_d} =$$ 37.981 kN

Area of Dowel Bar Required

$$A_s = \frac{F_u}{\Phi \times f_y} =$$ 105.197 sq. mm

Minimum Dowel Reinforcement per PIP STC03350 4.5.5 : Φ16 - 24

Footing Design

## Reinforcement Calculation

| | |
|---|---|
| Required development length for bars $\frac{0.87 \times d_b \times f_y}{4 \times beta \times \sqrt{f_{cu}}}$ : | 1.504 m |
| Available development length for bars (From face of Pedestal to face of Footing) : | 1.610 m |

| | |
|---|---|
| $\beta$ : | 1.000 |
| $A_{st}$ % (Minimum) : | 0.120 |
| $A_{st}$ % (Balanced) : | 0.000 |
| $A_{st}$ % (Maximum) : | 4.000 |
| Effective depth : | 1.795 m |
| $X_{umax}$ /D : | 0.479 |
| Moment : | 0.025 kNm/m |
| $A_{st}$ % (Required) : | 0.12000 |
| Minimum Spacing : | 25.000 mm |
| Maximum Spacing : | 450.000 mm |
| Spacing Required : | 450 mm c/c |
| Bar Size : | 25 mm |

**CHAPTER 6**

**RESULTS AND DISCUSSIONS**

## 6.1 GENERAL

In the present chapter the design results are presented which is an outcome from the manual calculation done in the previous chapter. This chapter presents the results and discussions of the study.

## 6.2 DATA ON SUB-STRUCTURE

### 6.2.1 PEDESTAL

Table 6: Pedestal data for the vertical vessel

| | |
|---|---|
| SIZE | 2.48m |
| LENGTH OF EACH SIDE | 1.03m |
| LENGTH OF DIAMETER | 2.68m |
| DEPTH BELOW GROUND LEVEL | 1.3m |
| PROJ. ABOVE GROUND LEVEL | 0.3m |
| AREA | 5.09m$^2$ |

### 6.2.2 ANCHOR BOLT

Table 7: Anchor Bolt data for the vertical vessel

| | |
|---|---|
| GRADE | 4.6 |
| DIAMETER | 45mm |
| YIELD CAPACITY | 400 MPa |
| TENSILE STRENGTH | 240 MPa |

#### 6.2.3 FOOTING

Table 8: Footing data for the vertical vessel

| | |
|---|---|
| SIZE | 6m |
| LENGTH OF EACH SIDE | 2.485m |
| LENGTH OF DIAMETER | 6.5m |
| HEIGHT | 0.4m |
| AREA | 29.82m$^2$ |

### 6.3 PLAXIS ANALYSIS

The analysis of the foundation is carried out using plaxis software to check whether the soil underneath is failing under shear or not. In our case no shear failure of soil is seen.

Table 9: Soil parameters assumed during plaxis analysis

| | |
|---|---|
| IDENTIFICATION | SAND |
| MATERIAL MODEL | MOHR-COULOMB |
| MOIST UNIT WEIGHT | 18 KN/m$^3$ |
| COHESION | 0.2 KN/m$^2$ |
| ANGLE OF INTERNAL FRICTION | 30$^o$ |
| POISSION’S RATIO | 0.35 |

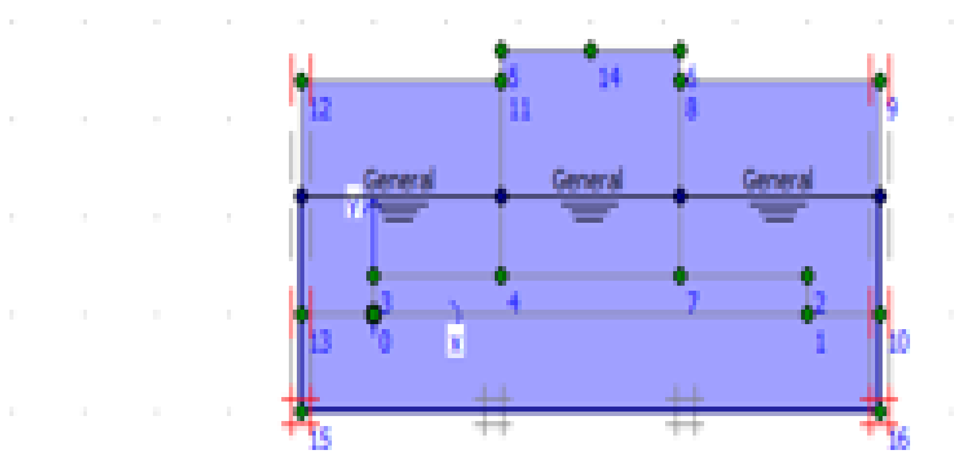



**Fig**. 7 Plaxis Modeling

## 6.4 DISCUSSIONS

- Octagonal foundation is adopted whenever size of pedestals having a diameter or least dimension across sides that is equal to or greater than 1.5m.
- Unlike a rectangular footing where calculation of section modulus is quite easy, for an octagonal foundation it becomes very difficult.
- While modeling the foundation in Staad pro, a plate model is adopted with different thickness for both the pedestal and the footing.
- Since there is no proper specification for anchor bolt design, we have taken the help of STE03350 - Vertical Vessel Foundation Design Guide guidelines.

# CHAPTER 7

# SUMMARY AND CONCLUSION

## 7.1 SUMMARY

The objective of the present report is identified as to evaluate the manual method of design procedure as given in Process Industry Practices for vessel foundation. To achieve this analysis case study of a typical vertical vessel superstructure is carried out considering wind and seismic loads. Then the foundation of the vessel is designed with the base forces using the manual method given in Process Industry Practices. This includes design for the anchor bolts, pedestal and footing. The footing is checked for one-way and punching shear, stability and soil bearing. The same foundation modeled in different commercial finite element software (STAAD-Pro, STAAD-Foundation and Plaxis) and analyzed. Performance of the designed foundation as obtained from the finite element analysis is then compared with that obtained from manual calculations.

## 7.2 CONCLUSIONS

Following is the important conclusions made from the present study:

1) Maximum bending moment obtained from the FE software for the given support forces are found to be higher than those calculated manually according to Process Industry Practices guideline. Therefore, the design process outlined in PIP underestimates the bending moment demand as per the present study. This may be due to the modeling of soil stiffness in the FE software.

## 7.3 SCOPE FOR FUTURE WORK

1) The present study is based on one typical case study. There is a provision for repeating this study considering a large number of foundations with varying parameters to arrive at a more comprehensive conclusion.

2) The study can be extended considering piles-supported footings.

**REFERENCES**

1. Horn, D (2004) “Monopole Base Design”, Technical Manual 1, C-Concepts, Inc.
2. STE03350 - Vertical Vessel Foundation Design Guide; Process Industry Practices
3. ACI committee 318 (2005) Building Code Requirements of Reinforced Concrete, American Concrete Institute, Detroit
4. IS 456 (2000) Indian Standard Code of Practice for Plain and Reinforced Concrete, Bureau of Indian Standards, New Delhi.