Guide for Design of Substation Structures

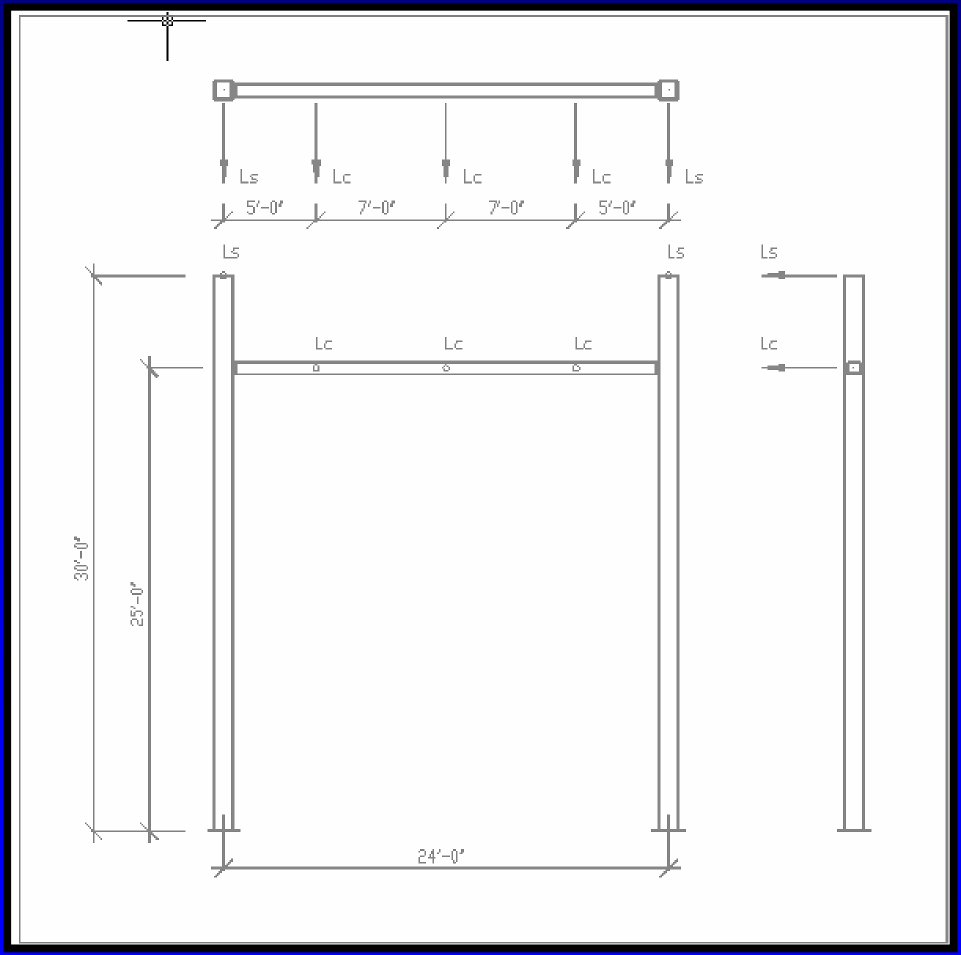
Prepared by

Substation Structure Design Guide Subcommittee,

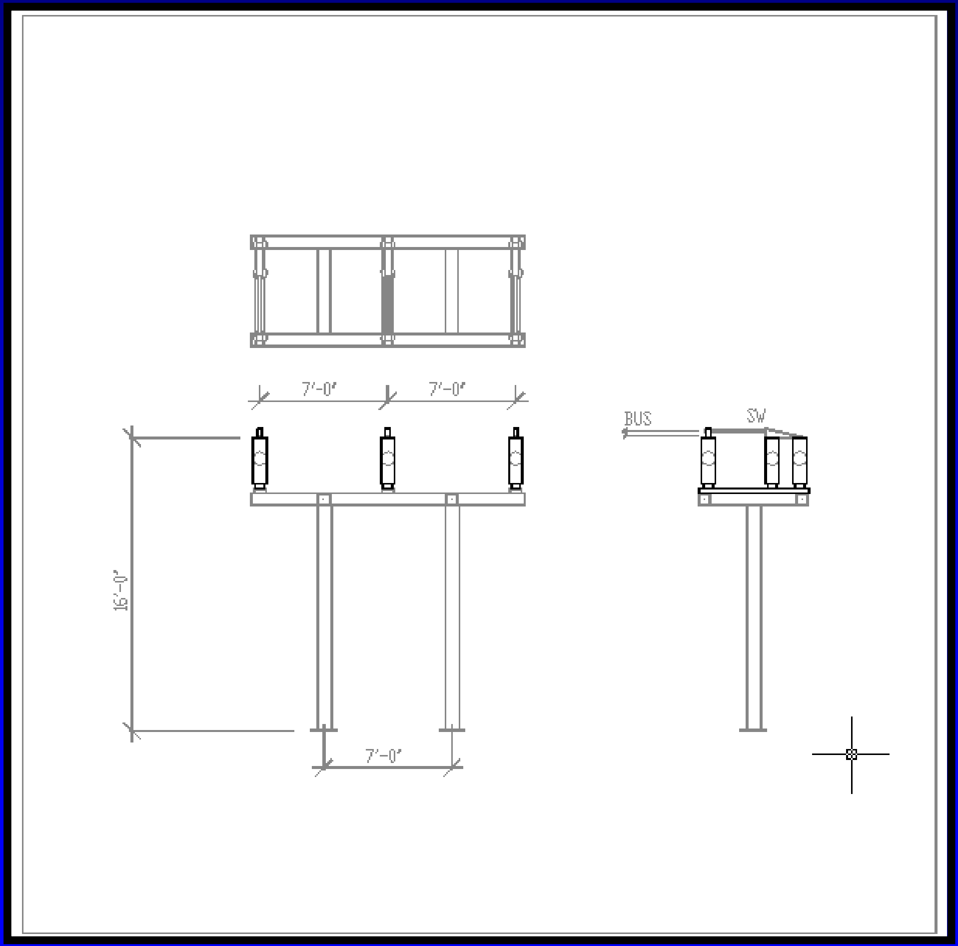
of the Committee on Electrical Transmission Structures (CETS)

TWO EXAMPLES IN THE DOCUMENT FOR DETERMINING STRUCTURE LOADS

LINE TERMINATION STRUCTURE



69 KV DISCONNECT SWITCH SUPPORT



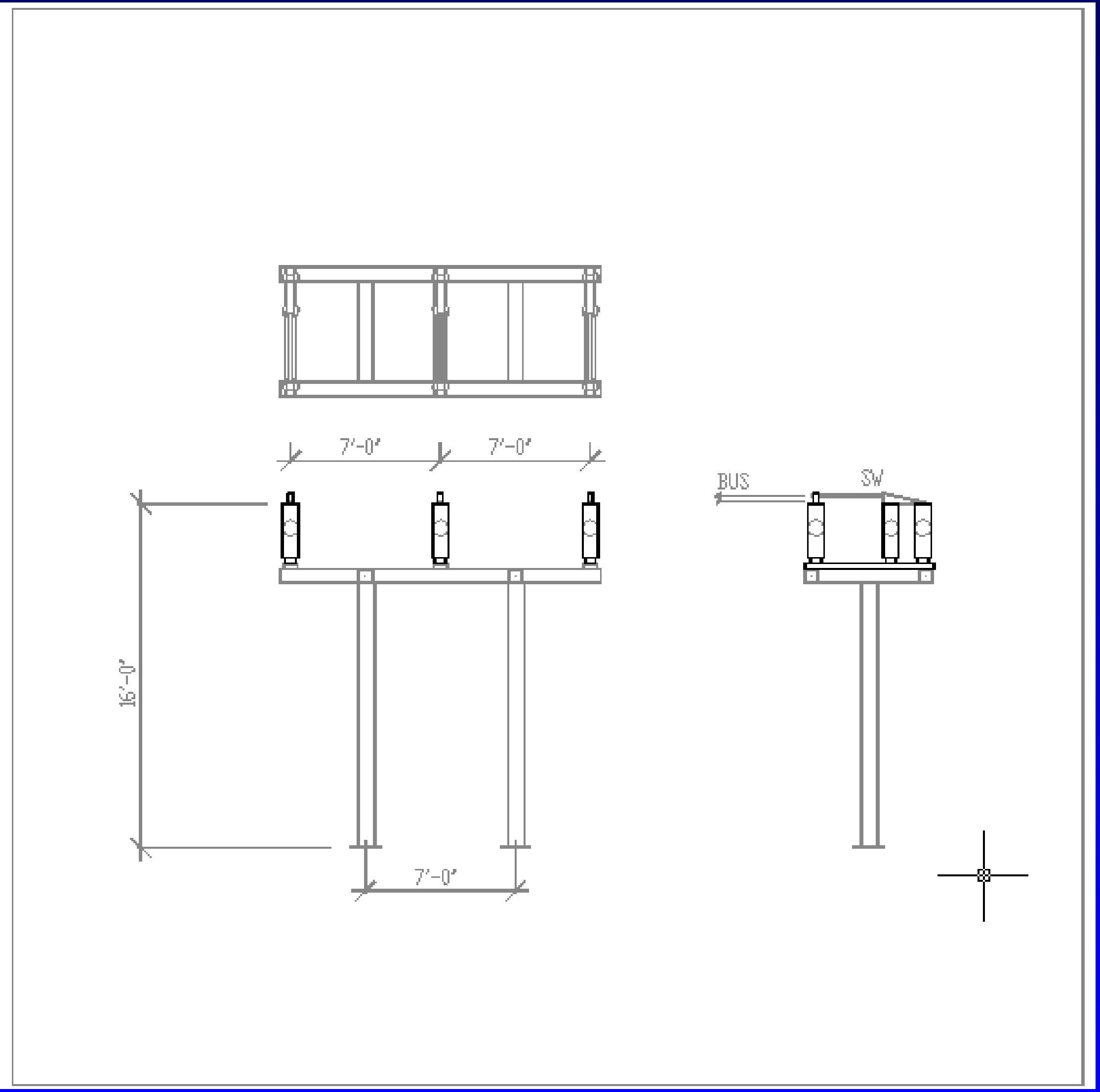


FIGURE 3.6 69kV Switch Support Structure

3.7.1 Example Load Cases for 69kV Switch Support Structure (Figure 3-6)

Load Case 1

Extreme Wind
90 mph Basic Wind Speed, 3 Sec. Gust, Exp. C
50 Year Mean Recurrence
Load factors from Table 3.17

Load Case 2

Combined Ice + Wind
40 mph Wind + 1.0 in. Ice
50 Year Mean Recurrence
Load factors from Table 3.17

Load Case 3, Earthquake

S_S=0.590 S_1=0.186

Soil Profile D

Load factors from Table 3.17

Load Case 4

Short Circuit

15kA Sym

Load factors from Table 3.17

Other Load Cases

Construction /Maintenance Loads

None considered for this example

See Section 3.2.9

Equipment operating Loads

None considered for this example

See Section 3.2.2

Table 3-17 Ultimate Strength Design Cases and Load Factors

LOAD CASES	LOAD FACTORS AND COMBINATIONS
Case 1	$1.1\ D + 1.2\ W\ I_{FW} + 0.75\ SC + 1.1\ T_W$
Case 2	$1.1\ D + 1.2\ I_W I_{FI}$*+ $1.2\ W_I I_{FWI}$** $+ 0.75\ SC + 1.1\ T_W$
Case 3	$1.1\ D + 1.0\ SC + 1.1\ T_W$
Case 4	$1.1\ D + 1.25\ E(\text{or } E_{FS}) I_{FE} + 0.75\ SC + 1.1\ T_W$

* The Importance Factor for Ice is applied to the thickness

** The Importance Factor for wind with ice is 1.0, for wind speeds obtained from Figures 3-3a, b, c, d, e, and f per ASCE 7

Note: Replace load factor 1.1 on D with 0.9 for cases in which dead load is counted on to resist other applied loads.

3.7.2 Calculation Of Loading Factors

Extreme Wind Load Case 1

69kV Switch Support Structure:

Assume a rigid structure equipment support (Section 3.2.5.5.1, Para. 2)

$G_{SRF} = 0.85$

$P_v = 0.00256 \times 0.98 \times (90\ mph)^2 \times 1.00 \times 0.85 \times C_f \times A$
$= 17.27 \times C_f \times A$
$= 17.27 \times 1.0 \times A = 17.27\ psf \times A$ wires & rigid bus
$= 17.27 \times 0.9 \times A = 15.55\ psf \times A$ circular equipment shapes (Post Insulators)
$= 17.27 \times 2.0 \times A = 34.55\ psf \times A$ square structural shapes

$I_{FW} = 1.0$: **Extreme Wind Importance Factor (50 year mean recurrence)**

Load Combination/Factors: $1.1\ D + 1.2\ W\ (1.0) + 0.75\ SC + 1.1\ T_W$ **Table 3.17**

Combined Ice and Wind, Case 2:

40 mph Wind + 1.00 in. radial Ice
D - Dead Load
T_W - Line Loads
I_W – Ice

- **Weight of ice on wires, Use 57pcf**
- **Weight of ice on equipment, Use 100% of equipment weight**
- **Weight of ice on structure, Ignore**

I_{FI} = 1.0 (50 yr mean recurrence)
I_{FWI} = 1.0 (Per ASCE -7, Figures a, b, c, d, e, and f)

69kV Switch Support Structure:

$P_V = 0.00256 \times 0.98 \times (40\ \text{mph})^2 \times 1.00 \times 0.85 \times C_f \times A$
$= 3.41 \times C_f \times A$
$= 3.41 \times 1.0 \times A = 3.41$ psf x A wires & rigid bus
$= 3.41 \times 0.9 \times A = 3.07$ psf x A circular equipment shapes
$= 3.41 \times 2.0 \times A = 6.82$ psf x A square structural shapes

Load Combination/Factors:
$1.1\ D + 1.2\ I_W\ I_{FI} + 1.2\ W_I(1.0) + 0.75\ SC + 1.1\ T_W$ **Table 3.17**

Short Circuit Load, Case 3

$F_{SC} = 3.596\ \gamma\ I_{SC}^2 / (10^7\ D)$ IEEE 605 (Applicable Equation and design parameters to be recommended by the Electrical Engineer)

γ = 1.00 phase-phase

I_{SC} = 15kA = 15,000A

D = 7 feet

$F_{SC} = 3.596 \times 1 \times (15{,}000A)^2 / (10^7 \times 7\ ft.)$

$F_{SC} = 11.6$ plf

Load Combination/Factors: $1.1\ D + 1.0\ SC + 1.1\ T_W$ Table 3.17

Earthquake Load, Case 4

$F_a = 1.33$ Table 3-12, Site Class D, S_S=0.590 – by interpolation

$F_v = 2.06$ Table 3-13, Site Class D, S_1=0.186 – by interpolation

$S_{DS} = 2/3\ F_a\ S_S$ Eq. 3-6

$S_{DS} = 2/3 \times 1.33 \times 0.590$

$S_{DS} = 0.523$

$S_{D1} = 2/3\ F_v\ S_1$ Eq. 3-7

$S_{D1} = 2/3 \times 2.06 \times 0.186$

$S_{D1} = 0.255$

$S_a = S_{DS} = 0.523$ for $T < S_{D1}/S_{DS}$ Eq. 3-8

$S_a = S_{D1}/T = 0.255/T$ for $T > S_{D1}/S_{DS}$ Eq. 3-9

For these example assume $S_a = S_{DS}$ controls

$S_a = S_{DS} = 0.523$

$F_E = (S_a/R)\ W\ I_{FE}\ I_{MV}$ Eq. 3-10

$F_E = (0.523/2.0) \times W \times 1.25 \times 1.0$

$F_E = 0.33\ W$

Where:

R = 2.0 for cantilever support (USD)

I_{FE} = 1.25 for essential structures & equipment

I_{MV} = 1.0 assume significant single mode response

Load Combination/Factors: $1.1\ D + 1.25\ E + 0.75\ SC + 1.1\ T_W$ Table 3.17

3.7.4 69kV Switch Support Structure (Figure 3.6), Calculation of Individual Load Components

69kV Disconnect Switch

- **Weight = 500 lbs./phase**
- **Wind area = Estimate, 10 sq. ft.**

Rigid Bus 3" Standard Bus Size (sps) AL (266.8 MCM ACSR damper)

- **Span = 30 feet**
- **Diameter = 3.5 inches**
- **Weight = 2.991 plf**
  = (Bus wt. 2.621 plf + Damper wt. 0.370 plf)

Structural members –Square Hollow Structural Section, HSS

Extreme Wind Load, Case 1

D (Dead Load)

D_{SW} = 500 lbs./ Phase

D_{BUS} = 2.991 plf x (30 ft. / 2) = 45 lbs./Phase

$D_{Structure}$

T_w (Wire Tension): N/A

W (Wind Load)

W_{SW} = 15.55 psf x 10 sq. ft. = 156 lbs./Phase

W_{BUS} =17.27 psf x (3.50 in. x 30 ft. / 2 / (12 in/.ft.))
= 227 lbs./Phase

$W_{Structure}$ = 34.55 psf x $A_{Structure}$

Extreme Wind Importance Factor: I_{FW} = 1.0

Short Circuit Load

SC_{BUS} = 11.6 plf x 30 ft. / 2 = 167 lbs.

Load Combination/Factors: 1.1 D +1.2 W(1.0) + 0.75 SC

Combined Ice and Wind Load Case 2

D (Dead Load)

D_{SW} = 500 lbs./Phase

D_{BUS} = 45 lbs./Phase

$D_{Structure}$

I (Ice Load)

I_{BUS} = 57pcf (∏ $(5.50^2 - 3.50^2)$/4 sq. in. x 30 ft./2/(12 in./ft.)2)

= 84 lbs./Phase

$I_{Structure}$= 0

I Ice Importance Factor: I_{FI} = 1.0

T_w (Wire Tension): T_w = N/A

W_{WI} (Wind Load in combination with Ice)

W_{SW} = 3.07 psf x 10 sq. ft. = 31 lbs./Phase

W_{BUS} = 3.41 psf x (5.50 in. x 30 ft. / 2 / (12in./ft.)) = 23 lbs./Phase

$W_{Structure}$ = 6.82 psf x $A_{Structure}$ (Without Ice)

Short Circuit Load

SC_{BUS} = 8.1 plf x 30 ft. / 2 = 122 lbs.

Load Combination/Factors: 1.1 D + 1.2 I (1.0) + 1.2 W_{WI} + 0.75 SC

Earthquake Load Case 4

D (Dead Load)

D_{SW} = 500 lbs./Phase

D_{BUS} = 45 lbs./Phase

$D_{Structure}$

T_w (Wire Tension): T_w = N/A

E (Earthquake Load)

E_{SW} = 0.33 x 500 lbs. = 165 lbs./Phase

E_{BUS} = 0.33 x 45lbs. = 15 lbs./Phase

$E_{Structure}$ = 0.33 W lbs.

Short Circuit Load

SC_{BUS} = 8.1 plf x 30 ft. / 2 = 122 lbs.

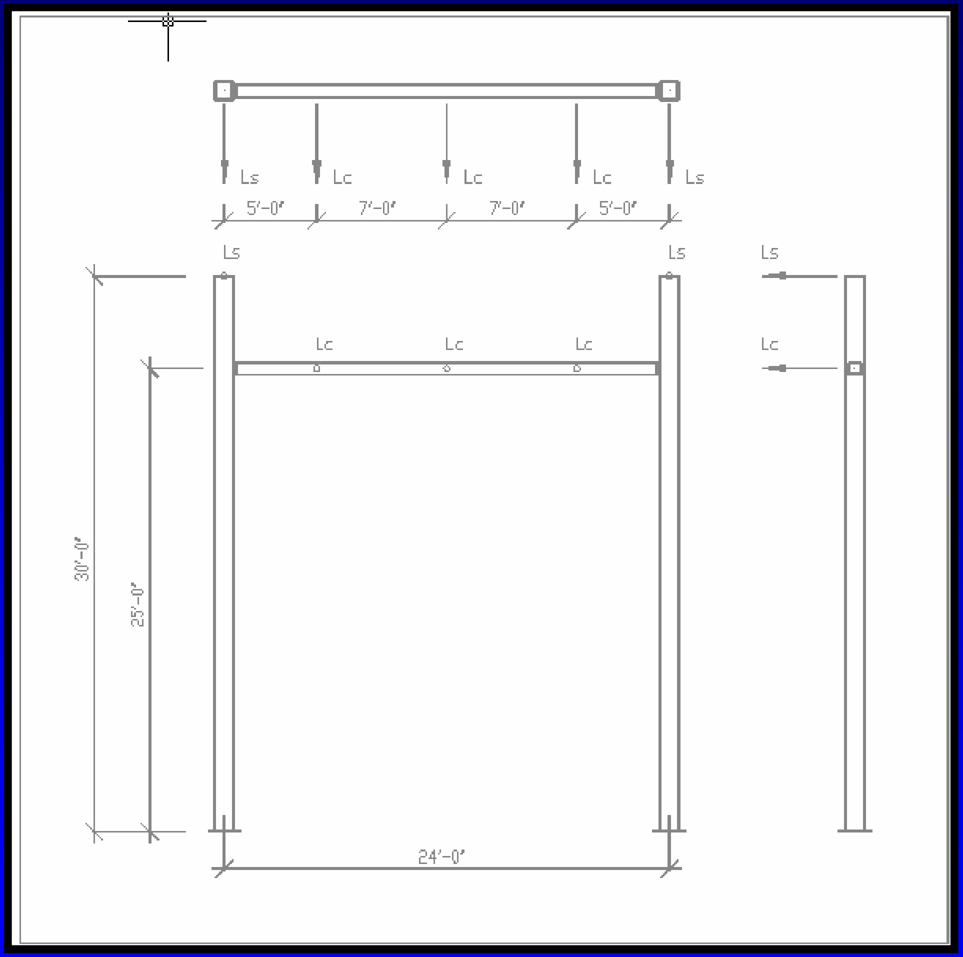
Load Combination/Factors: 1.1 D +1.25 E + 0.75 SC

Short Circuit Load Case 3

Load Combination/Factors: 1.1 D +1.00 SC_{Bus}+ 1.1 T_w

The designer would apply these load combinations to the structure. Then, using the appropriate analysis method, the member stresses are checked. The deflection load cases would be developed and the deflection limits of Section 4.0 checked.

LINE TERMINATION STRUCTURE



Load Case
NESC Heavy, Grade B (Dead-end Structure)
4 psf Wind + 0.5 in. radial Ice
Load factors from NESC (ANSI C2)

Load Case 1
Extreme Wind
90 mph Basic Wind Speed, 3 Sec. Gust, Exp. C
50 Year Mean Recurrence
Load factors from Table 3.17

Figure 3.5, Dead-End Structure

Extreme Wind Load Case 1

Extreme Wind – 90 mph , Exp C
D - Dead Load
T_W - Line Loads
W – Wind

$P_V = Q\, k_Z\, V^2\, I_{FW}\, G_{RF}\, C_f\, A$

$Q = 0.00256$

$k_Z = 0.98$ see Table 3.1 - H=30 ft., Exp C

$V = 90$ mph Given

$I_{FW} = 1.00$ see Table 3-3 - 50 Yr.

$G_{SRF} = 0.96$ see Table 3-4a (Wire-support Structure), H<33 ft., Exp C

$G_{WRF} = 0.92$ see Table 3-6b, H<33 ft., Exp C, 100 ft.= L< 250 ft.

$C_f = 1.0$ Table 3-7 (aspect ratio > 40) for wires & rigid bus

$C_f = 0.9$ Table 3-9 for circular equipment shapes

$C_f = 2.0$ Table 3-9 for square structural shapes

Extreme Wind Load Case 1

Dead-End Structure:

$V = 0.00256 \times 0.98 \times (90\ mph)^2 \times 1.00 \times 0.96 \times C_f \times A$

$= 19.5 \times C_f \times A$

$= 19.5 \times 1.0 \times A = 19.5$ psf x A wires & rigid bus

$= 19.5 \times 0.9 \times A = 17.6$ psf x A circular equipment shapes

$= 19.5 \times 2.0 \times A = 39.0$ psf x A square structural shapes

$I_{FW} = 1.0$: Extreme Wind Importance Factor (50 year mean recurrence)

Load Combination/Factors: 1.1 D +1.2 W (1.0) + 0.75 SC +1.1 TW Table 3.17

Table 3-4a Structure Response Factor, G_{SRF}, Wire Supporting Structures, $\varepsilon = 0.75$

Height, h (ft)	Exposure B	Exposure C	Exposure D
≤ 33	1.17	0.96	0.85
> 33 to 40	1.15	0.95	0.84
> 40 to 50	1.12	0.94	0.84
> 50 to 60	1.08	0.92	0.83
> 60 to 70	1.06	0.91	0.82
> 70 to 80	1.03	0.89	0.81
> 80 to 90	1.01	0.88	0.81
> 90 to 100	1.00	0.88	0.80

Table 3-4b Structure Response Factor, $G_{SRF,}$ Flexible Non-wire Supporting Structures, $\varepsilon = 1.0$

Height, h (ft)	Exposure B	Exposure C	Exposure D
≤ 15	1.59	1.20	1.02
> 15 to 33	1.48	1.15	0.99
> 33 to 40	1.37	1.11	0.96
> 40 to 50	1.33	1.08	0.95
> 50 to 60	1.28	1.06	0.94
> 60 to 70	1.25	1.05	0.93
> 70 to 80	1.22	1.03	0.92
> 80 to 90	1.19	1.02	0.91
> 90 to 100	1.17	1.00	0.90

$$G_{SRF} = \left(1 + 3.6\,(\varepsilon)\,E_S\,(B_S)^{0.5}\right) / k_v^{\,2}$$

(Eq. 3-3)

Where:

ε = 0.75 Wire Supporting Structures (Dead-end and Line Termination)

ε = 1.00 Flexible Non-Wire Supporting Structures, < 1 Hertz

EXAMPLES

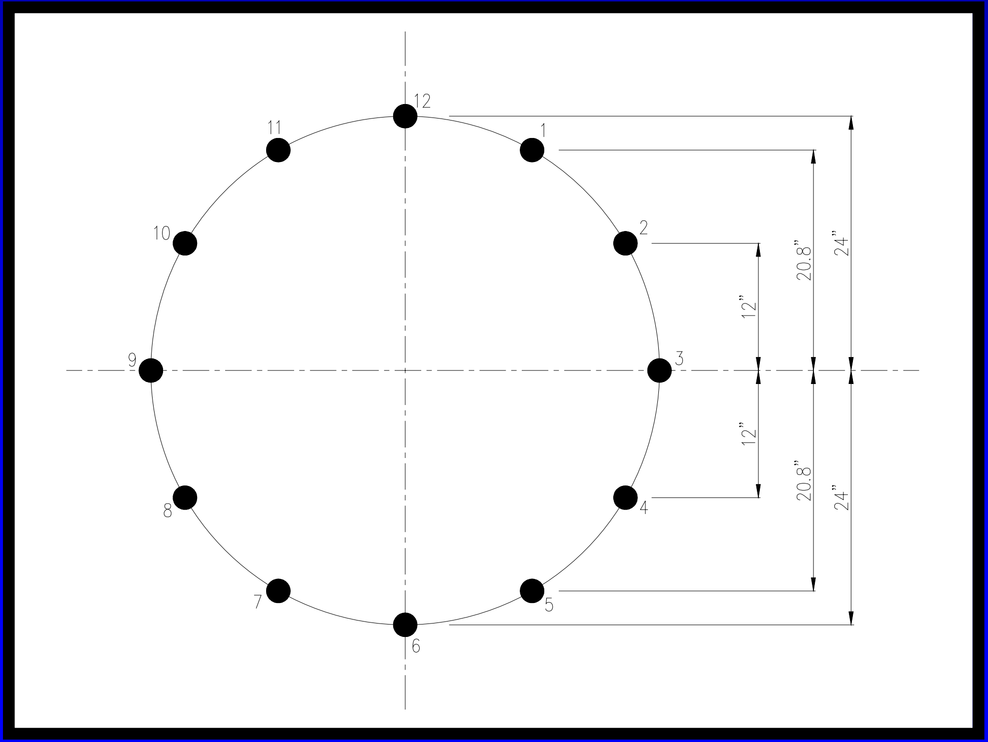
1. BASE PLATE ON CONCRETE
2. BASE PLATE ON LEVELING NUTS
3. **BASE PLATE ON LEVELING NUTS IN A DRILLED PIER**

7.6.3 Baseplate on Leveling Nuts in a Drilled Pier.

(Distance from top of concrete to bottom of baseplate (h) < 2 times bolt diameter.)

Structure Type: Single Pole Dead-End Structure, 12 Anchor Bolts on a 48 in. Bolt Circle, ASTM A615, Jumbo, Grade 75 Rebar

(F_y = 75 ksi, F_{ut} = 100 ksi)



Applied load with load factors

$P_u = 34$ kips
$V_u = 46$ kips
$M_u = 2380$ ft-kips

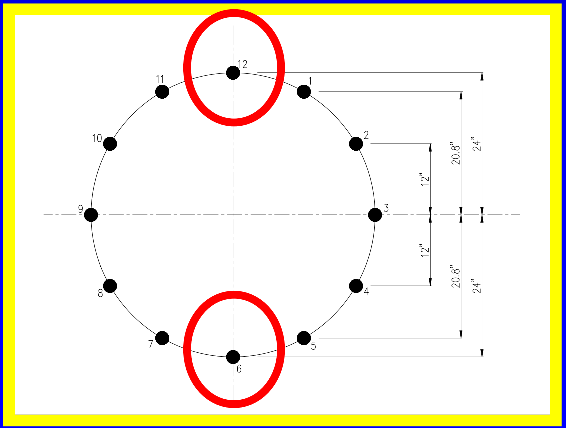
Calculate load per bolt

$$P_u = \frac{34 \text{ kips}}{12 \text{ Bolts}} = 2.83 \text{ kips}$$

$$V_u = \frac{46 \text{ kips}}{12 \text{ Bolts}} = 3.83 \text{ kips}$$

Maximum bolt load

$$P_6 = P_{12}$$



$$P_{12} = \frac{M_u d_{12}}{\Sigma d^2_{1\,to\,12}} = \frac{2380\ ft-kips\,(12''/\,ft)(24'')}{4(12'')^2 + 4(20.8'')^2 + 2(24)^2} = 198\ kips$$

$$\mathrm{P_{TOTAL}} = 2.83\ \mathrm{kips} + 198\ \mathrm{kips} = 201\ \mathrm{kips}$$

$$\mathrm{A_a} = \frac{\mathrm{P_u}}{\mathrm{f_{dt}}} = \frac{\mathrm{P_u}}{\phi \mathrm{f_y}} = \frac{201\ \mathrm{kips}}{0.9(75\ \mathrm{ksi})} = 2.98\ \mathrm{in}^2\ \langle \mathrm{CONTROLS} \rangle$$

or

$$\mathrm{A_a} = \frac{\mathrm{P_u}}{0.8\mathrm{f_{ut}}} = \frac{201\ \mathrm{kips}}{0.8(100\ \mathrm{ksi})} = 2.51\ \mathrm{in}^2$$

$$\mathrm{A_\upsilon} = \frac{\mathrm{V_u}}{\phi \mathrm{f_y}} = \frac{3.83\ \mathrm{kips}}{0.85(75\ \mathrm{ksi})} = 0.06\ \mathrm{in}^2$$

$$\mathrm{A_s} = \mathrm{A_a} + \mathrm{A_\upsilon} = 2.98\ \mathrm{in}^2 + 0.06\ \mathrm{in}^2 = 3.04\ \mathrm{in}^2$$

REQUIRED AREA

A_s required 3.04 in^2
Use No. 18 Jumbo (#18J), Grade 75 (A_s = 3.25 in^2)

Development of Deformed Bars in Tension, ACI-318 12.2.2

$$l_d = d_b \frac{f_y \Psi t \Psi e \lambda}{20\sqrt{f_c'}} = 2.25 \frac{75{,}000(1)(1)(1)}{20\sqrt{4000\ psi}} = 133.4\ in$$

l_d = 133.4 in. Use 134 in.
Reduction for (A_s required) / (A_s provided) from ACI 318 12.2.5
As required = 3.25 in^2 (Use actual #18J bar A_s of thread area)
As provided = 4.00 in^2 (area of #18J bar)

$$l_d = 134\ in\left(\frac{3.25}{4.00}\right) = 108'' = 9'\!-\!1''\ Embedment$$

THE END