

# The optimization design of Piled raft foundation for substation building in US code

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**Abstract:** In order to get a more safety and economic foundation, finite element method was performed for a piled mat cap and piled strip cap by the software of STAAD. Through the finite element analysis, plate distribution region of bending moment and shear stress were researched; meanwhile, considering the compatibility of deformation of element plate, how to chose the design value of plate stress was researched. The result showed that: single plate value is not representative , average of value of 9 plates (3x3 array) is close to the fact. Strip cap is better than mat cap both from the moment value and shear value of plate element in this project; strip cap was recommended due to its remarkable economic benefit.

## 1 Introduction

Substation building is an essential facility in the substation, which ensures the reliability of urban power supply. Figure 1 is a building of 230kV substation in the Philippines. The substation building is a fifth-layer concrete frame structure, which is 26.8 meters high. 230kV gantry on the top of substation building , which is 21 meters high. Pile foundation was used in substation building. Pile arrangement and pile cap types were the major work for the engineer designer<sup>[1]</sup>.



Figure 1. substation building in the Philippines

## 2 Design input condition

### 2.1 Wind load

- 1) Wind load maximum wind speed (3seconds gust speed at 10m height above soil) is 75m/s.
- 2) Exposure category D.
- 3) Structure Category II.
- 4) Gust effect factor  $G=0.85$ .

### 2.2 Seismic loads

Seismic zone factor  $Z=0.4$ , Soil type  $S_D$ , Seismic source type B.

$R$ (response modification factor) for substation building the structure system should choose Special moment-resisting frame, the value of  $R$  is 8.5; refer to steel supports (non-buildings structures not similar to buildings), proposed  $R$  will be 3 for gantries<sup>[2]</sup>.

### 2.3 Load combinations

This project was suggested to design with US code, both Ultimate Limit State and Serviceability Limit State should be considered in piled raft foundation design<sup>[3]</sup>. The ULS and SLS load general combinations according to contractual specifications are based on ASCE7-10.

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### 2.4 Pile parameter

This project uses pile foundation. Type of the pile and single pile capacity are shown in the following:

- Type of pile : cast-in-situ bored pile.
- Pile diameter:800mm.
- Allowable compressive capacity: 1340kN.
- Allowable tensile capacity: 615kN.
- Allowable lateral capacity: 70kN.

### 3 Calculation principle<sup>[4-6]</sup>

Staad Pro V8i(SS6) software shall be adopted for substation building structure analysis and design. The strength design and allowable stress design were adopted for the analysis. The STAAD plate finite element is based on hybrid finite element formulations. A complete quadratic stress distribution is assumed. For plane stress action, the assumed stress distribution is as follows.

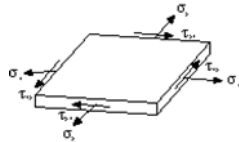


Figure 2. Assumed stress distribution

$$\begin{pmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{pmatrix} = \begin{bmatrix} 1 & x & y & 0 & 0 & 0 & 0 & x^2 & 2xy & 0 \\ 0 & 0 & 0 & 1 & x & y & 0 & y^2 & 0 & 2xy \\ 0 & -y & 0 & 0 & 0 & -x & 1 & -2xy & -y^2 & -x^2 \end{bmatrix} \begin{pmatrix} a_1 \\ a_2 \\ a_3 \\ \vdots \\ a_{10} \end{pmatrix}$$

Figure 3. Complete quadratic assumed stress distribution

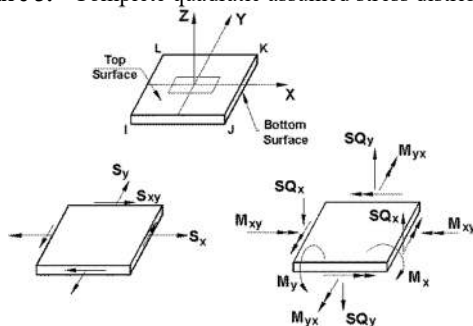
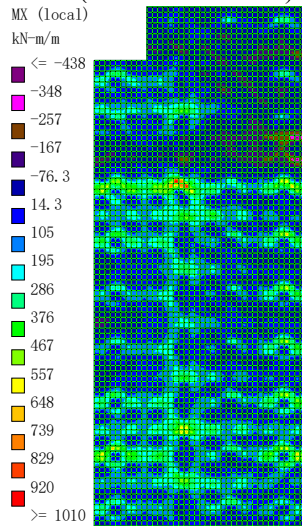


Figure 4. Sign convention of element forces  
 S<sub>qx</sub>, S<sub>qy</sub> : Shear stresses (Force/ unit len./thk.)  
 S<sub>x</sub>, S<sub>y</sub>, S<sub>xy</sub>: Membrane stresses (Force/unit len./thk)



M<sub>x</sub>, M<sub>y</sub>, M<sub>xy</sub>: Bending moments per unit width (Moment/unit len.)

### 4 Project Design

The customer suggest us use mat pile cap. We wanted to optimize the pile cap. So we suggest two schemes to piled raft cap design of substation building. One is mat cap ,another is strip cap. The analysis model is shown in the following figure.

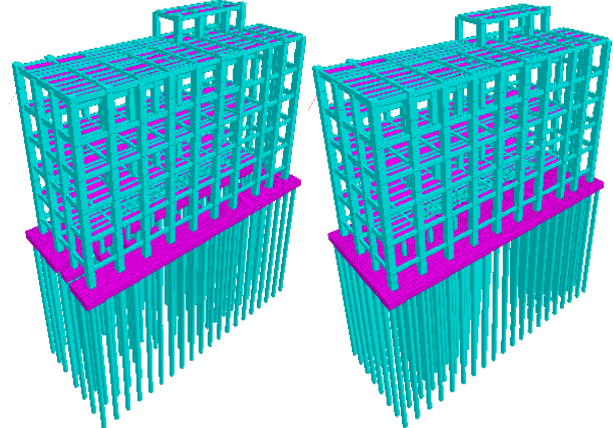


Figure 5. Two schemes model for substation building

The parameter of pile and pile cap is shown in the following table. In order to get accurate result, cap plates were meshed to square plate element, which is 0.5m x 0.5m.

Table1. Two schemes model for substation building

Parameter	Mat	Strip
pile number	156	137
cap area	955m <sup>2</sup>	756.2m <sup>2</sup>
cap thickness	1.1m	1.1m
meshing size	0.5m	0.5m

#### 4.1 Bending moment

The result of bending moment for piled raft cap is shown in the following figure.

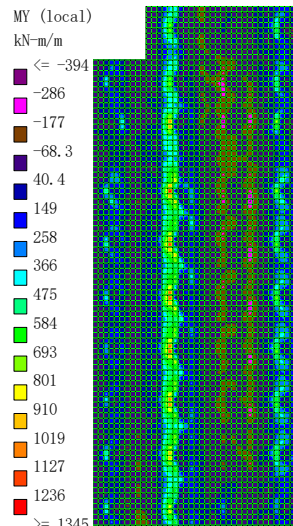
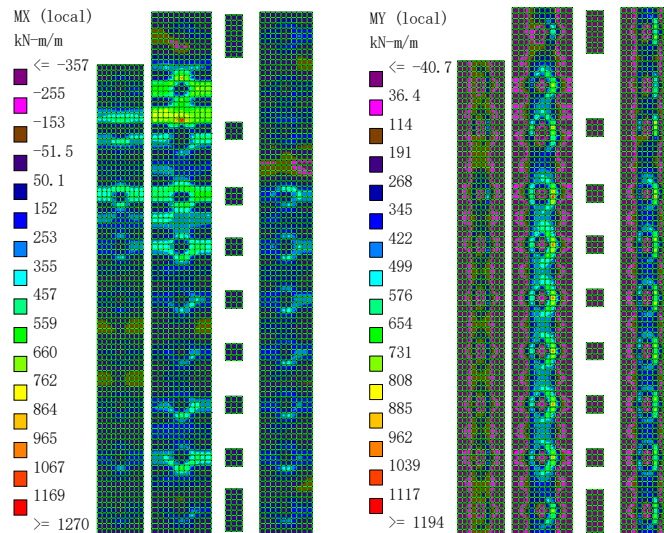


Figure 6. Color nephogram of bending moment M<sub>x</sub> and M<sub>y</sub> for mat cap



**Figure 7.** Color nephogram of bending moment  $M_x$  and  $M_y$  for strip cap

**Table2.** Maximum value of bending moment

Moment	Mat	Strip
	(kN-m/m)	
$M_x$ -top	1010	1270
$M_x$ -bot	-438	-540
$M_y$ -top	1345	1194
$M_y$ -bot	-671	-224

We used the Wood-Armer equations for reinforcement calculations<sup>[7]</sup>, as follows: $M_x$ ,  $M_y$ , and  $M_{xy}$  are calculated, by STAAD. They are used to compute the values of design moments,  $M_{xd}$  and  $M_{yd}$ .

For top reinforcement, we computes:

$$M_{x1} = M_x + \text{abs}(M_{xy})$$

$$M_{y1} = M_y + \text{abs}(M_{xy})$$

$$M_{x2} = M_x + \text{abs}(M_{xy} / M_y)$$

$$M_{y2} = M_y + \text{abs}(M_{xy} / M_x)$$

If both  $M_{x1}$  and  $M_{y1}$  are positive,  $M_{xd} = M_{x1}$  and  $M_{yd} = M_{y1}$ .

If both  $M_{x1}$  and  $M_{y1}$  are negative,  $M_{xd} = 0$  and  $M_{yd} = 0$ .

If  $M_{x1}$  is negative and  $M_{y1}$  positive,  $M_{xd} = 0$  and  $M_{yd} = M_{y2}$ .

If  $M_{y1}$  is negative and  $M_{x1}$  positive,  $M_{xd} = M_{x2}$  and  $M_{yd} = 0$ .

For bottom reinforcement:

$$M_{x1} = M_x - \text{abs}(M_{xy})$$

$$M_{y1} = M_y - \text{abs}(M_{xy})$$

$$M_{x2} = M_x - \text{abs}(M_{xy} / M_y)$$

$$M_{y2} = M_y - \text{abs}(M_{xy} / M_x)$$

If both  $M_{x1}$  and  $M_{y1}$  are positive,  $M_{xd} = 0$  and  $M_{yd} = 0$ .

If both  $M_{x1}$  and  $M_{y1}$  are negative,  $M_{xd} = M_{x1}$  and  $M_{yd} = M_{y1}$ .

If  $M_{x1}$  is negative and  $M_{y1}$  positive,  $M_{xd} = M_{x2}$  and  $M_{yd} = 0$ .

If  $M_{y1}$  is negative and  $M_{x1}$  positive,  $M_{xd} = 0$  and  $M_{yd} = M_{y2}$ .

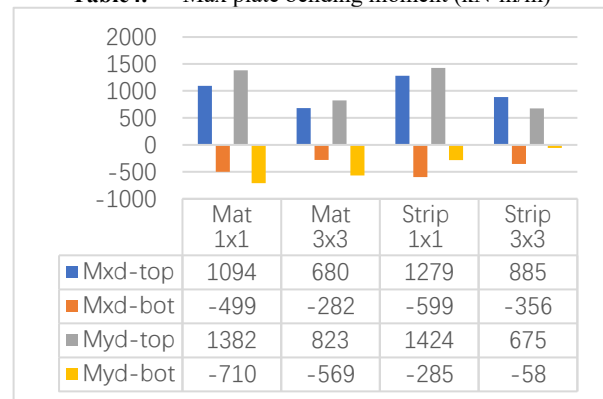
**Table3.** Maximum value of bending moment for design

Moment	Mat	Strip
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	(kN-m/m)	
$M_{xd}$ -top	1094	1279
$M_{xd}$ -bot	-499	-599
$M_{yd}$ -top	1382	1424
$M_{yd}$ -bot	-710	-285

The color nephogram of bending moment showed that only a few moment value of plates reached the maximum value. Consider the compatibility of deformation of element plate, the average of value of nearest 9 plates (3x3 array) was performed as the design value conservatively, which made the calculate results close to the fact.

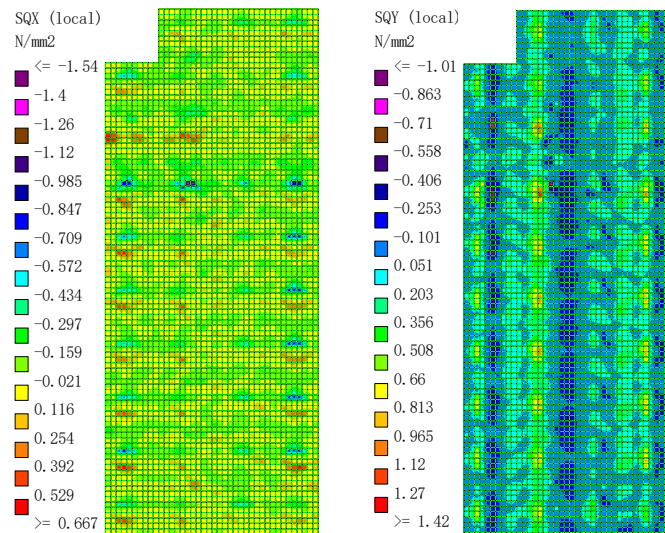
**Table4.** Max plate bending moment (kN-m/m)



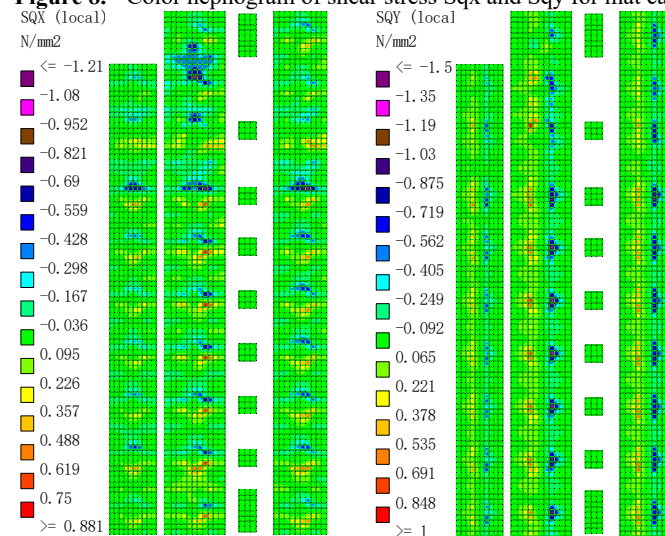
From the table above, mat cap plate top value of moment are 823 and 680 , strip cap plate top value of moment are 885 and 675 . The moment on the top plate of Strip cap increase 7.5% than the moment of mat cap. Mat cap plate bottom value of moment are -569 and -282, strip cap plate top value of moment are -356 and -58 . The moment on the bottom plate of Strip cap reduce 37.4% than the moment of mat cap. Strip cap is better than mat cap from the moment value of plate element.

#### 4.2 Shear stress

The result of shear stress for piled raft cap is shown in the following figure.



**Figure 8.** Color nephogram of shear stress Sqx and Sqy for mat cap

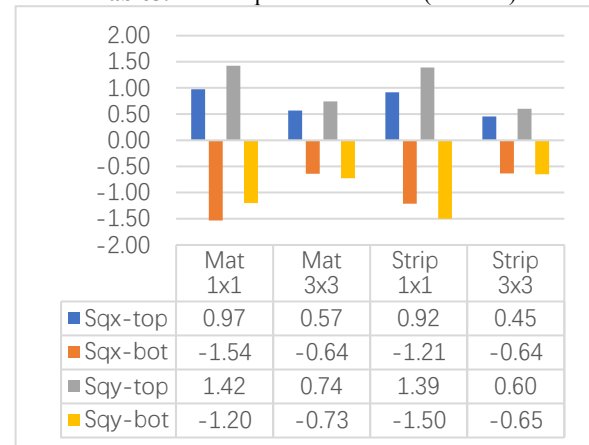


**Figure 9.** Color nephogram of shear stress Sqx and Sqy for strip cap

The color nephogram of shear stress showed that only a few stress value of plates reached the maximum value. Consider the compatibility of deformation of element plate, the average of value of nearest 9 plates (3x3 array) was performed as the design value conservatively, which made the calculate results close to the fact.

From the table below, mat cap plate top value of shear stress are 0.74 and 0.57, strip cap plate top value of shear stress are 0.6 and 0.45. The shear stress on the top plate of Strip cap reduce 18.9% than the shear stress of mat cap. Mat cap plate bottom value of shear stress are -0.73 and -0.64, strip cap plate top value of shear stress are -0.65 and -0.64. The shear stress on the bottom plate of Strip cap reduce 11.0% than the shear stress of mat cap. Strip cap is better than mat cap from the shear stress value of plate element.

**Table5.** Max plate shear stress (N/mm<sup>2</sup>)



## 5 Result

1) single plate value is not representative, average of value of 9 plates (3x3 array) is close to the fact.

2) The moment on the top plate of Strip cap increase 7.5% than the moment of mat cap. The moment on the bottom plate of Strip cap reduce 37.4% than the moment of mat cap. Strip cap is better than mat cap from the

moment value of plate element.

3) The shear stress on the top plate of Strip cap reduce 18.9% than the shear stress of mat cap. The shear stress on the bottom plate of Strip cap reduce 11.0% than the shear stress of mat cap. Strip cap is better than mat cap from the shear stress value of plate element.

4) Strip cap reduce 20.8% reinforcement concrete than mat cap. We recommend strip cap in the project due to its remarkable economic benefit.

## Acknowledgments

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