NUMERICAL INVESTIGATION ON STRUCTURAL BEHAVIOR OF MAT FOUNDATION: A PARAMETRIC STUDY

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ABSTRACT

The soft soil of Bangladesh has relatively low bearing capacity. Now-a-days high rise buildings are common features of major cities in Bangladesh. Heavy column loads may demand for large footing areas summing up to more than half of the total foundation area available. As their foundation, engineers often opt for mat. Hence, a parametric study revealing the sensitivity to different parameters to the behavior of mat foundation is necessary. In this research work, a numerical analysis has been carried out to investigate the influence of various factors such as mat thickness, modulus of elasticity of mat foundation, coefficient of subgrade modulus and Poisson's ratio to the behavior of the mat foundation, by using finite element software PLAXIS 3-D Foundation and SAFE V12. The soil is modeled as a 3-D solid element having linear elastic material properties connected to the mat foundation and the mat foundation is modeled as a linear elastic plate element in PLAXIS 3D. Whereas, the soil is considered as spring element at discrete position below the mat and the mat foundation is modeled using elastic plate element in SAFE V12. Then the results (settlement, bending moment and shear) are compared with the conventional rigid method of mat foundation design. It has been found that mat response is not much sensitive to most of its parameters. The most significant role played in this regard has been identified to be that of mat thickness and coefficient of subgrade modulus.

Keywords: *Mat foundation, finite element method, conventional rigid method, parametric study*

1. INTRODUCTION

A mat or raft foundation is usually a large concrete slab supporting a number of columns or an entire structure. Mat foundations are used where soil has low bearing capacity and when the column loads are so high (in multi-storey buildings) that spread footings will cover more than 50% of the building area (Bowels, 1997). Other advantages of mat foundations are to reduce the differential settlements depending on the rigidity, or to bridge over subsurface cavities. It provides basement floor which has considerable commercial values in urban areas. In case of basement at or below ground water table, mat acts as water barrier. No doubt, in terms of ease of construction, utility and economy; mat is going to prevail as a superior choice to foundation engineers. Apart from buildings, mat has application beneath silo clusters, chimneys, storage tanks and various tower structures.

There are different methods for the analysis and design of mat foundations; i.e., the conventional rigid method, the approximate flexible method, the numerical methods (finite difference, finite element, and finite grid methods), and the soil–structure interaction (SSI) approach. The conventional rigid method is an approximate method where the mat is assumed to be infinitely rigid. The mat is divided into several strips in x and y directions loaded by a line of columns and resisted by soil pressure. The soil pressure is linearly distributed and the centre of the soil pressure coincides with the line of action of the resultant column loads. These strips are then analyzed and designed as combined footings. This method can be used when the mat is very rigid, the column spacing pattern is fairly uniform in both directions, and column loads do not vary much over 20% (ACI, 1988). This method is not recommended at present because of the substantial amount of approximations and the widespread availability of computer programs using the finite element method. The finite element method considers the mat foundation a plate on elastic foundation and transforms it into a computer-oriented procedure of matrix structural analysis. The plate is idealized as a mesh of finite elements interconnected only at the nodes (corners), and the soil may be modelled as a set of isolated springs (Winkler foundation) (Haddadin et. al., 1971). Commercial software based finite element programs such as ETABS, STAAD. Pro V8i, SAP2000, PLAXIS, SAFE etc are readily available today and capable of easing the engineer's workload, yet will provide a sophisticated solution to a complex problem. This research work has involved an extensive investigation of structural parameters effect on mat foundation using Finite Element Program PLAXIS 3D Foundation and SAFE V12 and comparing the results with conventional rigid method.

2. METHODOLOGY

2.1 Geotechnical & Material Parameters

The plan of a mat foundation with column loads is assumed and shown in figure 1. The size of the mat is 76 ft×96 ft, all columns are 24 in. × 24 in. in section, and $q_{\text{all (net)}}$ =1.5 kip/ft^2.

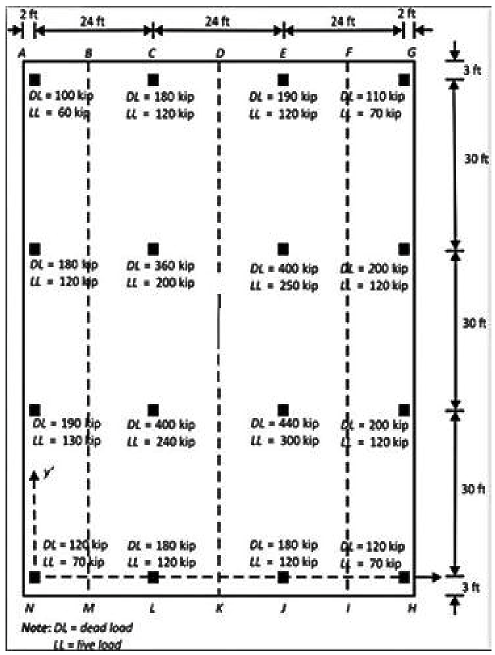


Figure 1: Mat Foundation

The variable parameters of the soil structure interaction model for parametric study are tabulated in table 1.

Table 1: Variable Parameters of Mat Foundation

Modulus of elasticity of mat foundation (E_c) Kip/ft^2	Subgrade modulus (Ks) Kip/ft^3	Modulus of elasticity of soil (Es) Kip/ft^2	Poisson's ratio (μ)	Mat thickness (t) ft
417709.44	159.15	11611.58	0.2	1.6
522136.18	318.29	23222.4	0.25	3.28
626564.16	477.44	34834.02	0.3	4.92
730991.52	636.59	46446.6	0.35	6.56
-	-	-	0.4	-

The parameters are assumed based on some ideal ranges. For examples, Poisson's ratio of a stable, isotropic, linear elastic material cannot be less than −1.0 nor greater than 0.5. The subgrade modulus value of clay ranges as, stiff: 76.03 – 165.89 Kip/ft^3, very stiff: 158.98 – 317.96 kip/ft^3 and hard > 317.96 kip/ft^3. Here, soil ranges from very stiff to hard value. Mat thickness usually ranges from 0.5 to 2 m (1.6 to 6.56 ft). And the concrete material strength is assumed within the range of 2600 psi to 8000 psi.

Vesic's equation to convert subgrade modulus of soil (K_s) to modulus of elasticity of soil (E_s) is

$$\kappa = \frac{E_s}{B(1-\mu_s^2)} \tag{1}$$

Where
E_s = Modulus of elasticity of soil
B= Foundation width
μ= Possoin's ratio

2.2 Conventional Rigid Method of Analysis

Factored load (1.4xdead Load + 1.7xlive Load) =Q, using the column load is calculated to determine the moment of inertia (Ix, Iy), eccentricity and moments (Mx, My). Soil pressure at different points is calculated from the following formula

$$q = \frac{Q}{A} \pm \frac{MxY}{Ix} \pm \frac{MyX}{Iy} \tag{2}$$

A = BL =Base area of the mat foundation
I_x moment of inertia about x - axis = $BL^3/12$
I_y moment of inertia about y - axis = $LB^3/12$
M_x moment of the column loads about the x - axis = $\sum Q.e_y$
M_y moment of the column loads about the y - axis = $\sum Q.e_x$

Then average soil reaction for strip ABMN (width=14 ft), strip BCDKLM (width=24 ft), strip DEFIJK (width=24 ft) and strip FGHI (width=14 ft) is determined. Using these values, shear force diagram and bending moment diagram are drawn to determine the maximum moment and maximum shear force for uniform thickness.

2.3 Finite Element Analysis by PLAXIS 3D

The interaction of the structure and its soil is based on continuum model. Three-dimensional physical model of the structural system consisting of (i) raft; (ii) soil is created. The soil is modelled as a 3-D solid element having linear elastic material properties connected to the mat foundation. The mat foundation is modelled as a linear elastic plate element. At first, The Super-Structure is removed and replaced by the corresponding column load. A sufficiently large zone of the infinite soil mass of length equal to five times of breadth of mat from the edge of mat and depth equal ten times breadth of mat has been selected as the zone of influence. Total 836 ft x 856 ft length of width and 760 ft depth of soil structure interaction model has been created. The load applied on the structural system is assumed to be point load over the entire surface area of the mat on the position of the columns. The model created by using the above condition is analyzed by using the finite element software PLAXIS 3D Foundation to find out the settlement, maximum bending moment and shear force of the structural system.

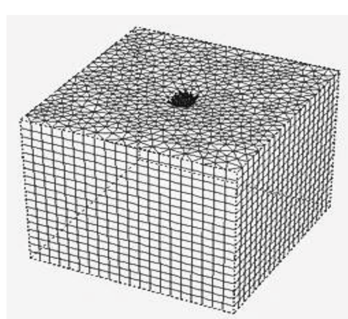


Figure 2: 3D view of deformed mesh

2.4 Finite Element Analysis by SAFE V12

The interaction of the structure and its soil is based on Winkler (discrete) model. The mat dimensions (76ft x 96ft) is entered in SAFE V12 program and is automatically meshed based upon the maximum mesh dimension. The soil has been considered as linear spring element at discrete position below the mat and the mat foundation is modelled using linear elastic plate element. Then the loads (dead load and live load) are applied as point load at the centre point of each column. After modelling of mat, the material and geometric parameters of mat foundation and soil support are defined. Then the analysis procedure of SAFE V12 software is followed to analyze the mat foundation. The results obtained from the finite element analysis are compared with the results obtained from the conventional rigid method as well as an extensive parametric study is conducted.

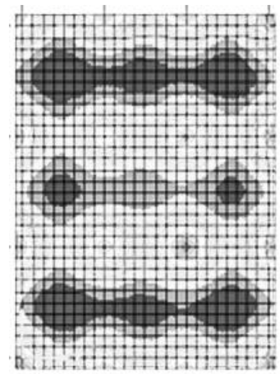


Figure 3: Settlement of mat foundation

3. RESULTS AND DISCUSSIONS

A hand detailed calculation relating to the analysis of mat foundation using the conventional rigid method is included in this research to better understand the problems associated with this method and its limitation and comparing the results with the finite element method. The results are interpreted and compared through graphical representations.

3.1 From Conventional Rigid Method of Analysis

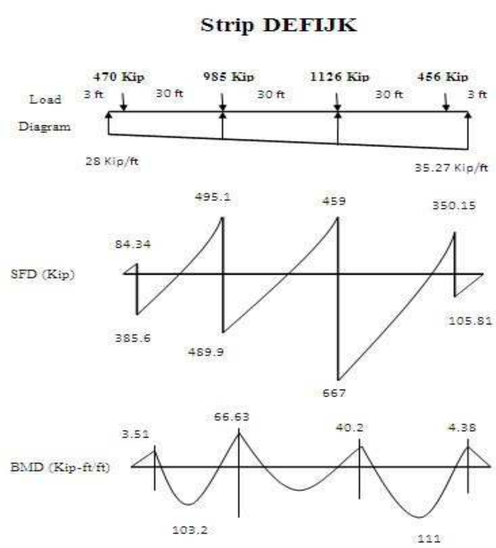


Figure 4: Load, shear force and bending moment diagram of strip DEFIJK

Maximum negative moment is obtained as 111 Kip-ft/ft (111 kip-ft/ft x 24 ft =2664 Kip-ft). Maximum shear is 667 Kip. Punching shear is checked. Failure occurs under maximum column load 1126 kip for thickness 1.6 to 6.56 ft. Minimum thickness required to avoid shear failure is 7.0 ft

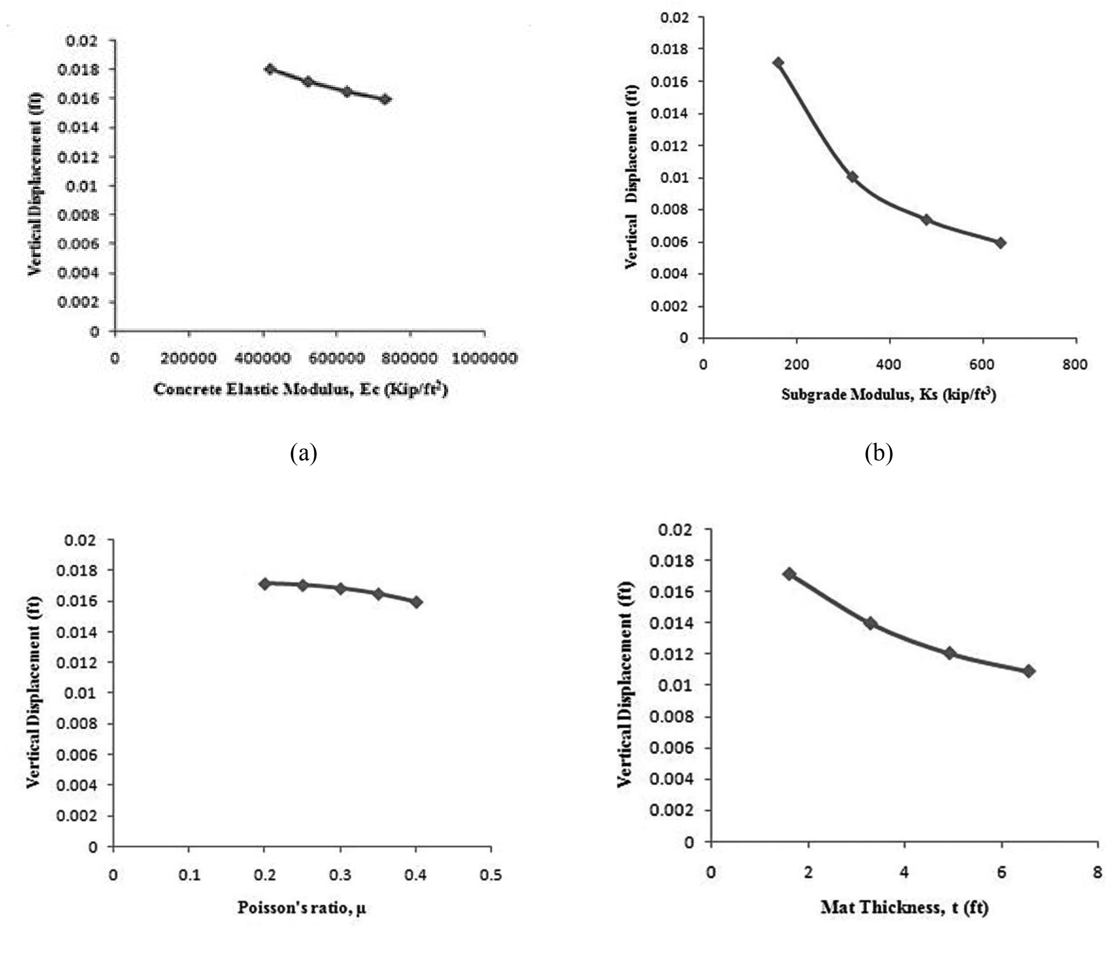
3.2 Parametric Study of Mat Foundation

This research work involves an extensive investigation of structural and geotechnical parameters effect on the mat foundation using Finite Element Program PLAXIS 3D and SAFE V12. A comparative study has been made among some critical positions of the mat foundation using finite element methods in order to perceive the influence of different parameters that assist to understand the practical safety limit of the design characteristics.

3.2.1 Finite Element Analysis

3.2.1.1 Vertical Displacement

In general, vertical displacement decreases with the increase in value of each parameter (concrete elastic modulus, subgrade modulus, Poisson's ratio and mat thickness), using both PLAXIS 3D and SAFE V12.



(a) (b)

(c) (d)

Figure 5: Vertical Displacement VS (a) Concrete Elastic Modulus (b) Subgrade Modulus (c) Poisson's Ratio (d) Mat Thickness, in FEM Analysis by PLAXIS 3D

Vertical displacement decreases with the increase of concrete elastic modulus, Ec and Poisson's ratio, μ. The decreasing rate is subtle in nature and insignificant compared to other parameters. While vertical displacement decreases with the increase of subgrade modulus, Ks and math thickness, t. The decreasing rate is drastic in nature and significant compared to other two variable parameters. Hence, mat thickness and subgrade modulus are the governing parameters in controlling vertical settlement of mat foundation. Choosing the mat thickness of right measurement and subgrade modulus of exact magnitude to control settlement is crucial and necessary.

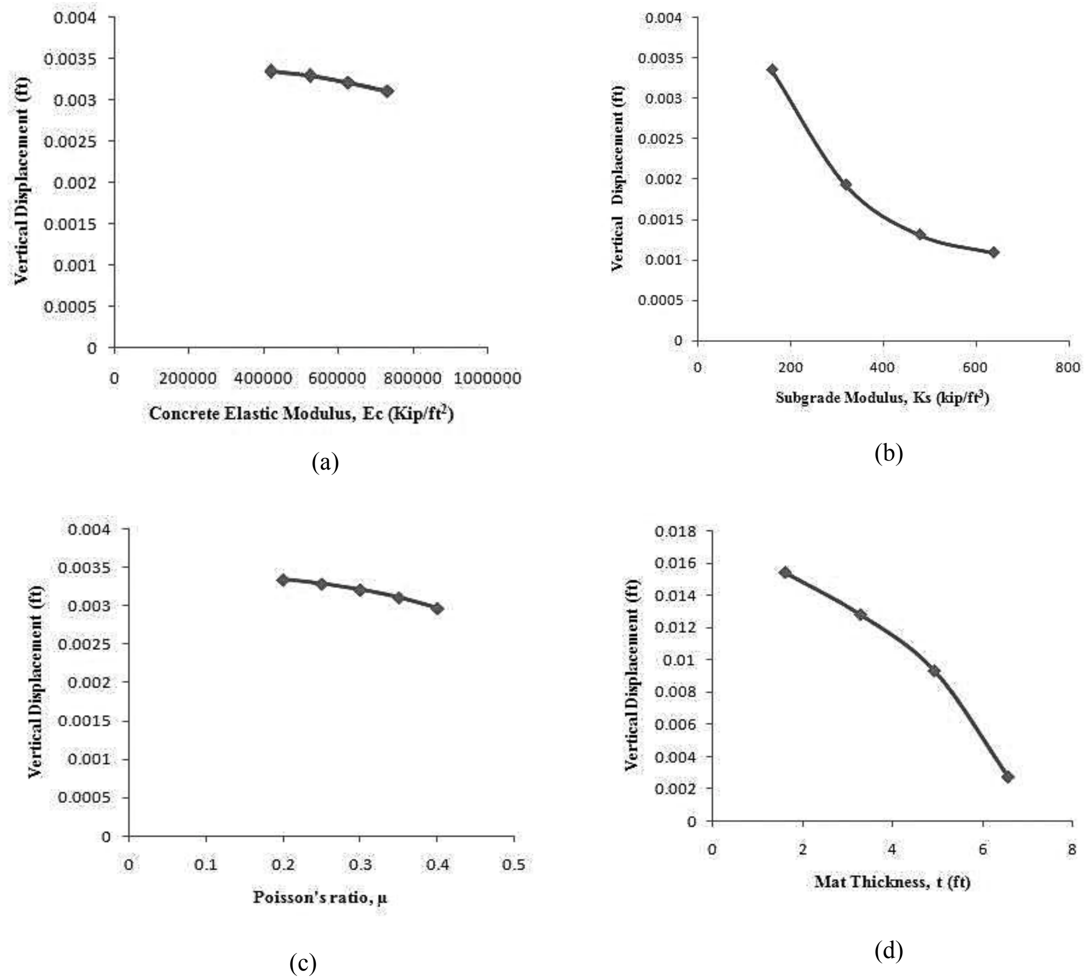


Figure 6: Vertical Displacement VS (a) Concrete Elastic Modulus (b) Subgrade Modulus (c) Poisson's Ratio (d) Mat Thickness, in FEM Analysis by SAFE V12

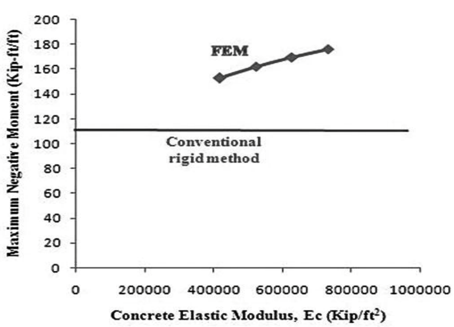
3.2.2 Finite Element Method vs Conventional Rigid Method

The figures below depict the effect of various design parameters on the critical (maximum negative) bending moment and maximum shear and a comparison between two methods of analysis.

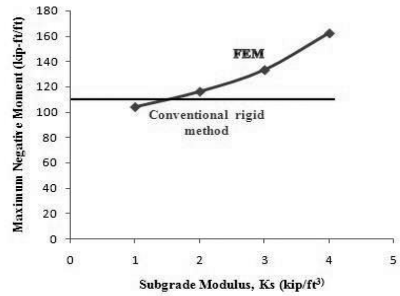
3.2.2.1 Maximum Negative Bending Moment

An important parameter for structural engineering is bending moment of mat foundation. Such a parameter dictates the required thickness of the mat as well as the amount of top and bottom steel reinforcement to the two horizontal directions.

Figure 7 and 8 shows the effect of various design parameters on the maximum negative bending moments of the mat. The plotted graphs show the same curve patterns and trends in case of finite element analysis by both PLAXIS 3D and SAFE V12.



(a)



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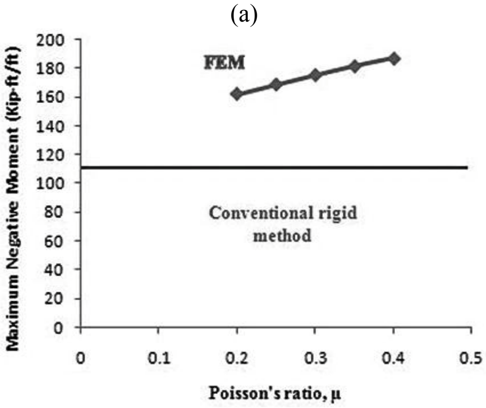

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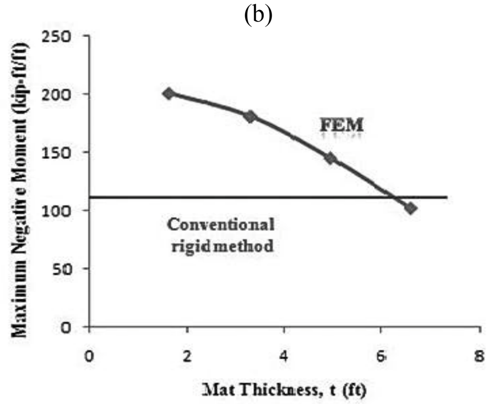
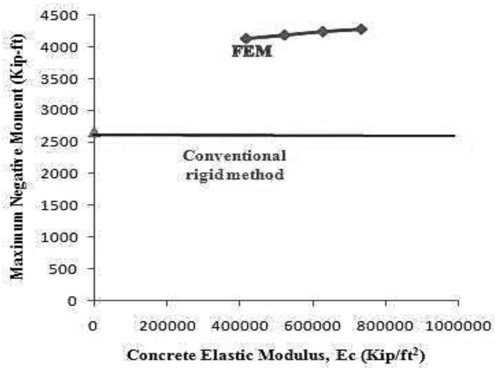


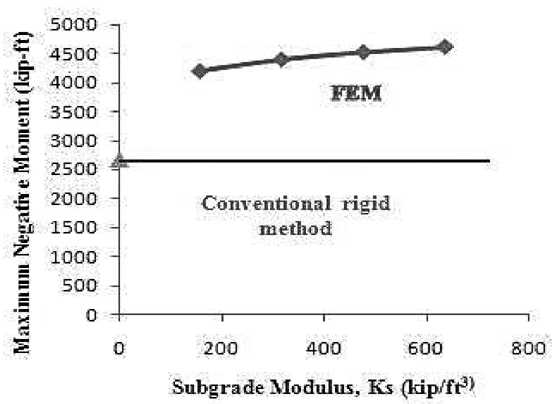
(d)

Figure 7: Maximum Negative Moment VS (a) Concrete Elastic Modulus (b) Subgrade Modulus (c) Poisson's Ratio (d) Mat Thickness, in FEM Analysis by PLAXIS 3D

The results show that concrete modulus of elasticity and Poisson's ratio has the insignificant effect on the bending moment in the mat. In contrast, mat thickness has great impact on the bending moment. As the mat thickness increases, it makes the mat more rigid. With regard to the effect of the soil subgrade modulus, an increase in the soil modulus of subgrade shows a slight effect on the maximum negative bending moment in case of FEM analysis by SAFE V12, however, the increasing pattern is rather rapid while doing FEM analysis by PLAXIS. The results obtained from the conventional rigid method and the finite element method coincides for the mat thickness of 6.28 ft (PLAXIS) and 5.6 ft (SAFE). And both the results coincide for subgrade modulus of 1.7 kip/ft^2 in FEM analysis by PLAXIS.



(a)



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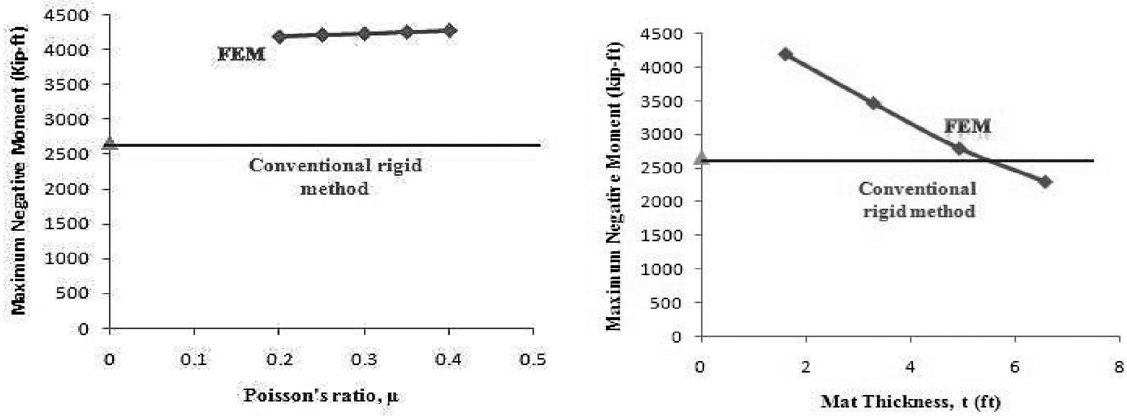


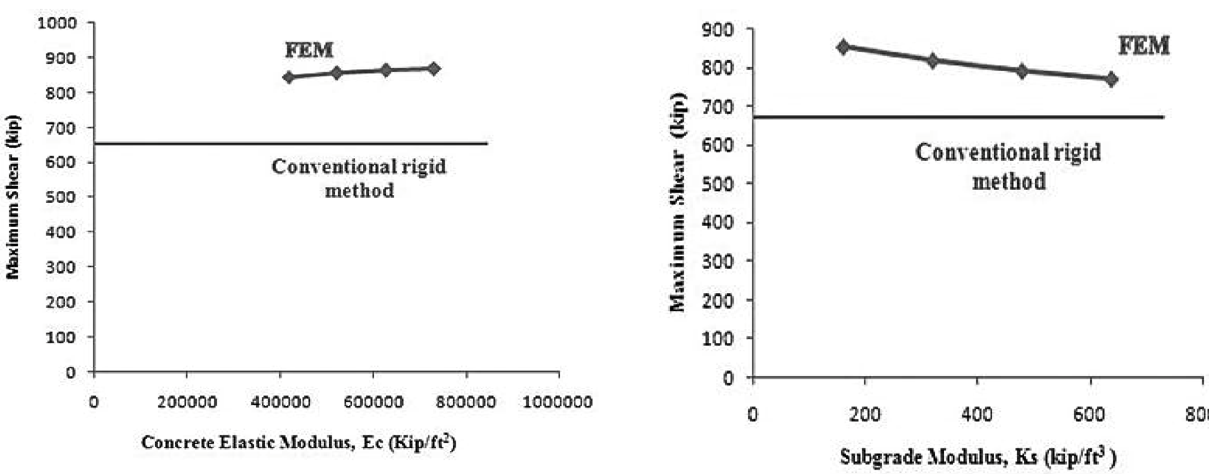
(c) (d)

Figure 8: Maximum Negative Moment VS (a) Concrete Elastic Modulus (b) Subgrade Modulus (c) Poisson's Ratio (d) Mat Thickness, in FEM Analysis by SAFE V12

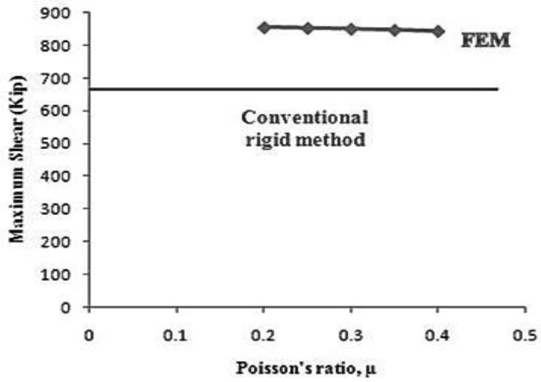
3.2.2.2 Shear force

Shear force is very important parameter as it affects the minimum mat thickness such that stirrups would not be needed and in order to avoid punching shear under columns with small cross sectional dimensions. The figures below demonstrate the effect of considered parameters on the critical (absolute value) shear force within the mat foundation.

The analysis using Finite Element Analysis software PLAXIS 3D shows that the concrete modulus of elasticity and Poisson's ratio has little effect on the shear force in the mat. Though there is a great difference in the obtained result of conventional rigid method and finite element method. In addition, the subgrade modulus of soil also has negligible effect on shear. The maximum shear decreases gradually with the increase of subgrade modulus. Even though the result obtained from conventional rigid method varies with the result obtained from finite element method, the difference between them decreases with the increase of subgrade modulus and approaches to intersect. The effect of the mat thickness on the shear does not have a clear ascending or descending trend. The result shows that the shear force of the mat increases with the mat thickness up to 3.28 feet, thereafter, it decreases. This finite element analysis result varies greatly from the conventional rigid method result.



(a) (b)



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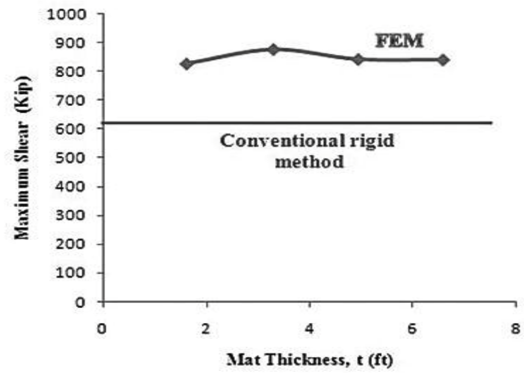
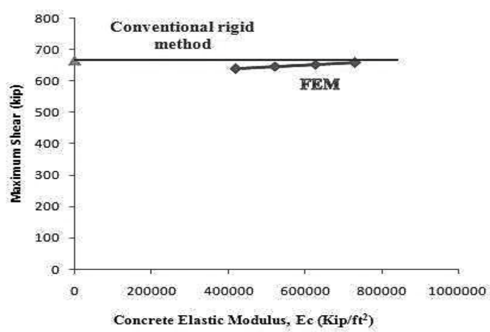


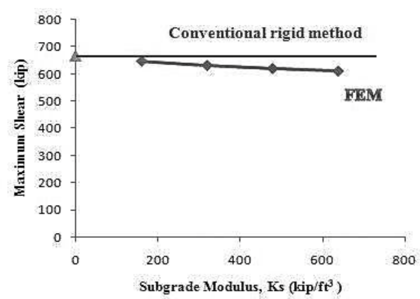
(d)

Figure 9: Maximum Shear VS (a) Concrete Elastic Modulus (b) Subgrade Modulus (c) Poisson's Ratio (d) Mat Thickness, in FEM Analysis by PLAXIS 3D

Similarly, the analysis using Finite Element Analysis software SAFE V12 shows that the concrete modulus of elasticity, Poisson's ratio and subgrade modulus have little effect on the shear force in the mat and the effect of the mat thickness on the shear once again does not have a clear ascending or descending trend just like the previous results by PLAXIS 3D. The result shows that the shear force of the mat increases with the mat thickness up to 3.4 feet, thereafter, it decreases. However, the difference in the obtained result of conventional rigid method and finite element method by this analysis is significantly little as compared to the previous result by PLAXIS 3D. Even though the result obtained from conventional rigid method varies with the result obtained from finite element method, the difference between them decreases with the increase of concrete elastic modulus, Poisson's ratio and with the decrease of modulus of subgrade and approaches to intersect. For mat thickness of 1.85 ft, both methods have the same result as shear value of 667 kip.



(a)



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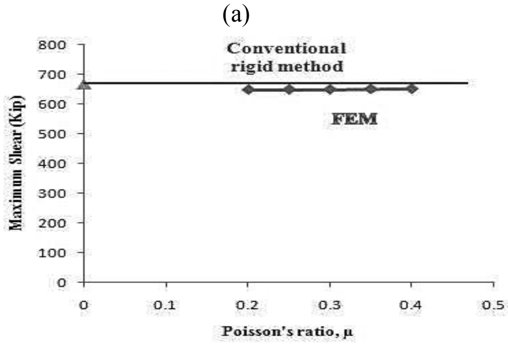

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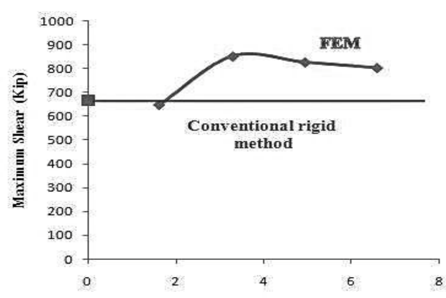

(d)

Figure 10: Maximum Shear VS (a) Concrete Elastic Modulus (b) Subgrade Modulus (c) Poisson's Ratio (d) Mat Thickness, in FEM Analysis by SAFE V12

4. CONCLUSIONS

Based on the findings of this research work, the following conclusions are summarized. In case of finite element method using both PLAXIS 3D and SAFE V12, vertical displacement decreases with the increase in value of each parameter. Maximum negative bending moment increases with the increase in value of modulus of elasticity of foundation material, Poisson's ratio and subgrade modulus, while maximum negative bending moment decreases rapidly with the increase of mat thickness. Maximum shear increases with the increase of modulus of elasticity of foundation material but decreases with the increase of Poisson's ratio, subgrade modulus and in case of mat thickness, the shear value increases up to a certain value, then decreases. Concrete modulus of elasticity and Poisson's ratio has negligible impact on vertical displacement, bending moment and shear force on the mat. Mat thickness and subgrade modulus of soil has significant effect on the considered load effect on the mat surface and internally within the mat. Hence, Subgrade modulus and mat thickness are observed to be the governing parameters in this investigation of parametric study. So, these two parameters require careful consideration while selecting the right measurement or magnitude. The reason behind the variation in magnitude of the results obtained from FEM analysis by PLAXIS and SAFE V12 is that in PLAXIS, the continuum model is followed; whereas, in SAFE V12, the followed model is Winkler Model. The limitation of conventional rigid method in this study is that it does not take into account of the variable parameters considered here, and this is just an approximate study. Finite element method is more efficient and accurate method when compared with all other methods. In comparison, FEM is less cumbersome and time saving method than conventional rigid method. Hence, finite element analysis is preferred for design optimization of mat foundation.

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