

## Parametric Study on Behaviour of Retrofitted Piled Raft Foundation

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**Abstract:** Mat supported on piles is being increasingly used for high-rise buildings with basements in poor soils. Very little is known about the exact behaviour of piled raft foundations in service. However behaviour of retrofitted piled rafts, which are a hybrid foundation of mat provided as retrofitting solution and failed pile foundations, is non-identical. In order to model the mat for retrofitting, engineer needs to analyze the sensitivity of different parameters to their behaviour. In this paper, a numerical analysis has been carried out to investigate the influence of mat thickness and soil subgrade modulus of uniform and varying values to the behaviour of mat foundation rendered to retrofit a short felled pile foundation executed for a high-raised building in Kerala, by using finite element software SAFE v 16. The soil and the piles are modeled as spring element at discrete position below the mat and the mat foundation is modeled using elastic plate element. The results of the study show that mat thickness and soil subgrade modulus are found to be the governing parameters in designing a safe and economical retrofitting mat foundation. Furthermore, it is recommended to provide exact soil subgrade properties under the mat to perceive actual behaviour of foundation.

**Keywords:** Retrofitted Piled Raft foundation, CSI SAFE, Soil Subgrade Modulus.

### I. Introduction

Reinforced concrete mat foundations are popular foundation type commonly utilized in high rise buildings. There are several categories of mat foundations problems which by their nature required a classy computer analysis. They are mat with a non-uniform thickness, mat of complex shapes, mats where it is deemed necessary that a varying subgrade modulus must be used, mats where large moments or axial force transmitted to the mat. There are different approaches when an engineer considers a mat foundation design option [1], and they are: (a) conventional rigid method, in which mat is divided into a number of strips that are loaded by a line of columns and are resisted by the soil pressure. These strips are analyzed same as to that of analysis of the combined footing; (b) approximate flexible method as suggested by ACI Committee 336(1988) and (c) discrete element method. In this method, the mat foundation is divided to a number of elements by gridding using one of the finite-element methods (FEM). The FEM considers mat foundation as 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 modeled as a set of isolated springs (Winkler foundation), whereas piles can be modeled as point springs or line springs with their stiffness value [5]. One of disadvantages of finite element formulations is computationally intensive but computers and available programs make the use of FEM economical and rigid.

### II. Literature Review

A framed structure of 3 bay x 5 bay supported on mat is considered by D. Daniel Thangaraj and K. Ilamparuthi (2010) to evaluate the influence of mat thickness and nonlinear behavior of soil on forces and deformation of the frame. A detailed parametric study was done by varying the relative stiffness of superstructure,  $k_{sb}$  and the raft,  $k_{rs}$ . The interaction analysis showed less total and differential settlements than the non-interaction

analysis did. A parametric study on raft foundation was carried out by G. S. Kame *et al.* (2008) using classical theory of Winkler foundation. The parameters taken are raft thickness, soil modulus and different load parameter. At lower modulus, deflections are increasing with increase raft thickness and vice versa. They have found that positive moment increase with raft thickness and negative bending moments are decreased. They have seen that soil modulus has considered positive bending moment and are decreased at higher modulus and negative moments are increased.

A numerical analysis has been carried out by T. T. Sinthia *et al.* (2016) to investigate the influence of various factors such as mat thickness, modulus of elasticity of mat foundation,  $K_s$  and Poisson's ratio to the behavior of the mat foundation, by using finite element software PLAXIS 3-D Foundation and SAFEV12. The soil was considered as spring element at discrete position below the mat and the mat foundation was modeled using elastic plate element in SAFE V12. Then the results (settlement, bending moment and shear) were compared with the rigid method of mat foundation design. The most significant role played in this regard had been identified to be mat thickness and  $K_s$ . S.W.Tabsh & M.M.El-Emam (2014) investigated the same factors as mentioned above. They modelled mat with shell elements on elastic springs using SAFE Program. They found out that in addition to the above factors, span length of mat has also impact on soil pressure and  $K_s$  only have slight impact on shear.

Based on the above, there is a need to investigate the accuracy of governing parameters mat thickness and varying soil subgrade modulus to mat response. Most of the text-books on structural engineering and reinforced concrete design, while dealing with examples on piled raft analysis, generally consider a simple symmetrical shape with more or less symmetrical/uniform loading. But in practice this never happens. Even when the shape may be symmetrical, the loading is not. To make the study realistic, foundations for actual buildings are considered in this research work for the investigation of effect of structural parameters on retrofitting mat foundation.

### III. Methodology

A comparative study has been made among some critical positions of the mat foundation in order to perceive the influence of mat thickness ( $t$ ) and Subgrade Modulus ( $K_s$ ) to understand the practical safety limit of the design characteristics. The parameters are assumed based on some ideal ranges. Initially, uniform subgrade modulus value of soil ranges is assigned as values suggested by Bowles (1982). Here soil ranges from very loose sand to clayey soil. Then, exact magnitude of subgrade modulus for distinct areas is also assigned based on the soil data of the site. The values are computed using the equation provided by Bowles as  $K_s = 40 \cdot 3(\text{FS}) \cdot \text{Allowable Bearing Capacity}$ . Mat thickness usually ranges from 0.5 m to 2 m. The variable parameters of the soil structure interaction model for parametric study are tabulated in table 1, whereas table 2 shows the magnitude of allowable bearing capacity and soil subgrade modulus for various boreholes.

**Table no 1: Variable Parameters adopted for the study**

$K_s$ (kN/m <sup>3</sup> )	$t$ (m)
10400	1
18000	1.2
36000	1.4
44800	1.6
56000	1.8

**Table no. 2: Values of Bearing Capacity and Soil Subgrade for various boreholes**

BH No	Allowable Bearing Capacity (kN/m <sup>2</sup> )	$K_s$ (kN/m <sup>3</sup> )
3	158	19000
4	158	19000
5	100	12000
6	125	15000
7	100	12000
8	150	18000
9	92	11000
10	108	13000
11	175	21000
12	75	9000
13	158	19000
14	75	9000
15	75	9000

The static gravity and lateral loads obtained at base of building analyzed using ETABS 2017 is imported to SAFE file. The mat foundation of area 3635 m<sup>2</sup> is modeled in SAFE software as a 2-dimensional slab on discrete elastic springs supports that are defined by the coefficient of subgrade modulus of soil and pile as compression springs in vertical and lateral directions at the nodes defined by stiffness value equal to load carried by pile under the particular column divided by corresponding settlement. A default mesh size of 1.2 m x 1.2 m was provided. The foundation is safe with a mat thickness of 1 m and provision of pedestal around heavily loaded column with dimension 3m by 3m of thickness 0.5m. Figure 1 shows the raft layout. Reinforcement steel provided is of HYSD 500 bars.

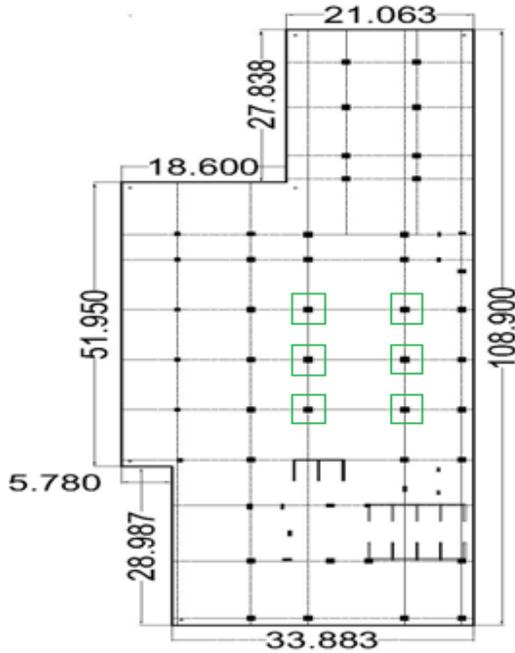


Fig no.1: Raft layout

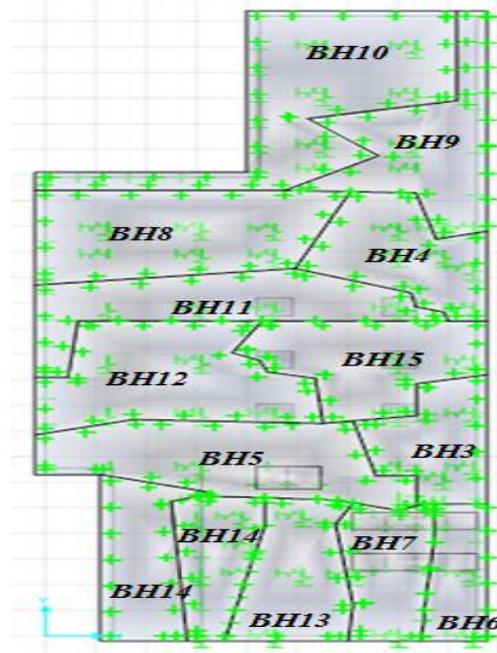


Fig no.2: Finite element model

#### IV. Results and Discussion

##### Vertical Deflection:

In general, vertical displacement decreases with the increase in value of both parameters. Figure 3 shows the variation of vertical deflection with design parameters adopted for the study. The decreasing rate of vertical displacement with the increase of  $K_s$  and mat thickness is drastic in nature and found to be the governing parameters in controlling the vertical settlement of the foundation.

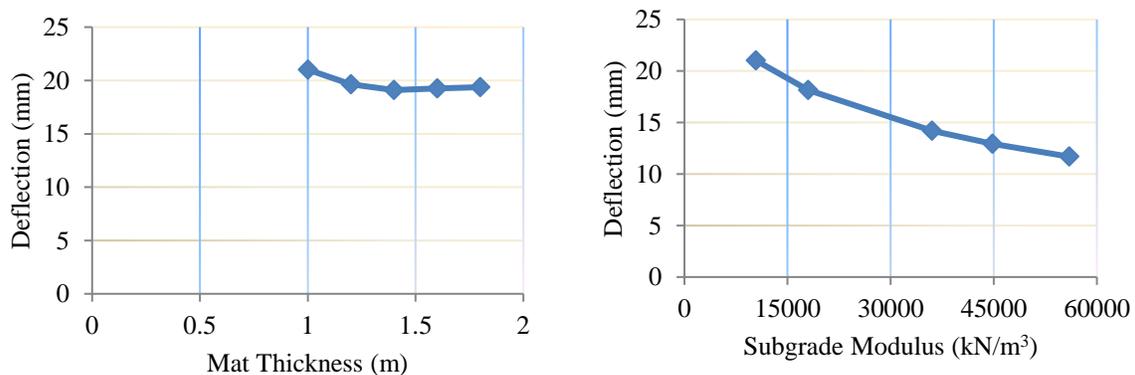


Fig no. 3: Variation of Vertical Deflection

**Soil Pressure:**

Figure 4 shows the effect of engineering parameters on the vertical soil stress that is bearing against the underside of the foundation. The results indicate that concrete mat thickness and subgrade modulus have significant effect on the considered parameter. It can be seen that soil pressure increase with increase in both mat thickness and decreases with increase in soil subgrade modulus. Increment in soil pressure with respect to mat thickness is due to the addition of self weight of foundation, whereas decrement in soil pressure with respect to subgrade modulus reflects the higher stiffness of supporting springs.

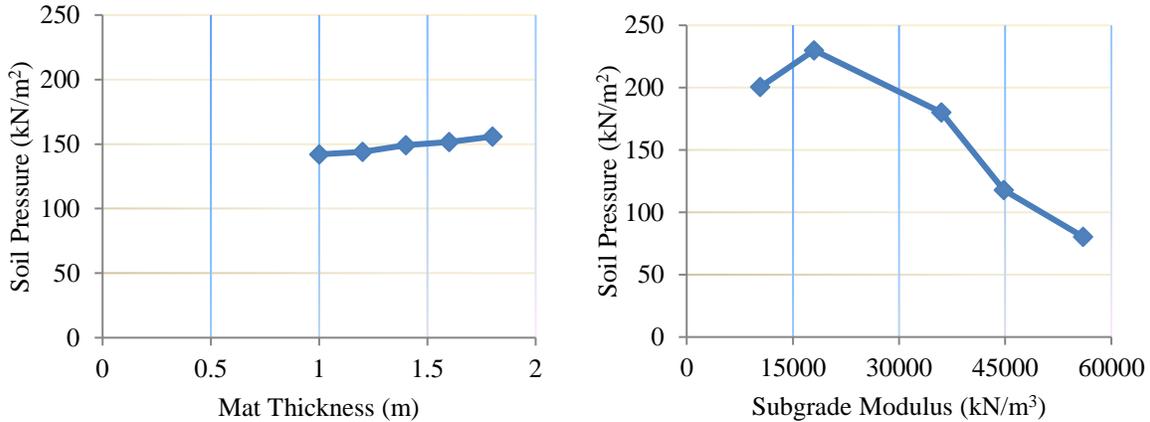


Fig no. 4: Variation of Soil Pressure

**Flexural Moments:**

An important design parameter for structural engineer is the bending moment in a raft foundation. Such a parameter dictates the desired thickness of the raft, as well as the amount of top and bottom steel reinforcement within the two horizontal directions. Figure 5 shows the effect of design parameters on the critical (maximum) positive and negative bending moments on the foundation respectively.

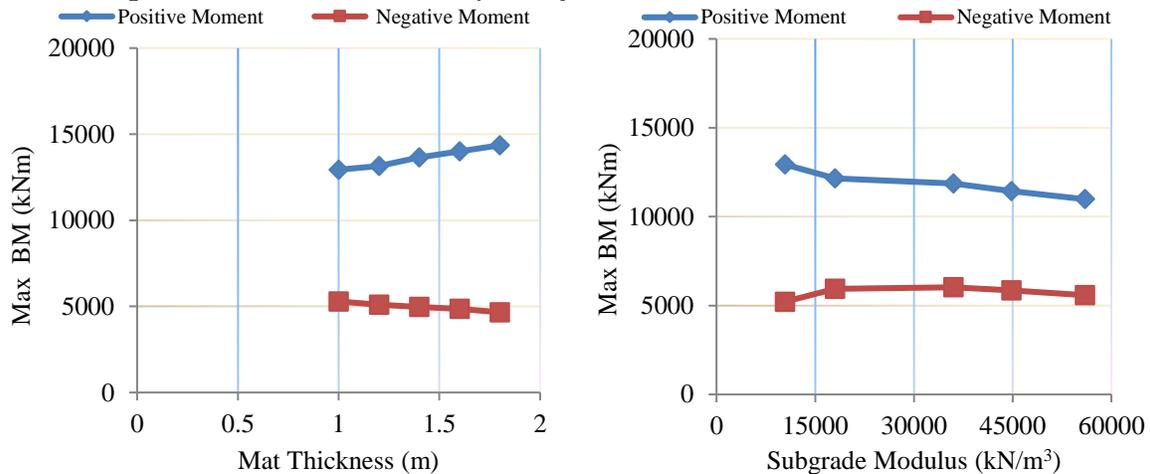


Fig no. 5: Variation of Flexural moments

The results show again that both the concrete mat thickness and subgrade property have a great effect on the bending moment in the retrofitted piled raft. As we can see, as mat thickness is increased, the soil pressure is increased in small amounts due to add up of self weight of the foundation and hence bending moment is increased. With regard to the effect of soil subgrade modulus, an increase in the soil modulus shows a slight effect on both the maximum positive and negative bending moments. As the soil below the mat become stiffer, a slight increase occurs in the negative moment up to a certain point beyond which negative moment decreases with increase in subgrade property, which is accompanied by a marginal decrease in the positive bending moment.

**Shear Force:**

Shear force is an important parameter because it affects the minimum raft thickness such that stirrups wouldn't be needed and so as to avoid punching shear under columns with small cross-sectional dimensions. Figure 6 demonstrates the effect of the considered parameters on the absolute value of shear force within the raft. Similar to the results on soil pressure and bending moment, the analysis showed that the concrete mat thickness and Soil subgrade modulus has significant effect on shear force in the mat. The variation of shear force is increasing with increase in the values of both mat thickness and subgrade modulus.

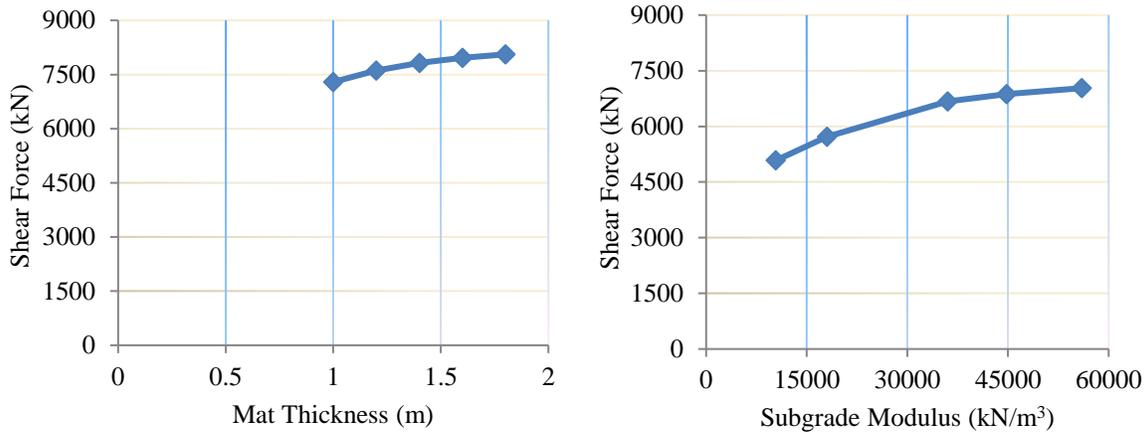


Fig no. 6: Variation of Shear force

**Varying Soil Subgrade Modulus:**

For the parametric study of various design parameters on retrofitted foundation, the soil subgrade property assigned is of uniform value for the whole mat. Usually, for the ease of analysis and design of mat, engineers provide uniform soil subgrade modulus by taking average of the subgrade property. But in reality, the soil properties vary and have different soil layers for different areas especially in a site of larger area. As provided for the real case of analysis in this work, a parametric study by giving different values of soil subgrade modulus for different areas is also studied. It can be seen from figure 7 that it assumes uniform soil distribution by applying uniform subgrade modulus. But in actual practice, contact pressure under the foundation is non uniform.

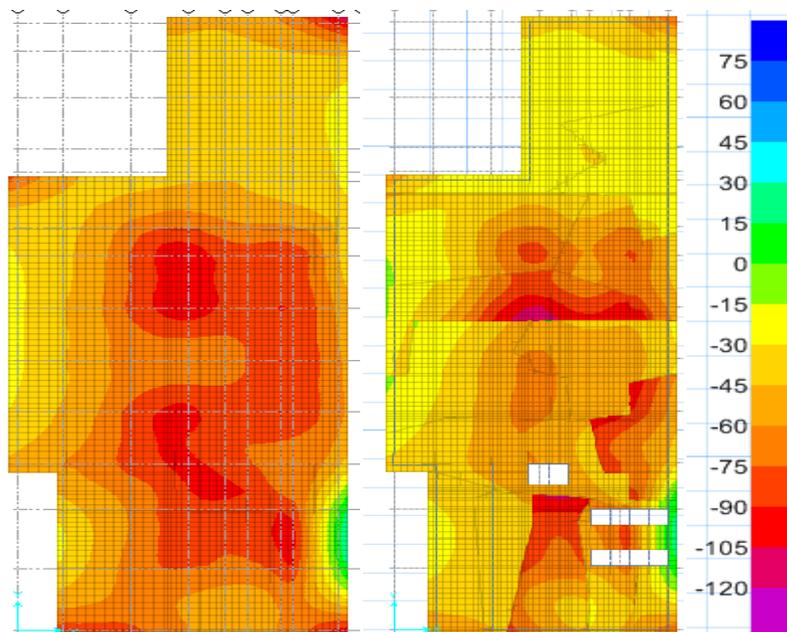
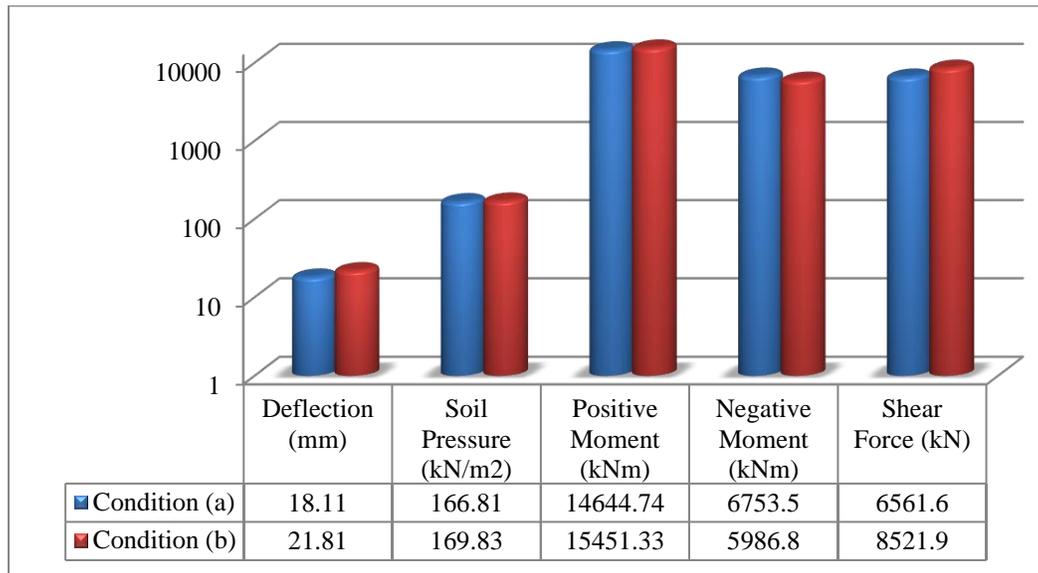


Fig no. 7: Soil Pressure diagram for uniform (left) and varying (right) magnitude of soil subgrade modulus

• **Case I**

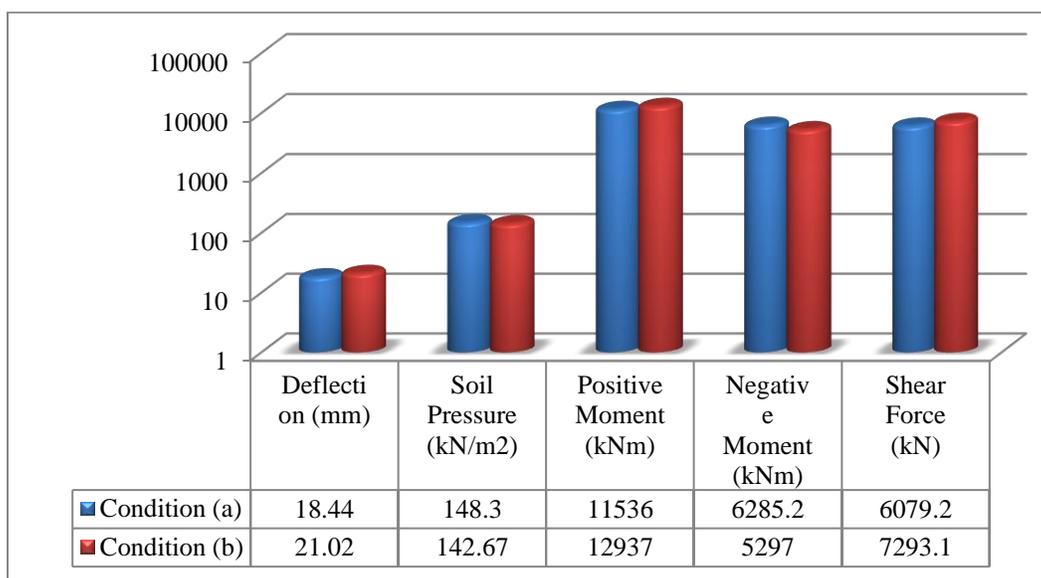
Initially two values of subgrade modulus was taken for demonstrating the soil condition of a loose sand and clayey soil with allowable bearing capacity of 100 kPa in the site. The values taken were 10400 kN/m<sup>3</sup> and 36000 kN/m<sup>3</sup>. Two conditions were assumed for applying these values in distinct areas; (a) clayey soil under the heavily loaded columns (under the building); (b) loose sand soil under the heavily loaded columns. Figure 8 shows the effect of the conditions with different soil subgrade modulus on design characteristics like vertical deflection, soil pressure, BM and SF. Note that the vertical axis is in logarithmic scale.



**Fig no. 8:** Effect of Varying Soil Subgrade Modulus (Case I) on design characteristics

• **Case II**

In this case, the soil subgrade property, assigned in opposite manner (a) to that of real case analysis (b) was compared and studied i.e., the subgrade property having lower values was assigned with larger values as in table 2 and vice versa. Figure 9 demonstrates the comparison on different design characteristics adopted for the study. The variation in soil pressure diagram can be seen in figure 5.8.



**Fig no. 9:** Effect of Varying Soil Subgrade Modulus (Case II) on design characteristics

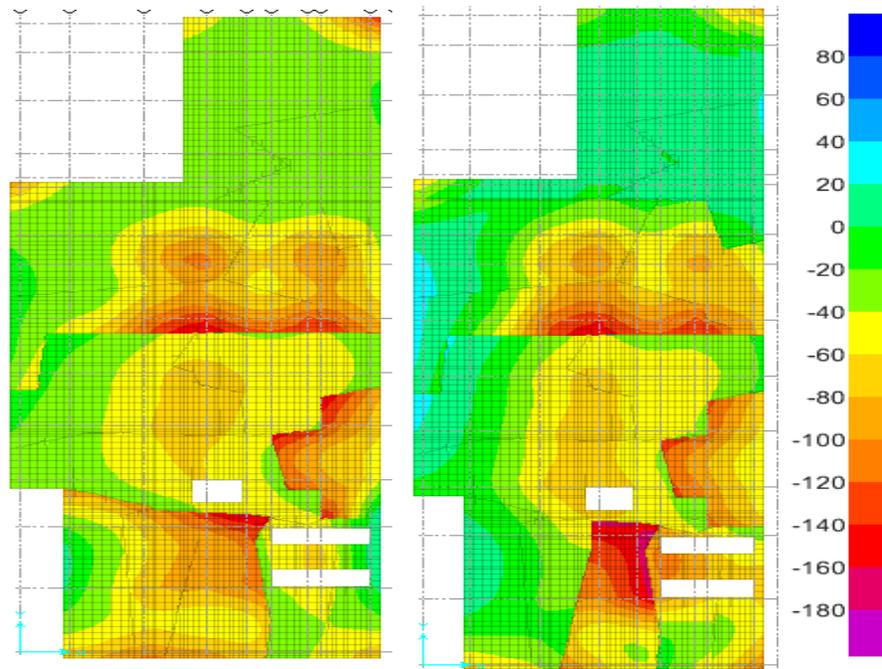


Fig no. 10: Soil Pressure variation for Case II – condition a (left) & condition b (right)

Rather than providing uniform subgrade property for the whole mat, it is always better to provide different subgrade values corresponding to the soil profile of the ground for clear understanding of the variation in design characteristics. We know that structure supported on good load bearing capacity of soil would be subjected to low soil pressure, bending moment and shear force. As expected, when soil subgrade of higher value was assigned in the area of heavily loaded columns, it was observed from figure 8 and 9 that bending moment and shear force were considerably reduced. But negative moment which causes tension at the top face was increased concurrently. Changing the magnitude of soil subgrade modulus has significant effect on pressure distribution on soil below foundation. As coefficient of subgrade modulus increases, soil pressure is concentrated in springs immediately below columns; while springs in between columns are less vulnerable to pressure distribution. Hence, soil behavior tends to “rock” for higher values of soil subgrade modulus. So it is recommended to adopt a mat thickness which is safe in punching shear and also limits the reinforcement for economical design.

## V. Conclusion

A Parametric study of retrofitted piled raft foundation was adopted. To produce approximate analysis of the retrofitting mat using FEM, study on varying soil subgrade values assigned in distinct areas was also obtained. Results show that 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, these two parameters require careful consideration while selecting the right measurement or magnitude. Choosing the mat thickness of right measurement and subgrade modulus of exact magnitude to control settlement is also necessary. In general, the moments decrease with the increase in mat thickness as it makes the mat more rigid. But here we are providing the mat as a retrofit solution and therefore designed for the remaining loads thereafter transmitted to the existing pile foundations. So increasing the mat thickness would definitely increase the soil pressure and hence the moments. However, flexural moments are decreasing; especially maximum positive moment, with increase in soil subgrade property because the soil below the mat would become stiffer.

Working with large areas of foundation requires input of exact soil properties under the foundation to produce their actual behaviour. In practice, the soil pressure under the foundation is non-uniform depending upon the column loads, column spacing etc.

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