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Sensitivity of Raft Foundation's Structural Behaviour to Changes in Geometry and Materials

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Abstract **-** The finite element method is used to examine the sensitivity of the response of rafts subjected to concentrated loads to changes in geometry and material within the foundation. The parameters that are varied in the analysis include the mat thickness, soil modulus of subgrade reaction, concrete modulus of elasticity and spacing between columns. The structural response of the mat is studied by investigating the critical soil bearing pressure beneath the mat, as well as the internal bending moment and shear within the foundation. Findings of the study showed that the most important variables that can impact the structural behaviour of a mat are the thickness and spacing between columns, and to a lesser extent the soil modulus of subgrade reaction and concrete modulus of elasticity. Results of the sensitivity analysis are used to develop a relative mat rigidity factor that can quantitatively predict the degree of rigidity of a mat foundation, which can help in determining whether or not the traditional rigid approach can be safely used to analyse a given raft.

Keywords**:** Finite element analysis; Foundation; Mat; Modulus of subgrade reaction; Raft; Soil-structure interaction.

1. Introduction

A raft or mat foundation is a relatively thin reinforced concrete plate that carries the entire load of a structure and distribute it to a large area of soil under its footprint, as shown in Fig. 1 [1]. It can be either conventionally reinforced with rebars or posttensioned with strands. Such a foundation is considered shallow and is effective in limiting differential settlement within the supported structure. Rafts provide additional advantages such as low construction cost, suitability for weak soils, and watertight construction below the water table [2]. While the majority of rafts are laid directly on soil, some of them can be supported on piles for increased strength and enhanced serviceability. To eliminate the possibility of punching shear under the columns, rafts can have their thickness increased locally over a small region below the columns, in lieu of increasing the thickness of the entire raft. Rafts can also utilize beams and girders within their system for added rigidity.


Fig. 1: Typical raft foundation under construction [1].

Traditionally, a symmetrical raft foundation under symmetrical loading has been approximately analysed by assuming it infinitely rigid, irrespective of the material properties of the raft and soil and the interaction between them [3]. Such an assumption greatly simplifies the analysis because it leads to uniform soil pressure underneath the foundation. Critical bending moments and shear forces along the two major directions of the raft can then be approximately computed using different methods, some of which are more accurate than the rest. For example, the internal load effect within the mat method can be calculated using statics by taking strips of the mat along the columns in the longitudinal and transverse directions of the mat. More accurately, the critical shear and moment values can be obtained by formulas based on elastic analysis, such those of the direct design method or the two-way slab panel formulas. If the columns planted on the mat do not have uniform spacing or do not line up along a straight line, then the equivalent frame method can be used; in that case, the statistically indeterminate frame will need to be analysed by a method, such as the moment distribution. Once the critical internal shear forces within the raft are calculated, the thickness of the foundation is determined such that one-way and two-ways action shears do not govern since rafts are not typically reinforced with stirrups. Longitudinal steel reinforcement along both major directions at the bottom of the raft below the columns and at top of the raft between the columns are computed based on the magnitude of the positive and negative bending moments, respectively. The flexural reinforcement must be checked against the temperature and shrinkage code requirement and increased if needed. However, assuming the soil bearing pressure under the mat to be constant is not always a conservative assumption, as it does not only influence the serviceability limit state but also affect the structural safety of the mat. In some cases, nonuniform soil bearing pressure distribution can cause more critical internal bending moments and shear within the mat than those resulting from assuming uniform soil pressure under the mat. Consequently, incorrect calculation of the load effect within the mat can directly affect the mat thickness selection and steel reinforcement choice at the top and bottom of the mat.

2. Objective and Scope

The objective of the current study is to conduct a sensitivity analysis to investigate the extent of influence of various geometric and material properties on the structural response of symmetrical rafts. The variables that are considered in the study are the raft thickness, soil modulus of subgrade reaction, modulus of elasticity of concrete and spacing between columns. The considered limit states are the maximum and minimum soil bearing pressure, critical positive and negative bending moments, and absolute maximum shear. The approach used to address the stated objective utilizes the linearly elastic finite element method to analyse the foundation twice, once by considering the flexibility of the foundation and another time by ignoring it. The load effect within the raft is then examined and compared to that of a rigid raft.

3. Previous Research

Careful examination of previously published research on the subject of soil bearing pressure distribution and load effect in rafts suggests that the relative rigidity of the foundation is dependent on the mat thickness and modulus of elasticity, soil Poisson ratio and modulus of subgrade reaction, spacing between columns, cross-section dimensions of the columns and stiffness of the supported superstructure. These parameters affect the rigidity of the foundation in different ways and varying extent.

Teli et al. [4] investigated the impact of mat rigidity and soil properties on the response of the foundation of a multi-storeyed structure. They found out that modulus of subgrade reaction has higher influence on the soil bearing pressure as compared to flexural rigidity of raft. While the rigidity of the foundation highly influences the shear stress and bending moment in foundation, the effect of variation in the soil properties on structural design of the foundation is insignificant. Gong et al. [5] used model tests to demonstrate that when raft thickness is larger than one-sixth the span between columns, the rigidity of frame structure with raft foundation can be large enough to cause linear distribution of contact soil pressure on the foundation and the settlement can be calculated using elastic theory in combination with the principle of superposition. Alshorafa [6] studied the rigidity of mat foundation following theoretical and experimental approaches. He used the results to adjust the column loads and soil pressure under the mat to correct the shear and bending moment in the foundation that are obtained by the rigid foundation approach. Findings of the study showed that the critical moments obtained from the modified conventional rigid method are between those obtained by the conventional rigid method and the finite element procedure. Çekinmez [7] used the finite element software PLAXIS 3D to determine the effect of column spacing, stiffness of the soil and thickness of the foundation on the soil/foundation contact stress distribution, settlement distribution, scattering of modulus of subgrade reaction of a mat foundation. Results of the study are used to develop a relationship between size of the foundation, deformation modulus of foundation soil and modulus of subgrade reaction. The modulus of subgrade reaction is nonuniform for stiff mats, loaded by columns having large spacing and supported on stiffer subgrade soils. Pillay [8] compared the analysis results of rafts using the conventional, Winkler, and continuum methods. He found out that the conventional rigid method under-estimated the negative bending moment values for rafts supported on weak soil. Field observations revealed that cracking pattern corresponds well with those from continuum analysis. The Winkler method often gives overly conservative results. The combined model that incorporates the superstructure with the raft yields comparatively less absolute and differential settlements due to the levelling effect of the stiff superstructure.

The current study builds on the previously published research by the first author on spread footings [9] and extends the recent work of the two authors on mat foundation [10,11].

4. Results

The foundation in this study is analysed within the elastic range by the finite element method using a software [12]. The mat is modelled by thick shell elements with the underlying soil by elastic Winkler springs at the nodes. Loads on the mat are applied through the columns, in which the corner column and the edge columns are subjected to one-quarter and one-half of the load on the interior column, respectively. Details of the finite element model are shown in Fig. 2.

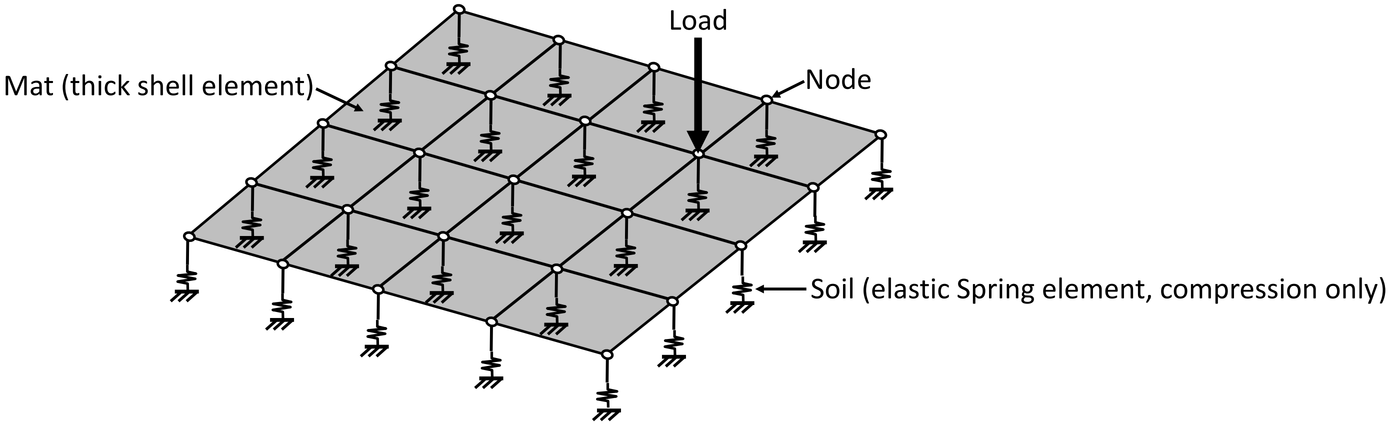


Fig. 2: Finite element model of the raft foundation.

To determine the effect of a mat's design parameter on the geotechnical behaviour and structural response, a case study consisting of 3 by 3 bays symmetrical mat with 6 m spacing between columns is considered, as shown in Fig. 3. The mat is 1 m-thick and made with concrete having 25 GPa modulus of elasticity and 0.2 Poisson's ratio. The mat rests on soil having 50 MN/m^3 modulus of subgrade reaction and 0.3 Poisson's ratio.

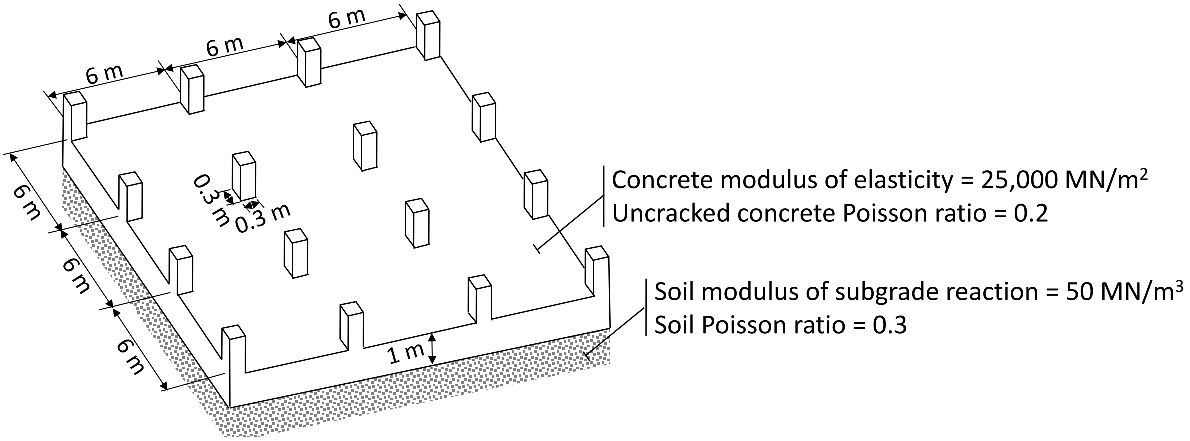
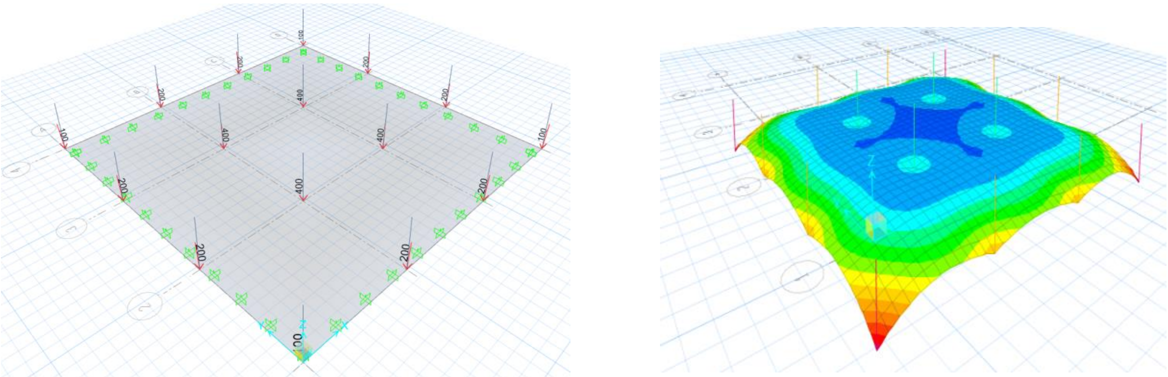


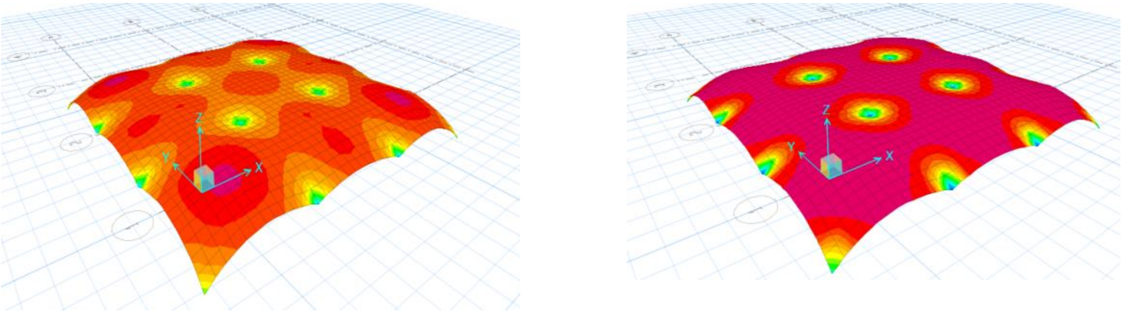
Fig. 3: Properties of raft foundation considered in the case study.

The symmatrical mat is subjected to concentrated loads from 16 columns that have 0.3 m by 0.3 m square cross-section, in which the load on the columns is proportional to the tributary area they are serving (i.e. load on a central column is twice the load on an edge column and four times the load on a corner column). Fig. 4 shows the geometry, loading and analysis results of the considered mat for the case of load on the interior columns equal to 400 kN. Note that the self-weight of the mat is ignored since its effect on the internal bending moment and shear force within the mat is negligibly small.



(a) Mat Geometry and Loading

(b) Soil Bearing Pressure



(c) Bending Moment

(d) Shear Force

Fig. 4: Finite element results of loaded mat.

4.1. Effect of Mat Thickness

The thickness of a mat, t, is an important parameter because it greatly affect the soil bearing pressure magnitude and and distribution, flexural strength and punching shear capacity. The mat considered in the case study is now analysed with with different thicknesses ranging from 0.25 to 2.0 m, while keeping all other parameters the same. Results of the analysis analysis are normalized with respect to those obtained from the analysis of an infinitely rigid mat, see Fig. 5. The findings indicate that the mat thickness has significant effect on the critical maximum soil pressure and moderate effect on the critical critical minimum soil pressure. As expected, an increase in the slab thickness makes the raft more rigid; resulting in reduced deformations, which leads to approximately uniform bearing pressure over the entire mat underneath area. Note that the maximum soil pressure is not necessarily located under the columns that are subjected to the largest loads. Instead, it was found below the corner columns due to the discontinuity of the raft at that location, which results in more deflection under these columns. The minimum soil pressure for the considered mat was observed at the centre of the interior panel. This is because the 12 columns along the raft perimeter experienced much more deflection compared to the interior columns, leading to upward bulging between the four central interior columns. Also, the mat thickness has great effect on the bending moment, particularly the positive moment that causes compression on the top of the mat. Note that negative moment occurs between the columns, whereas positive moment in regions located near the columns. In general, an increase in the mat thickness causes the positive moment to decrease and the negative moment to increase. For relatively thin mats (< 1 m), the positive bending moment is less sensitive to the change in thickness than the negative moment. The opposite is true for relatively thick mats (> 1 m). As the slab thickness increases, it makes the raft more rigid, causing it to curve less and leading to near-uniform soil bearing pressure within the whole raft panel. Note that within a panel, the negative moment and positive moment regions are somewhat equal to each other for thin mats. For thick mats, the contour line of contra-flexure is closer to the columns. The variation in bending moment with changes in mat thickness is mainly due to the change in soil bearing pressure distribution. In the case of thin mats, the soil pressure under the columns is very large, whereas in the case of thick mats the pressure is nearly uniform when subjected to the same loading. The findings can be explained by pointing out that large soil pressure under the columns (accompanied with small soil pressure near midspan) has little effect on the negative moment in regions midway between the columns. Alternatively, small soil pressure under the columns (accompanied with large soil pressure near midspan) has significant effect on the negative moment in regions midway between the columns. The effect of the mat thickness on the shear force in the reference mat is minimal, particularly for large mat thicknesses, because both the mat and the loading are symmetrical. Thus, the critical shear at the face of the columns is affected by the volume under the soil pressure under the mat, which is independent of the distribution of the soil pressure since the total loading is unchanged.

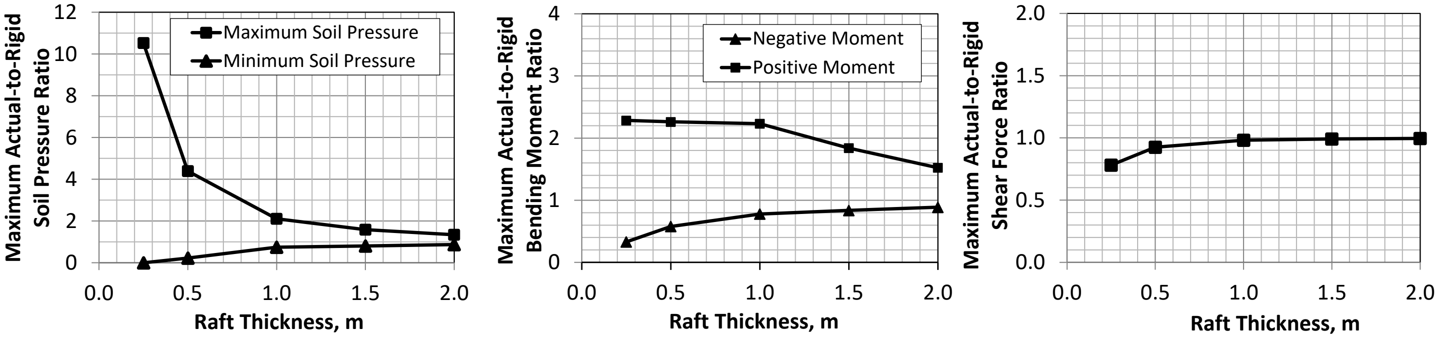


Fig. 5: Effect of mat thickness on the response of the foundation.

4.2. Effect of Modulus of Subgrade Reaction

The modulus of subgrade reaction, k_s, represents the relationship between soil contact pressure and mat settlement over a unit area of soil. The reference mat considered is now analysed with different moduli of subgrade reaction, ranging from 25 to 400 MN/m^3, while keeping all other parameters constant. Note that the lower values of k_s represent soil composed of soft clay or loose sand, while the high values signify soil composed of well-graded, sand-gravel mixture. The impact of the modulus of subgrade reaction of the soil on the mat behaviour is presented in Fig. 6, in which the results are normalized with respect to those obtained from the analysis of an infinitely rigid mat. Findings of the analysis indicate that as k_s increases, the maximum soil pressure occurring under the columns greatly increases. This is accompanied by a small decrease in the minimum pressure, which takes place in the central region of the panels. The reason for the change in critical soil pressure with the increase in k_s is due to the stiffness of the soil under the mat. For mats supported on stiff soil, there is concentration of high soil pressure directly under the columns, while for mats on soft soil the pressure is more evenly distributed under the mat. This means that for the case of high k_s, the raft under the columns deflect more than for the case of low k_s. However, regions of the mat located at the centre of the panels (which represent minimum soil pressure) experience the same minimum soil bearing pressure, irrespective of k_s. In all cases, the integration of the soil pressure over the underside area of the mat, which denotes the total applied load through the columns, is the same. The results also indicate that k_s has slightly more effect on the positive moment under the columns than on the negative away from the columns, which can be attributed to the change in the soil bearing pressure distribution due to soil stiffness. While the minimum soil pressure remains the same in both cases, the maximum soil pressure is a little lower when k_s is small compared to when k_s is large, although the length over which the maximum pressure is applied is different in the two cases. Since the soil pressure between the columns, which is independent of k_s, is responsible for the negative moment, the change in k_s does not significantly affect that moment. The increase in the positive moment with increase in k_s is due to the increase in the soil pressure in that region. Furthermore, the results show that this effect on the maximum shear within the mat is negligibility small because the critical shear in symmetrical mats is a function of the total applied load on the mat, which is the same and is independent of the distribution of the soil pressure underneath.

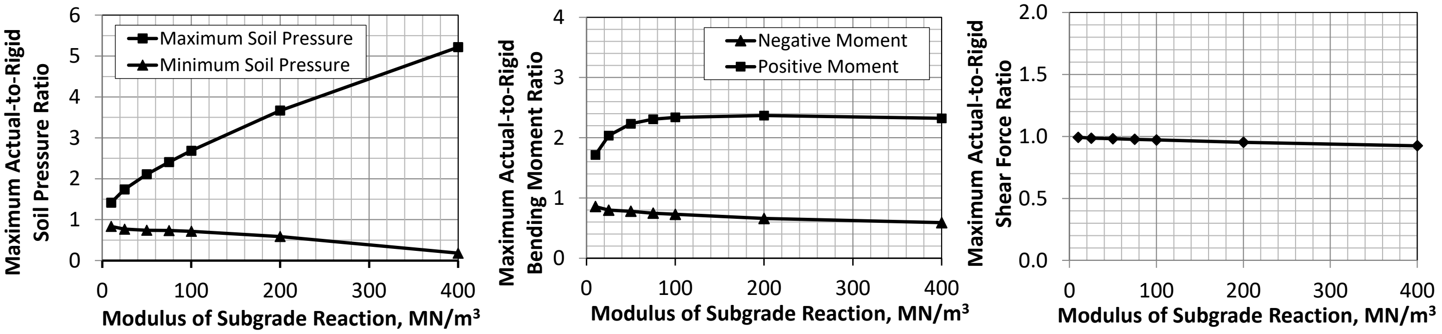


Fig. 6: Effect of modulus of subgrade reaction of soil on the response of the foundation.

4.3. Effect of Modulus of Elasticity of Concrete

The effect of the modulus of elasticity of the concrete, E_c, on the critical soil bearing pressure, bending moments, and shear is presented in Fig. 7, with the results being normalized with respect to those obtained from the analysis of an infinitely rigid mat. Most structural design codes provide equations for the modulus of elasticity in terms of the concrete compressive strength and mass density [13]. The reference mat is analysed with different moduli of elasticity, ranging from 20 to 50 GPa, while keeping all other parameters unchanged. While the results indicate negligible change in the minimum soil bearing pressure with a change in the concrete modulus of elasticity, there is some effect on the maximum soil pressure, especially for concrete having low moduli of elasticity. As the modulus of elasticity increases, the maximum soil pressure under the column decreases due to the increased rigidity of the mat, which eventually results in a near uniform distribution of the soil pressure below it. The corresponding results for the internal bending moment and shear within the mat indicate minimal effect of the concrete modulus of elasticity on the positive bending moment and almost no effect on the negative bending moment and shear.

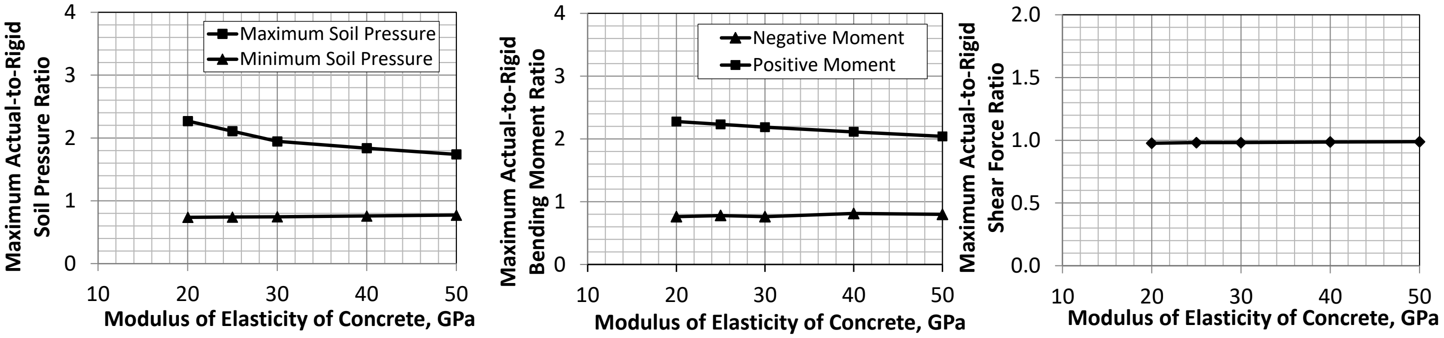


Fig. 7: Effect of modulus of elasticity of concrete on the response of the foundation.

4.4. Effect of Spacing between Columns

The effect of the centre-to-centre spacing between columns of a mat on the critical soil pressure, bending moment, and shear is shown in Fig. 8, with the results being normalized with respect to an infinitely rigid mat. The analysis considers column spacing ranging between 3 and 10 m. The analysis showed that the mat response greatly varies with the span length, even when the results are examined in a normalized format with respect to an infinitely rigid mat. This is because the distance between the supported columns significantly changes the behaviour of the mat from rigid to flexible as the span increases. For a mat consisting of small panels, the close spacing of the columns stiffens the mat and makes it hard to deform, causing the soil bearing pressure to be more evenly distributed underneath it. The opposite happens for a mat comprising of large panels; in that case, the soil pressure becomes concentrated within regions located in the vicinity of the columns. As expected, the results indicate that as the spacing between columns becomes longer, a sharp increase in the maximum pressure and moderate decrease in the minimum pressure take place, compared to their corresponding rigid mats. Likewise, the spacing between columns has high impact on the critical negative moment and moderate effect on positive moment, although its effect on the positive moment becomes stagnant for very large column spacing. The results also reveal that the maximum shear in a flexible mat is very identical to its rigid counterpart when considering spacing between columns.

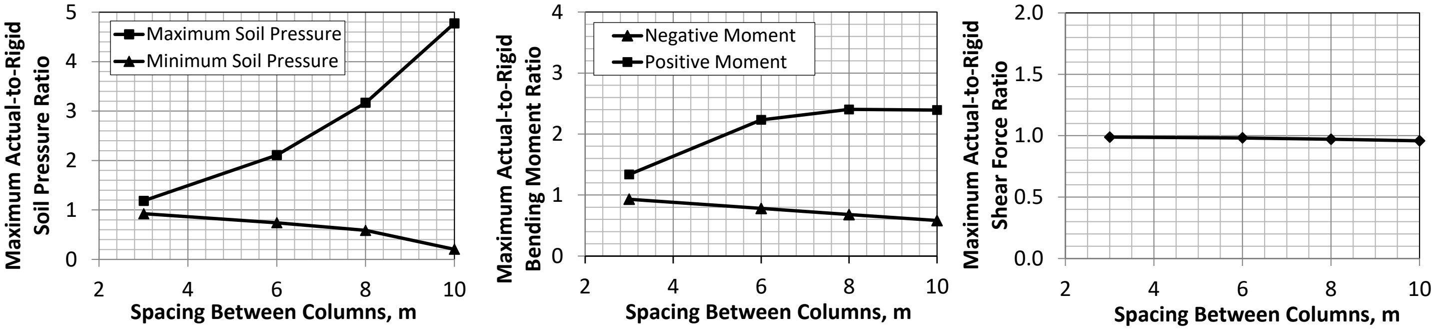


Fig. 8: Effect of spacing between columns on the response of the foundation.

4.5. Quantification of Mat Rigidity

For spread footings or mats supporting rigid structures, ACI Committee 336 [14] recommends the use of a relative stiffness factor, K_r, developed in by Meyerhof [15], to differentiate between flexible and stiff shallow foundations:

$$K_r = \frac{E_c\, I_b}{E_s B^3} \tag{1}$$

where E_c is the modulus of elasticity of the concrete, B is the width of the foundation, I_b is the moment of inertia of the structure per unit length at right angles to B (i.e. $t^3/12$), and E_s is the modulus of elasticity of the soil that is supporting the structure, given by:

$$E_s = k_s(1-\mu_s^2)B \qquad (2)$$

where k_s and μ_s are the modulus of elasticity and Poisson's ratio of the soil, respectively.

It is obvious from the previous two expressions that the measure of rigidity of a mat foundation is proportional to E_c and t^3, and inversely proportional to k_s, B^4 and $(1 - \mu_s^2)$. For a raft that is composed of rectangular panels of length L and width B with column cross-section dimensions along the length equal to l and along the width equal to b, a dimensionless rigidity factor of the foundation, K'_r, can be derived by substituting the expressions E_s and I_b in that of K_r, considering the clear span of both panel dimensions of the raft, and eliminating the constants:

$$K'_r = \frac{E_c\, t^3}{k_s(1-\mu_s^2)(L-l)^2(B-b)^2} \qquad (3)$$

To check the validity of the above expression in quantifying flexural rigidity of a raft, the case study considered in Fig. (3) is re-analysed again 70 times using the finite element method by considering a wide range of parameters. Each time, the shallow foundation is analysed twice, once as flexible with the actual values of the parameters and another time as infinitely rigid by drastically increasing the mat thickness. The parameters that are considered in the study are: (1) thickness of the foundation, (2) number of bays along the length and width, (3) concrete modulus of elasticity, (4) soil subgrade reaction, (5) column spacing along the length and width, (6) cross-section dimensions of the columns, and (7) aspect ratio of the panels within the foundation. Fig. 9 shows the relationship between the relative rigidity factor and critical soil pressure, bending moment and shear force within the raft, normalized with respect to those of an infinitely rigid foundation. The results indicate excellent correlation between the developed rigidity factor and maximum load effect. They show that mat rigidity greatly impact the maximum soil pressure and positive bending moment, moderately affect the minimum soil pressure and negative moment near the centre of the panels, and has almost no influence of the shear force. A relative rigidity factor $K'_r=1$ can be considered as the threshold above which a mat foundation can approximately be considered rigid.

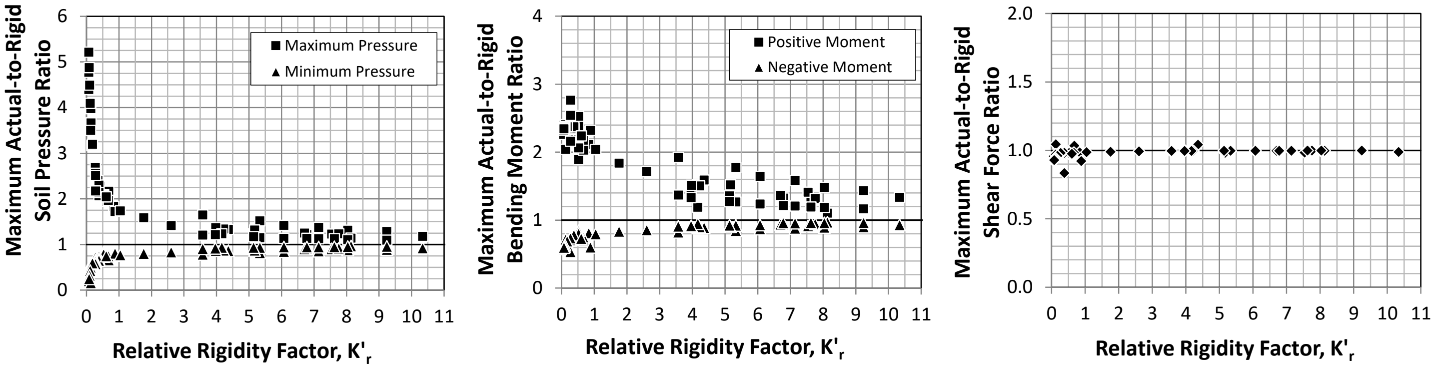


Fig. 9: Relationship between the relative rigidity factor and critical soil pressure, bending moment and shear.

5. Conclusion

Findings of the study lead to the following conclusions:

1. The stiffness of a mat foundation relative to the soil underneath greatly affects the magnitude and distribution of soil bearing pressure underneath the mat, which in turn influences the critical internal forces within the mat.
2. The relative stiffness of a mat foundation is greatly affected by the mat thickness and spacing between columns, and to a lesser extent the modulus of subgrade reaction of the soil and modulus of elasticity of the material that the mat is made from.
3. As the mat's relative stiffness increases, the soil bearing pressure approaches a near uniform distribution state, which causes a reduction in the maximum positive moment and amplification in the maximum negative moment.
4. The effect of the mat stiffness on shear is negligibly small since internal shear within a mat is a function of the total volume under the soil pressure contours on the under surface of the structure, which is constant for mats having different stiffnesses and subjected to the same loading.

5. Based on the early work of Meyerhoff on the subject, a quantitative measure for the relative mat rigidity with respect to the soil was developed for the sake of checking whether or not a given mat can be reasonably analysed using the traditional rigid approach.

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