Analytical Study on the Influence of Rigidity of Foundation and Modulus of Subgrade Reaction on Behaviour of Raft Foundation

Sujay Teli, Palak Kundhani, Virag Choksi, Pritam Sinha and Kannan K. R. Iyer

Abstract Shallow foundations are commonly used for supporting structures unless soil, loading and serviceability requirements necessitate deep foundations. Shallow foundations may be designed as rigid or flexible foundations depending on loading conditions as well as relative stiffness of foundation and supporting soil subgrade. For design of flexible foundations, soil is modelled as per Winkler approach or as a continuum. For analysis of most foundations, Winkler approach is found acceptable, wherein modulus of subgrade reaction is evaluated and applied as soil springs. The different factors which affect design of foundation include superstructure geometry and stiffness; type, magnitude and location of loading; rigidity of foundation and modulus of subgrade reaction. The current study attempts to understand the influence of rigidity of foundation and modulus of subgrade reaction on behaviour of raft foundation. A multistoreyed structure is analysed in Staad Pro V8i software for different combinations of foundation rigidity and modulus of subgrade reaction; and parameters such as base pressure, settlement, shear stress and bending moment have been compared. It is concluded from the study that modulus of subgrade reaction has higher influence on variation in foundation base pressure as compared to rigidity of foundation. It is also noted that impact of variation in modulus of subgrade reaction on structural design of foundation is negligible. However, the rigidity of foundation influences the shear stress and bending moment in foundation. It is opined that such studies would help in developing decision matrix to account for various parameters in optimization of foundation design.

Keywords Modulus of subgrade reaction · Rigidity · Flexible · Raft foundation · Staad pro

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1 Introduction

Shallow foundations are commonly used for transferring superstructure (viz., building, water tanks, industrial structures, etc.) loads to soil, unless the bearing capacity of soil is inadequate or expected settlement (total and differential settlement) are higher than permissible values. Shallow foundation includes isolated foundations with or without tie beams, combined foundations and raft (mat) foundations. For multistoreyed structures, Raft foundation is generally preferred when columns are closely spaced, intensity of loading is higher, and higher total/differential settlement of soil is anticipated. Raft foundation is economical compared to isolated foundation when the area of foundation covers more than half of structure base area [1].

Analysis approach for raft foundation depends on soil–structure interaction. Depending on the relative stiffness of the foundation superstructure system and subgrade soil, the foundation can be designed as rigid foundation or flexible foundation [2]. Rigid foundation can be analysed as a plate undergoing rigid body settlement, whereas flexible foundation needs to account for the flexural effects on load distribution and soil–structure interaction. Winkler model is one of the popular models for analysis of flexible raft foundation. In this model, the subgrade soil is replaced by number of linear elastic uncoupled springs. The modulus of subgrade reaction obtained from plate load test or correlations with field/laboratory tests is usually assigned as stiffness value of the springs after considering the effect of foundation size, depth of foundation and other site-specific geotechnical aspects. However, modulus of subgrade reaction is a complex interface parameter [3] and is also dependent on other factors such as geometry and stiffness of superstructure, foundation shape and rigidity as well as location and magnitude of loading [4]. Modulus of subgrade reaction is defined as the contact pressure required to cause unit settlement of foundation and is an important parameter for foundation design. A clear understanding of the behaviour of raft foundation in relation to the supporting subgrade is mandatory to ensure the economy and safety in design, and hence a clear understanding of factors affecting foundation design is necessary.

Earlier studies have reported that the factors affecting modulus of subgrade reaction includes foundation size, shape and rigidity, type and stiffness of soil as well as loading conditions. It has also been reported that the inability to account for these factors could result in about 50% error in estimation of modulus of subgrade reaction [4]. Mondal et al. [5] studied the influence of superstructure modelling on behaviour of raft foundation. The study concluded that modelling of superstructure reduces the design stresses and moment for foundation significantly, and hence results in economical design. The study also noted that modelling of horizontal stiffness of raft does not have much influence on the behaviour of raft foundation. Marto et al. [6] studied the relationship between modulus of subgrade reaction (K_s) and the footing dimensions through an analytical study in PLAXIS 2D software, with and without considering the effect of water. The study suggested that K_s is inversely proportional to width of the foundation but the relationship is non-linear.

The study also highlighted that water decreases the internal contact pressure of soil particles, which leads to reduction in the value of K_s due to lower resistance to stress and higher tendency to settle under loading. With increase in the size of the footing the reduction in internal contact pressure due to saturation of soil decreases, and for foundation size larger than 4 m, the variation in values of K_s for saturated and unsaturated soil is less than 25%.

Hany and Mohammed [7] studied the effect of footing-clayey soil system rigidity on the modulus of subgrade reaction (K_s) and suggested that footing rigidity has significant influence on the distribution of K_s beneath the footing. The study also noted that K_s distribution based on linear elastic and elastic perfect plastic models are quite different. It was also stated that at the edges of the footing, K_s distribution is not appropriate as per the linear elastic model, as this model does not account for the plasticity of soil. It was noted that an unrealistic tension in elastic soil model may be generated at the edge of the footings. Further, the study suggests that a new modification factor is required to take into account the rigidity of footing, while computing K_s from plate load test. The study concluded that K_s is uniformly distributed under the flexible footing; however, K_s is concentrated near edges and has low values at the centre of footing for the semi-rigid or rigid footings. Lemman et al. [8] carried out centrifuge test studies to understand the influence of foundation stiffness on strip foundation supported on sand. The study noted that relative stiffness of foundation and soil affects the contact pressure and settlement distribution below foundation. It was also noted that reduction in foundation stiffness results in reduction in contact pressure at edges. The study also observed that initially stiff foundation upon cracking behaves as more flexible foundation.

The review of literature suggests that not many studies have reported the influence foundation rigidity and modulus of subgrade reaction on different parameters for foundation design such as base pressure, settlement, bending moment and shear stress in foundation. It is opined that such studies would enhance the understanding of foundation behaviour due to variation of different factors and would help to arrive at a decision matrix for optimum design of foundation. With this perspective, the present study evaluates the influence of foundation rigidity and modulus of subgrade reaction on different parameters governing the foundation design.

2 Theoretical Background and Methodology

2.1 Theoretical Background: Winkler's Approach

Winkler's model represents the soil subgrade as a system of identical but mutually independent (discrete), closely spaced and linear elastic springs. Winkler's model of an elastic foundation assumes that the deflection y at any point on the surface of the foundation is proportional to the stress σ at that point, i.e. $\sigma = K_s.y$, where K_s is

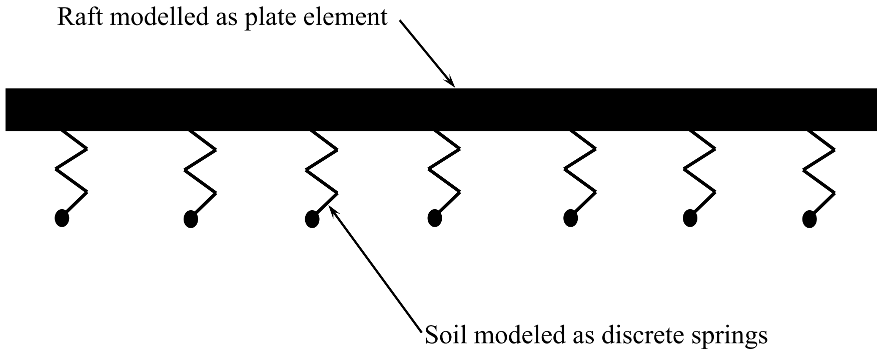


Fig. 1 Conceptual representation of Winkler soil springs connected with raft

called modulus of subgrade reaction of the foundation system. The modelling of foundation supported on discrete springs is based on modified Winkler's approach where the discrete soil springs are connected by continuous raft (plate), which distributes the load to different springs based on its rigidity and loading conditions. Figure 1 depicts the schematic view of Winkler soil springs connected with raft.

2.2 *Methodology*

STAAD Pro V8i software [9] is the one of the most popular finite element-based software in practice for analysis and design of structures including foundation, wherein the foundation and superstructure can be modelled together to understand the combined effects for simple as well complex structures. It is preferable to model foundation in Staad Pro along with superstructure if the foundation is expected to behave as flexible foundation. In Staad Pro, the flexible foundation can be modelled using plate elements. In the present study, a 10-storey reinforced concrete building frame with five bays each of 5 m span in both directions and 4 m as storey height is modelled in Staad Pro. The foundation raft is modelled as a mesh of four-noded plate elements, with each plate element of size 0.5 m × 0.5 m. The plate size is selected based on the authors past experience.

Figure 2 shows the plan view with dimensions and Fig. 3 shows typical three-dimensional view of the model. Further, Fig. 4 shows that local axes for plate element are different that the global axes for the overall model. A clockwise modelling of plate starting from top-left node results in local axes as shown in the figure. As per the foundation modelling procedure considered in the study, positive value of moment indicates tension at bottom (sagging moment), i.e., local *z*-direction. It may be noted that change in modelling procedure of plate element would result in different orientation of local axes and would result in different interpretation of results

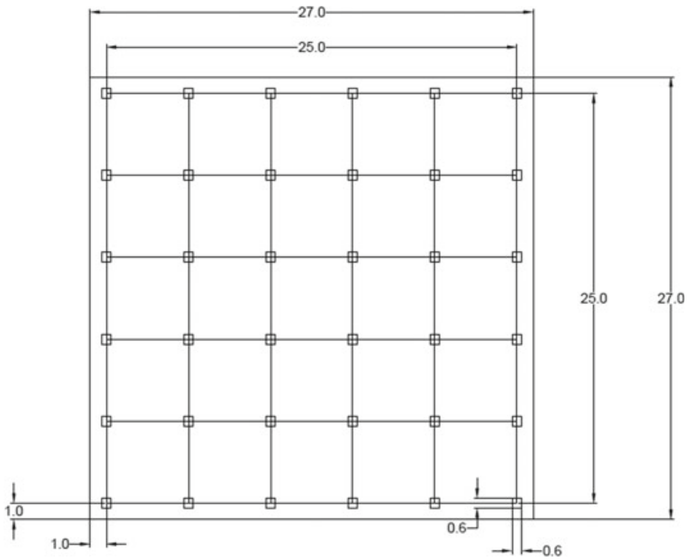
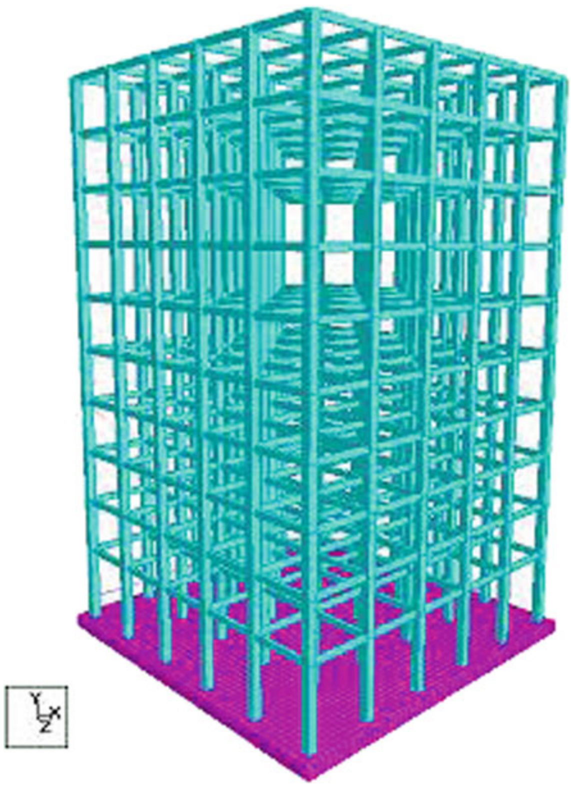


Fig. 2 Plan dimensions of building and foundation considered in the study (in metres)

Fig. 3 Three-dimensional view of multistoreyed building with raft foundation



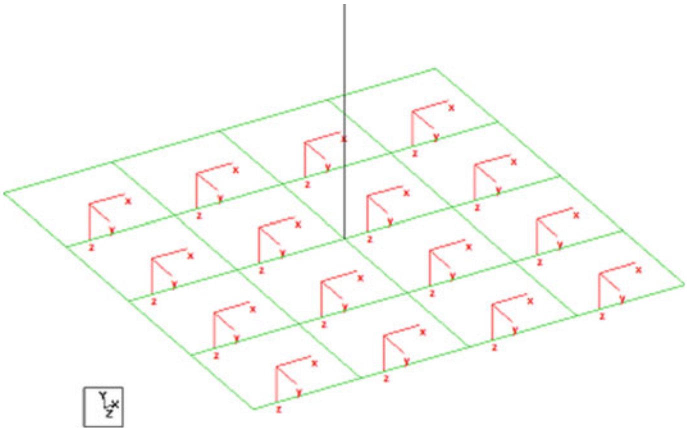


Fig. 4 Local and global axes in Staad Model

(shear stress and bending moment). The size of foundation raft is considered as 27 m × 27 m in the present study, with edge of raft having an offset of 1 m from centre of edge columns.

2.3 *Method of Analysis*

STAAD Pro uses the finite element method for analysis of any structure. A ten-storeyed symmetric building was analysed as a three-dimensional frame with appropriate dimensions of the beams (0.23 m × 0.45 m) and columns (0.6 m 0.6 m) under the combined impact of vertical dead load and live load. The 230 mm thick wall (not modelled) load was applied as uniformly distributed load on beams in the model. For the live load, the building was assumed to be an institutional building and the live load of 4 kN/m^2 was applied as per Indian Standard IS-875 Part-II [10]. The parameters and their values used in the study are summarized in Table 1.

At each node of the foundation raft (plate elements), vertical spring stiffness values were assigned with Staad command as depicted in Fig. 5. For the same building, considering five different values of modulus of subgrade reaction (K_s) and five different values of raft thickness (t_r), total 25 cases were analysed and the change in the foundation analysis parameters like base pressure, settlement, shear stress and bending moment were compared and explained in the next section.

Table 1 Parameters and values used in the study

Parameter	Values used in study					Units
Modulus of elasticity of concrete (E)	2.17×10^7					kN/m^2
Dimensions of raft	27 × 27 (For ten-storey building with five bays in both direction, each bay with 5 m centre to centre span and storey height of 4 m)					m
Modulus of subgrade reaction (K_s)	2000	4000	6000	8000	12000	kN/m^3
Thickness of raft	0.5	0.6	0.7	0.8	0.9	m
Flexural rigidity of raft (EI)	6103125	10546200	16746975	24998400	35593425	kN-m^2

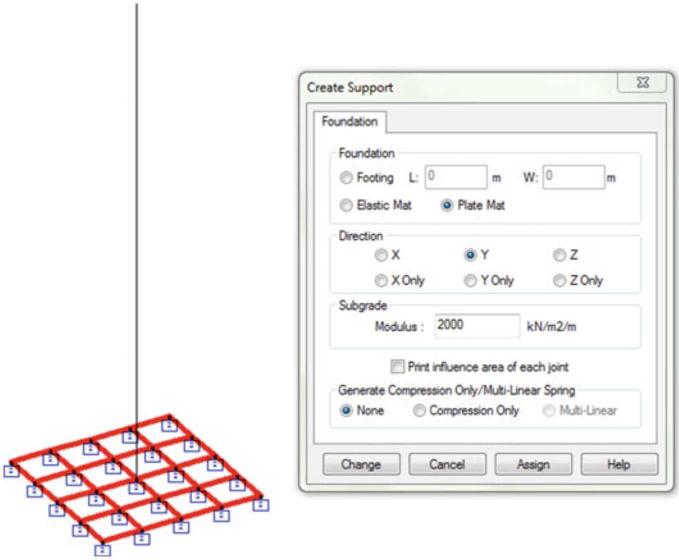


Fig. 5 Soil spring definition for raft foundation in Staad Pro

3 Results and Discussion

Total 25 cases have been analysed in the study. The raft foundation thickness (t_r) have been varied as 0.5 m, 0.6 m, 0.7 m, 0.8 m and 0.9 m. The values of modulus of subgrade reaction (K_s) have been varied as 2000 kN/m^3, 4000 kN/m^3, 6000 kN/m^3, 8000 kN/m^3 and 12000 kN/m^3. Figure 6 shows the maximum and minimum base pressure for different values of raft thickness, t_r and modulus of subgrade reaction, K_s.

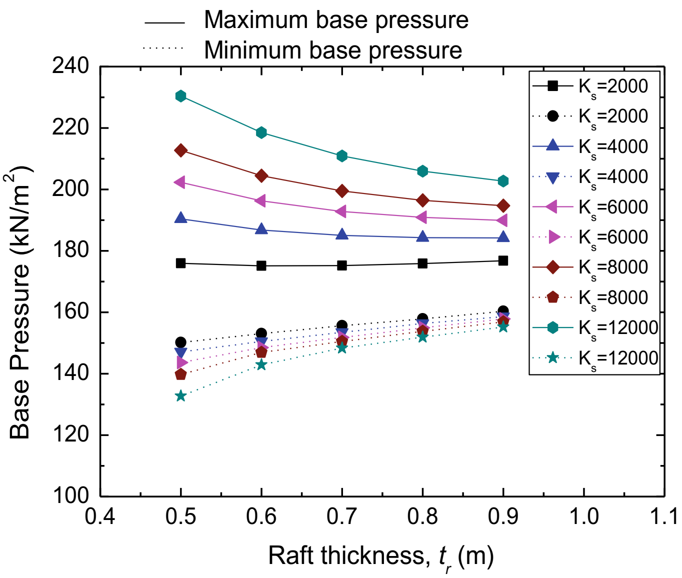


Fig. 6 Maximum and minimum base pressure of raft foundation for different values of 't_r' and 'K_s'

It can be observed from the figure that with increase in t_r and K_s, the maximum base pressure reduces and minimum base pressure increases. In order to understand the influence of t_r and K_s on variation in base pressure within foundation, the percentage variation between maximum and minimum foundation base pressure is plotted for different values of t_r and K_s as depicted in Fig. 7. The influence of K_s on base pressure is observed to be higher as compared to t_r. It can be observed from the figure that at higher values of K_s (12000 kN/m^3) and lower value of t_r (0.5 m), the base pressure variation is found to be maximum (42.4%). Further, minimum base pressure variation in foundation is observed for lower value of K_s (2000 kN/m^3) and higher value of t_r (0.9 m). This indicates that for lower values of K_s, the base pressure tends to be more uniform as compared to higher values of K_s. Moreover, increase in rigidity of foundation tends to make base pressure distribution more uniform. Hence, the rigidity of foundation and its relative stiffness with respect to soil affects base pressure distribution. Further, it can be noted from Fig. 8 that settlement of foundation is inversely proportional to K_s as expected. It can also be seen that settlement is not significantly influenced by thickness of raft (t_r). However, it can be clearly observed that the difference between maximum and minimum settlement (differential settlement) within foundation raft reduces with increase in t_r.

In order to quantify this, Fig. 9 shows the variation of differential settlement for different values of K_s and t_r. It can be observed from the figure that differential settlement is maximum (12.9 mm) for lower values of K_s (2000 kN/m^3) and t_r (0.5 m) and is minimum (3.95 mm) for higher values of K_s (12000 kN/m^3) and t_r (0.9 m). However, a comparison for Figs. 8 and 9 indicates that the differential

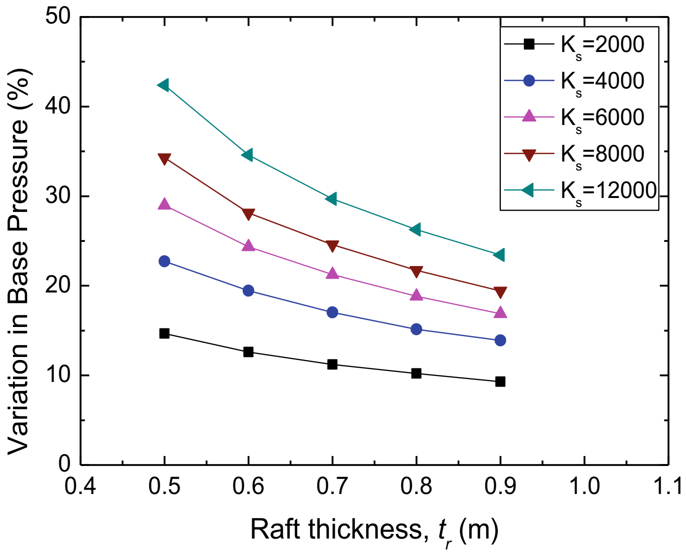


Fig. 7 Variation in base pressure of raft foundation for different values of 't_r' and 'K_s'

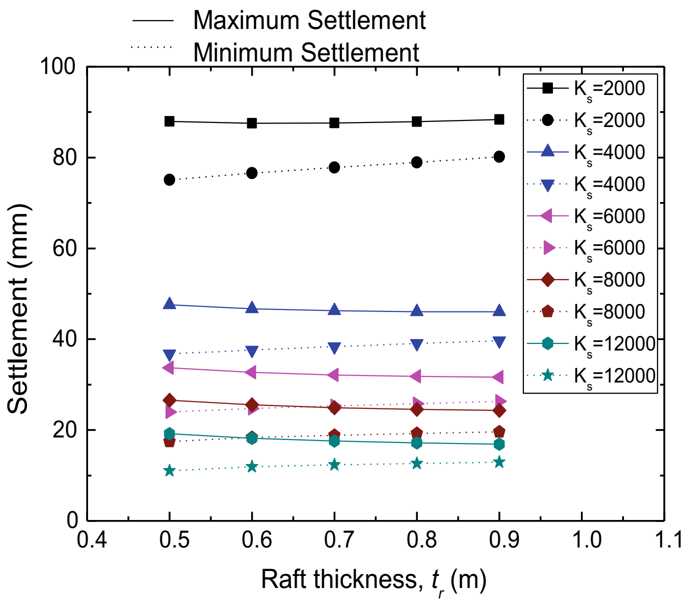


Fig. 8 Maximum and minimum settlement of raft foundation for different values of 't_r' and 'K_s'

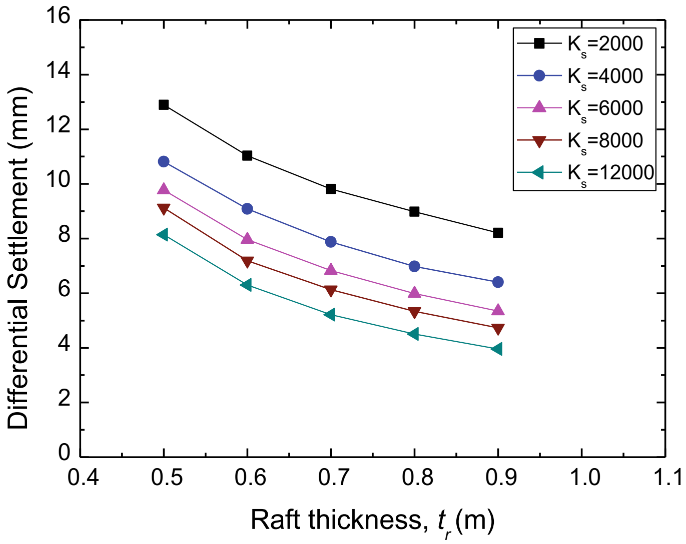


Fig. 9 Differential settlement of raft foundation for different values of 't_r' and 'K_s'

settlement expressed as percentage of maximum settlement for case with K_s = 2000 kN/m^3 and t_r = 0.5 m is 14.65%, whereas for case with K_s = 12000 kN/m^3 and t_r = 0.9 m, differential settlement is about 23.44% of maximum settlement. This indicates that for foundation with low rigidity supported on soft soil, the settlement distribution is relatively uniform as compared to foundation with higher rigidity on stiff soil. Further, for case with K_s = 12000 kN/m^3 and t_r = 0.5 m, the differential settlement is observed to be about 42.4% of maximum settlement in foundation. This suggests that for foundation with low rigidity on stiff soil, settlement is non-uniform due to non-uniformity in base pressure distribution (flexural effects) as seen from Fig. 7. It may be noted that the maximum settlement is generally observed at corner of the foundation and minimum settlement is observed between column locations on the raft foundation. The typical variation of base pressure for two cases (K_s = 2000 kN/m^3 and t_r = 0.5 m; K_s = 12000 kN/m^3 and t_r = 0.9 m) is depicted in Fig. 10.

In order to further compare the influence of K_s and foundation flexural rigidity, EI (refer Table 1) on percentage variation in foundation base pressure (percentage variation between maximum and minimum base pressure within foundation), the ratio of K_s and EI values with respect to their corresponding base values in the study (K_s = 2000 kN/m^3; EI = 6.10 $\times$ 10^6 kN-m^2, flexural rigidity for foundation of size 27 m $\times$ 27 m and 0.5 m thickness) are presented with respect to percentage variation in base pressure in Table 2. These ratios are designated as K_{sn} and EI$_n$, respectively. It can be clearly seen that increase in K_s values by six times increase the variation in base pressure by about 189%. However, an increase in EI by about 5.83 times results in reduction in variation in base pressure by about 36.59%. This clearly indicates that the

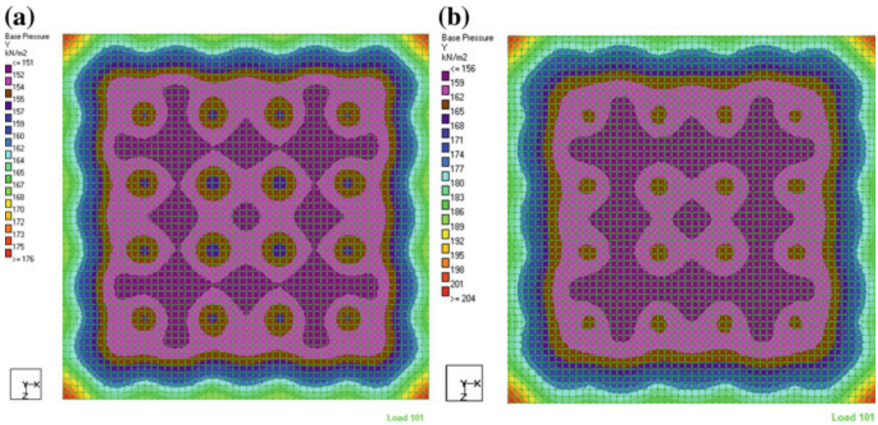


Fig. 10 Variation of base pressure diagram of raft foundation for (**a**) K_s = 2000 kN/m^3 and t_r = 0.5 m, (**b**) K_s = 12000 kN/m^3 and t_r = 0.9 m

Table 2 Influence of variation in K_s and EI values on percentage variation in base pressure

EI_n	Ks_n				
	1	2	3	4	6
1.00	14.65	22.72	29.00	34.31	42.40
1.73	12.59	19.46	24.34	28.13	34.60
2.74	11.20	17.03	21.24	24.57	29.68
4.10	10.22	15.14	18.82	21.73	26.26
5.83	9.29	13.91	16.88	19.43	23.43

influence of K_s on base pressure distribution is more prominent as compared to rigidity of foundation. Further, it can also be inferred that base pressure variation can be expected to be larger for soil after ground improvement (higher K_s) as compared to unimproved ground (lower K_s). However, lower values of total settlement and differential settlement for stiffer soil (after ground improvement) would result in higher allowable base pressure and would compensate for this effect. It may be inferred from the study that K_s influences the dimensioning of the raft foundation (based on its effect on base pressure and corresponding settlement). Hence, it is an important parameter of foundation design.

To understand the influence of K_s and t_r on the bending moment and shear stress in foundation, values of these parameters (Bending Moment, M_x along global x-direction) and Shear stress (SQ_x) perpendicular to global *x*-y plane are plotted as depicted in Figs. 11 and 12. It can be concluded from these figures that K_s has negligible influence on variation in M_x and SQ_x. However, it is observed that M_x increases marginally and SQ_x reduces with increase in t_r.

It may be noted that the increase in thickness of raft foundation is expected to result in better load distribution from raft to soil. This distribution is expected to reduce the total settlement, differential settlement variation below the raft and the bending

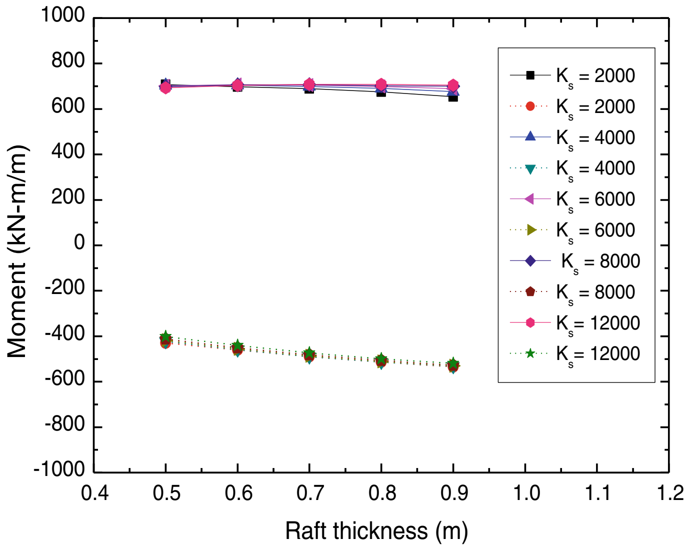


Fig. 11 Bending moment (M_x) in raft foundation for different values of 't_r' and 'K_s'

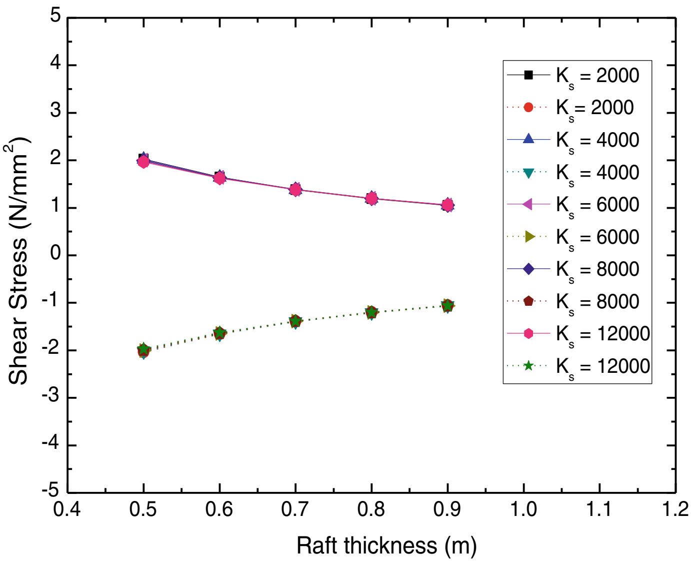


Fig. 12 Shear stress (SQ) in raft foundation for different values of 't_r' and 'K_s'

moment in raft. However, increase in thickness of raft would cause additional self-weight induced bending moment. It appears that the combined effect of both these aspects partly nullifies each other and hence the changes in bending moment appears to less with increase in foundation raft thickness. The reduction in shear stresses with increase in raft thickness can be attributed to increase in the shear resisting area with increase in raft thickness. Further, for design of raft foundation, as shear reinforcement is usually avoided, the thickness would also be governed by the limiting value of shear stress on foundation mainly based on the grade of concrete. Appropriate reinforcement design is usually provided to resist the bending moment in raft.

In spite of the findings, the current study has some limitations. The soil springs defined in Staad Pro are discrete springs, which are not inter-coupled. The distribution of stresses due to soil continuum cannot be accounted for in Staad Pro software. However, load distribution to different springs due to continuity of raft partially overcome this limitation especially under loaded area; however, the same cannot be concluded in unloaded areas under raft. Interestingly, a recent study by Lee et al. [11] suggested comparable foundation base pressure versus settlement response of foundation when soil is modelled as Winkler spring (no coupling) as compared to soil model which accounts for inter-coupling. Further, this study does not consider the effect of change in rigidity of foundation due to its cracking [12]. The study also does not account for variation in modulus of subgrade reaction at centre and edges of foundation depending of the type of soil. The present study also does not account for wind load and seismic load effects, which is part of extended study by the authors. However, in spite of these limitations, the study attempts to present a clear understanding of the influence of foundation thickness and modulus of subgrade reaction on base pressure, settlement, shear stress and bending moment in raft foundation. It is believed that such studies would be useful to arrive at a decision matrix for optimum foundation design in practice.

4 Conclusions

The present study evaluates the influence of change in foundation rigidity and modulus of subgrade reaction on the base pressure, settlement of foundation as well as shear stress and bending moment within the foundation. The following conclusions can be derived from the study:

1. The influence of modulus of subgrade reaction, K_s is more prominent on foundation base pressure distribution as compared to the influence of rigidity of foundation. It is concluded from the study that increase in K_s values results in higher variation in base pressure distribution, whereas increase in rigidity of foundation results in more uniform base pressure distribution.
2. It is observed that differential settlement is lower for stiff soil (higher K_s) as compared to soft soil (lower K_s). This is mainly due to significant reduction in total settlement of foundation. However, the percentage variation in maximum and minimum settlement is higher for stiff soil as compared to soft soil, which can be attributed to larger variation of base pressure in stiff soil. Further, differential settlement reduces with increase in rigidity of foundation.

3. It is noted from the study that maximum base pressure is higher for stiff soil as compared to soft soil. Hence, it can be inferred that soil after ground improvement (stiff soil) would experience higher maximum base pressure as compared to unimproved ground (softer soil) for the same foundation and loading conditions. However, higher allowable base pressure due to lower total/differential settlement and higher bearing capacity (shear criteria) for improved ground would compensate this effect.
4. The variation in modulus of subgrade reaction, K_s is observed to have negligible influence on bending moment and shear stress in raft foundation. However, increase in rigidity of foundation results in slightly higher bending moment and lower values of shear stress.

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