EFFECT OF STRUCTURE STIFFNESS ON STRESSES DISTRIBUTION UNDER THE FOUNDATION

[1]El-Sakhawy N. R. , [2]El-Kilany M. El., [3]El-Sayed T. A. , [4]El-dosoky A. I.

[1]Professor, Faculty of Engineering, Zagazig University, Egypt.
E-mail: nrel.mh@gmail.com
[2]Associate Professor, Faculty of Eng., Zagazig University, Egypt.
E-mail: melazab2014@yahoo.com
[3]Assistant Professor, Faculty of Engineering, Banha University, Egypt
E-mail: eng.taha.rc@gmail.com
[4]Grad. Student, Faculty of Engineering, Zagazig University, Egypt
E-mail: ahmeddosoky62@yahoo.com

ABSTRACT

Foundation response is a complex interaction of the foundation itself, the superstructure, and the soil. That interaction may continue for a long time until final equilibrium is established between the superimposed loads and the supporting soil reactions.

In many projects, designers of superstructure simulate soil as springs with subgrade reaction which mean that soil is one layer with liner reaction. This simulation neglects settlement of soil, types and properties of soil layers, underground water table and surrounded structures. The same happened in preparing the soil investigation and the soil report for any project which take only the loads transferred from the structure or assumed uniform distribution and do not take into consideration the effect of structure elements stiffness.

This paper presents a study to evaluate the effect of various factors on the stresses distribution under the foundation and on columns loads such as Soil type (modulus of subgrade reaction), Footing depth, Superstructure stiffness (slabs thickness-beams depth) and Number of stories. Numerical analyses were carried out in more than 300 model adapting three dimensional finite element software program (SAP2000 version 16).

The study concluded that the columns loads can be redistributed by controlling the relative stiffness between columns – slabs, columns – beams and columns – raft to achieve uniform stresses distribution under the foundation.

Keywords: Stresses distribution, modulus of sub grade reaction "Ks", structural analysis, SAP2000, foundation analysis, beam depth and slab thickness.

INTRODUCTION

The development of modern cities with limited surface space has led to an increase in the rate of construction of high-rise buildings. The foundation of such buildings presents a geotechnical challenge where the soil-structure interaction plays an important role to achieve the most economic design that satisfies all safety and serviceability requirements. The cooperation between both geotechnical and structural engineers is necessary to reach a successful design. In any structure, the superstructure and the foundation founded on soil constitute a complete structural system. [1].The analysis of the superstructure without modelling the foundation system and without considering the rigidity of structure may result in the misleading estimation of forces, the bending moments, the settlements etc. It is necessary to carry out the analysis considering the soil, the foundation and the superstructure. The real behaviour of the raft is obtained by the interaction analysis. [5]

The coefficient of sugared reaction "Ks" can be considered as an appropriate interface between the geotechnical and structural engineers. The sub grade reaction modulus is not a soil constant but it depends on many factors such as dimensions of foundation, soil conditions, load level, and superstructure rigidity. [6].Winkler theory is the common theory for calculating the contact stresses using the modulus of sub grade reaction, which does not consider all these factors. [7]

1.1 Soil Structure Interaction of Shallow Foundations

The prediction of contact stress and settlement under foundations depend on the super-structure, the foundation, the soil, and their simultaneous interaction. The exact distribution of contact stress is highly indeterminate problem. There are four available methods to determine contact stress under foundations:
1. Conventional analysis
2. Sub grade reaction theory.
3. Methods based on theory of elasticity (Linear Elastic model).
4. Numerical analysis (finite element method). [7]

1.2 Winkler Model (1867)

Winkler model assumes that the soil acts a bed of evenly spaced independent linear springs as shown in Fig. 1.1. It also assumes that each spring deforms in response to the vertical stress applied directly to that spring, and does not transmit any shear stress to the adjacent springs. Although, in real soils the displacement distribution is continuous. The deflection under a load can occur beyond the edge of the slab and the deflection diminished at some finite distance. [1]
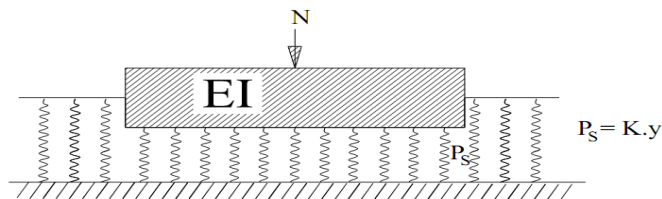

Fig. 1: The soil as infinite number of springs

1.3 Methods Employed for Determine the Coefficient of Sub grade Reaction

Jamshid and Maryam compared between different methods proposed for determination modulus of sub grade reaction Ks and evaluated their suitability and accuracy. They confirm that among the methods for determination of Ks value, Vesic relation leads to acceptable accuracy in evaluating settlement in comparison to the soft soil model. Accordingly, this relation is the governing relation for estimating Ks in our study. [3]

1.4 Node Springs and Modulus of Sub grade Reaction Ks for Mats and Plates

All methods employed for analysis mats and plates use the modulus of sub grade reaction Ks to support the plate. The modulus Ks is used to compute node springs based on the contributing plan area of an element to any node as shown in Fig.2 For these area contributions the fraction of Ks node resistance from any element equal (Ks (node) = Ks x Area) (KN/M3 x M2 = KN/M). [2&5]
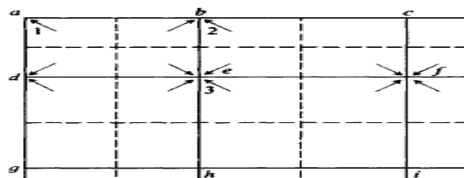

Fig.2: Method of prorating Ks to build node springs for rectangles

From Fig.2 node springs are computed as the following Table 1.1

Table 1: Node spring constant (Ks) as per Fig.1.2

Point	Contribution Area
1 (Corner)	1/4 of rectangle (abde)+1/4 of rectangle (bcef)
2 (Edge)	1/4 of rectangle (abde)
3 (Interior)	1/4 of each rectangle framing to a common node (as node 3)

1.5 Contact Pressure Distribution

The relative distribution of soil contact pressures and displacements varies depending on flexibility of the foundation and type of soil, as shown in Fig. 3. The distribution of contact pressure depends on the characteristics of the soil and the foundation. The governing characteristics are Young's modulus of the foundation material, E, Young's modulus of the supporting soil, Es, the thickness of the foundation, d, and the footing width, B. These factors express the relative rigidity, k, such as in Equation 1:

$$k = \frac{E}{E_s}\left(\frac{d}{B}\right)^3$$

Equation 1

 The foundation is too rigid, when $k \geq 2.00$. In this case, the contact pressure at the boundary is higher than that under the concentrated loads, as shown in Fig. 3. The foundation is flexible if $k \leq 0.005$. In this case the contact pressure concentrates under the loaded area. Elastic Winkler foundation should be solved numerically. The conventional method of design of a footing is to assume the footing as rigid and the distribution of contact pressure at the surface of contact between the base of a foundation and the supporting soil as planar. That is, uniform or uniformly varying surface of contact depends upon whether the foundation supports symmetric or eccentric loading. [4]
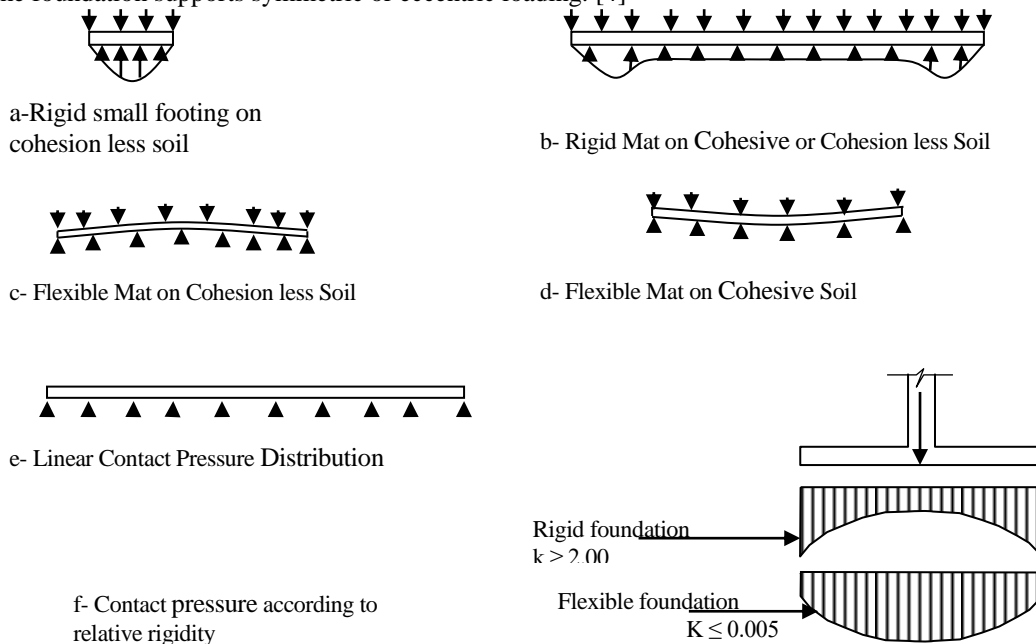
a-Rigid small footing on cohesion less soil

b- Rigid Mat on Cohesive or Cohesion less Soil

c- Flexible Mat on Cohesion less Soil

d- Flexible Mat on Cohesive Soil

e- Linear Contact Pressure Distribution

Rigid foundation
k > 2.00

f- Contact pressure according to relative rigidity

Flexible foundation
K ≤ 0.005

Fig. 3: Relative distribution of soil contact pressures and displacements

2. NUMERICAL STUDIES

2.1 Computer Analysis for Mat Foundation

Computer analysis for mat foundation is usually based on an approximation where the mat is divided into a number of discrete finite elements using grid lines. There are three general discrete element formulations which may be used:

1- Finite Difference (FD).
2- Finite Grid Method (FGM).
3- Finite Element Method (FEM).

All three of these methods use the modulus of sub grade reaction k, as the soil contribution to the structural model. Computers and available software make the use of any of the discrete element methods economical and rapid.

2.2 Finite Element Solution (Sap 2000) [8]

SAP2000 is a full-featured program that can be used for the simplest problems or the most complex projects.

2.2.1 Shell Element

The six faces of a shell element are defined as the positive 1 face, negative 1 face, positive 2 face, negative 2 face, positive 3 face and negative 3 face as shown in Fig. 4. In this definition the numbers 1, 2 and 3 correspond to the local axes of the shell element. [8]
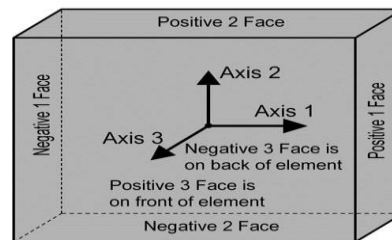

Fig. 4: Shell element faces

Note that the positive 3 face is sometimes called the top of the shell element in SAP2000 and the negative 3 face is called the bottom of the shell element.

2.2.2 Frame Element Internal Forces and Moments

The frame element internal forces and moments are present at every cross-section along the length of the frame. For each load pattern and load combination the frame internal forces and moments are computed and reported at each frame output station as following:

1- P, the axial force
2- V2, the shear force in the 1-2 plane
3- V3, the shear force in the 1-3 plane
4- T, the axial torque (about the 1-axis)
5- M2, the bending moment in the 1-3 plane (about the 2-axis)
6- M3, the bending moment in the 1-2 plane (about the 3-axis) [8].

2.2.3 Joint Local Axes

The joint local 1-2-3 coordinate system is identical to the global X-Y-Z coordinate system. Spring forces are reported as forces acting on the elements connected to the support. They are reported with respect to
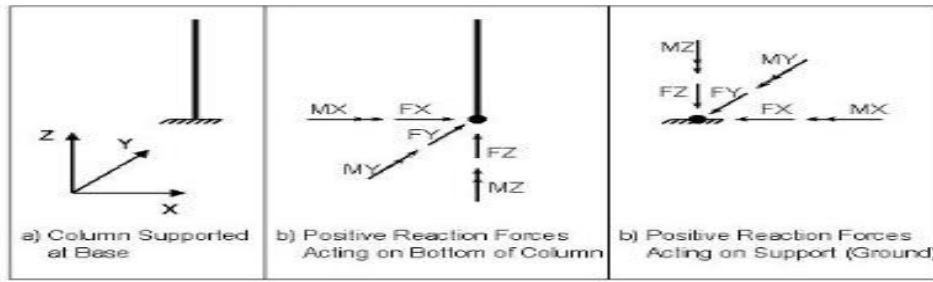
the global

coordinate system as shown in Fig. 5. Positive spring forces act in the same direction as the positive global axes. [8]

Fig. 5: Positive support reaction forces

2.2.4 Joint Spring

Both translational and rotational springs can be assigned to a joint. Spring direction and coordinate system are being assigned. Also, values of spring stiffness in the three translation and three rotation local directions are being assigned. Note that joint spring stiffness's are always specified in the local coordinate system. [8]

3. Variables of the Study

3.1 Models Geometries

Models geometries are constant and symmetric as shown in Fig. 6 & Fig. 7 Models dimensions are 10 m x 10 m, consist of two equal spans in the both directions, supported by 9 columns with dimensions 40 cm $\times$ 40 cm. The models are constructed on a square mat foundation. The mat will be founded at 1.5 m below the original ground level.

3.2 Statically Systems

The statically system is solid slab with constant slab thickness 20 cm, when each bay is surrounded by beams with width 30 cm and variable depth. Models are constructed on square raft with dimensions 10 m x 10 m and variable thickness.
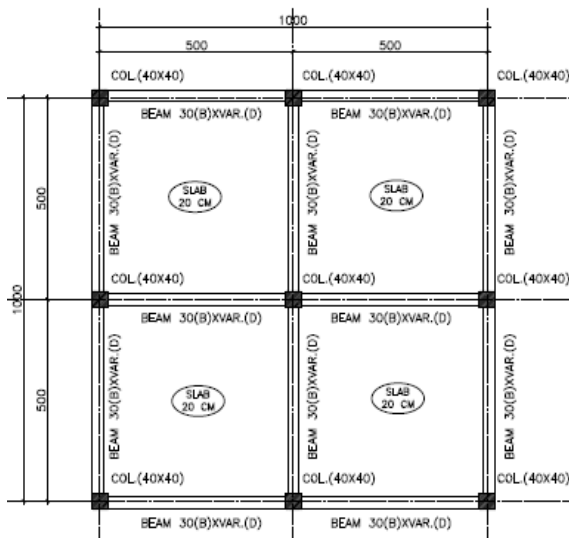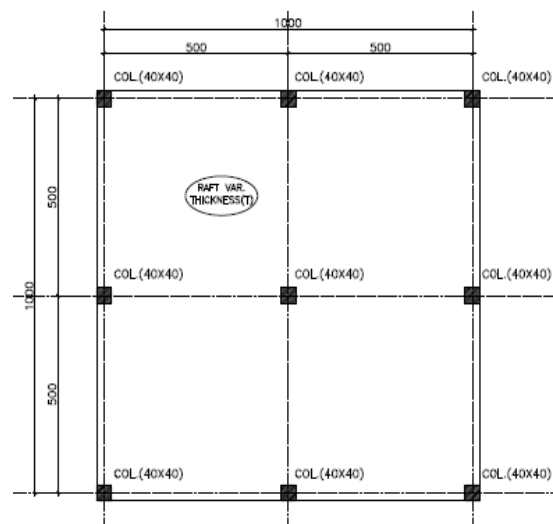

Fig. 6: Solid slab system　　　　　　**Fig. 7: Raft system**

3.3 Number of Stories

This study includes two types of models consist of five & ten stories with constant story height 3.0 m.

3.4 Structure Elements Dimensions

3.4.1 Raft Thickness
In models consist of five stories, raft thickness is variable from (40 cm = span/12.5) to (100 cm = span/5) and in models consist of ten stories, raft thickness is variable from (80 cm = span/8.33) to (140 cm = span/3.57).

3.4.2 Columns Dimensions
In all models, columns dimensions are constant and equal 40 cm x 40 cm (span/12.5 in the both direction).

3.4.3 Slab Thickness
Slab thickness is constant and equal 20 cm (span/25).

3.4.4 Beams Depth
Beams depth is variable from (40 cm = span/12.5) to (100 cm = span/5).

3.5 Applied Loads and Load Combinations
Loads applied on the models are uniform and constant in all stories and all models. In this study, own weight is calculated automatically by the program. Applied covering load is 3.0 KN/m2 and live load is 2.0 KN/m2. Columns reactions are computed by service load combination equal (1.0 own weight + 1.0 covering load + 1.0 live load).

3.6 Springs Constant
The modulus of sub grade reaction Ks is used to compute node springs based on the contributing plan area of an element to any node. (Joint spring = Modulus of sub grade reaction x area) as follow:
1- Interior springs = Ks x 1.0.   (Mesh 0.50 m x 0.50 m)
2- Edge springs = Ks x 0.50.   (Mesh 0.50 m x 0.50 m)
3- Corner springs = Ks x 0.25. (Mesh 0.50 m x 0.50 m)

3.7 Soil Types
Two types of soil are employed in this study. The properties and descriptions of the two types are summarized in Table 2.1. "Vesic" relation- Equation 2 is the governing relation for estimating Ks in our study. Substituting υs (poisson,s ratio) = 0.3, B (footing width) = 10 m, EcIc (flexural rigidity of the raft) =2.50×1010 KN.m2 and Es (soil modulus of elasticity) as shown in Table 2.

$$k_s = \frac{0.65\,E_s}{B\,(1-v_s^2)} \sqrt[12]{\frac{E_s B^4}{EI}} \quad \text{Equation 2}$$

Table 2: Soil properties and descriptions

Soil Type	Soil description	Soil Young's Modulus Es (KPa)	Bearing capacity B.C (KN/m^2)	Modulus of Sub grade Reaction Ks (KPa)
Type (1)	Medium Dense sand	570039	300	36000
Type (2)	Loose Sand	109046	120	6000

4. ANALYSIS AND RESULTS

The numerical analysis carried out by three dimensional finite element program (Sap 2000–ver.16).This analysis studies the effect of various factors on the stresses distribution under the foundation such as:
1- Soil type (modulus of sub grade reaction).
2- Raft thickness.
3- Superstructure stiffness (beams depth).
4- Number of stories
In order to indicate this effect in a clear way, columns loads (corner, edge, internal column) are computed and compared in all models. Variation in column load can be consider as an indication to the same

variation in stresses under this column because raft dimensions and meshing are constant and equal for all models. σ (stresses) =P (column load) /A (area), according to constant area (A) we can consider that ($\sigma \alpha$ P).

4.1 Models Consist of 5 Stories with Soil Type (1) (Modulus of Sub-grade Reaction Ks=36000 KPa):
Fig. 8 indicate that corner column load decrease by 9% when beams depths increase from 40 cm to 100 cm in models with raft thickness 40, 60 and 80 cm and decrease by 5% in models with raft thickness 100 cm. It also clears that there is an insignificant difference between corner column load in models with raft thickness 40 cm and models with raft thickness 60 cm. Corner column load increase by 6% at beams depth 40 cm when raft thickness increase from 40 cm to 100 cm and increase by 10% at beams depth 100 cm.
Fig. 9 indicates that there is an insignificant difference in edge column load when beams depths increase from 40 cm to 100 cm in all models. They also clears that there is big difference between edge column load in models with raft thickness 40 cm and other models.
Fig. 10 indicates that internal column load increase by 10% when beams depths increase from 40 cm to 100 cm in models with raft thickness 40 cm and increase by 6% in models with raft thickness 60 cm. It also clears that there is an insignificant difference in internal column load when beams depths increase from 40 cm to 100 cm in models with raft thickness 80 cm and 100 cm. Internal column load decrease by 10% at beams depth 40 cm when raft thickness increase from 40 cm to 100 cm and decrease by 22% at beams depth 100 cm.
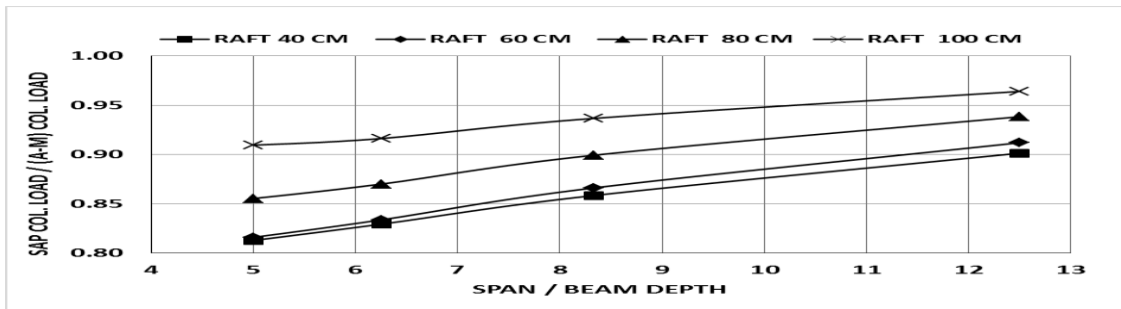

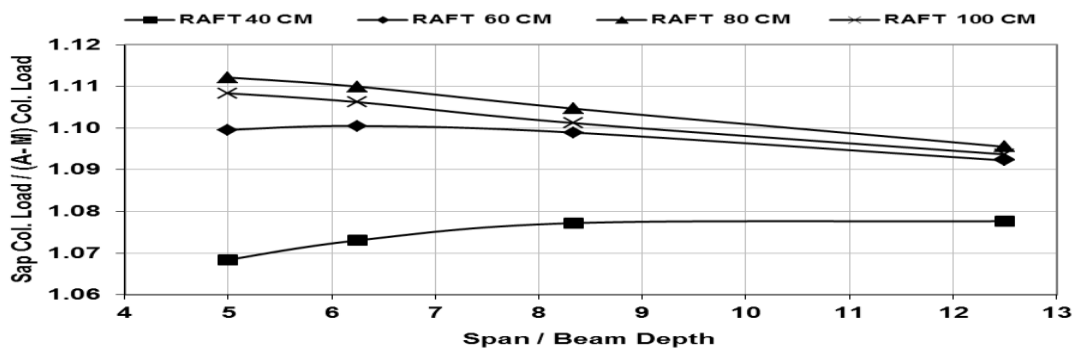**Fig. 8: Corner column load in models consist of 5 stories and soil type (1)-Ks=36000 KPa**

Fig. 9: Edge column load in models consist of 5 stories and soil type (1) -Ks=36000 KPa
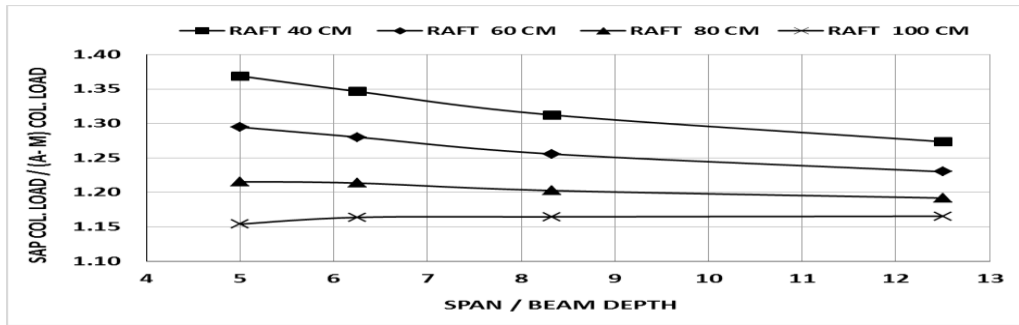
Fig. 10: Internal column load in models consist of 5 stories and soil type (1) -Ks=36000 KPa

4.2 Models Consist of 10 Stories with Soil Type (1) (Modulus of Sub-grade Reaction Ks=36000 KPa):

Fig. 11 indicates that corner column load decrease by 5% when beams depths increase from 40 cm to 100 cm in models with raft thickness 80 cm and increase by 5% in models with raft thickness 140 cm. It also clears that there is an insignificant difference in corner column load when beams depths increase from 40 cm to 100 cm in models with raft thickness 100 cm and 120 cm. Corner column load increase by 11% at beams depth 40 cm when raft thickness increase from 80 cm to 140 cm and increase by 21% at beams depth 100 cm.

Fig. 12 indicates that there is an insignificant difference in edge column load when beams depths increase from 40 cm to 100 cm in all models. Edge column load decrease by 2% at beams depth 40 cm when raft thickness increase from 80 cm to 140 cm and decrease by 4% at beams depth 100 cm.

Fig. 13 indicates that there is an insignificant difference in internal column load when beams depths increase from 40 cm to 100 cm in models with raft thickness 80 cm and 100 cm. It also clears that internal column load decrease by 6% when beams depths increase from 40 cm to 100 cm in models with raft thickness 120 cm and decrease by 8% in models with raft thickness 140 cm. Internal column load decrease by 9% at beams depth 40 cm when raft thickness increase from 80 cm to 140 cm and decrease by 18% at beams depth 100 cm.
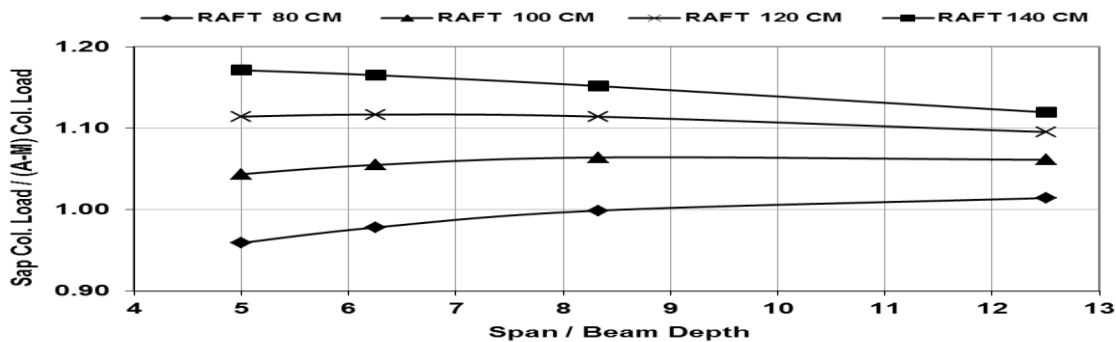

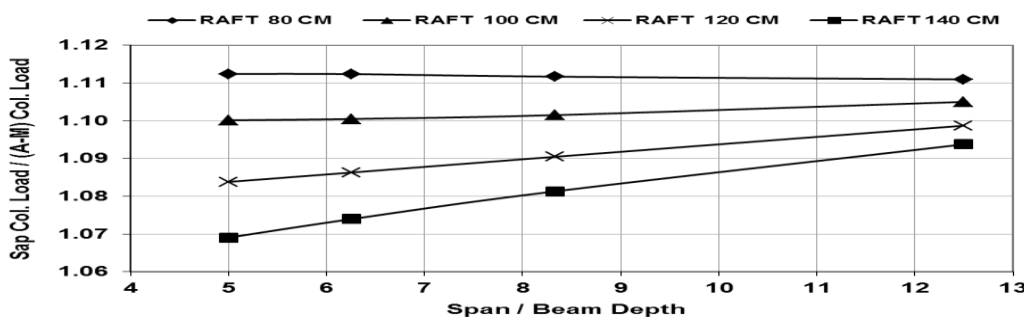**Fig. 11: Corner column load in models consist of 10 stories and soil type (1) -Ks=36000 KPa**

Fig. 12: Edge column load in models consist of 10 stories and soil type (1) -Ks=36000 KPa
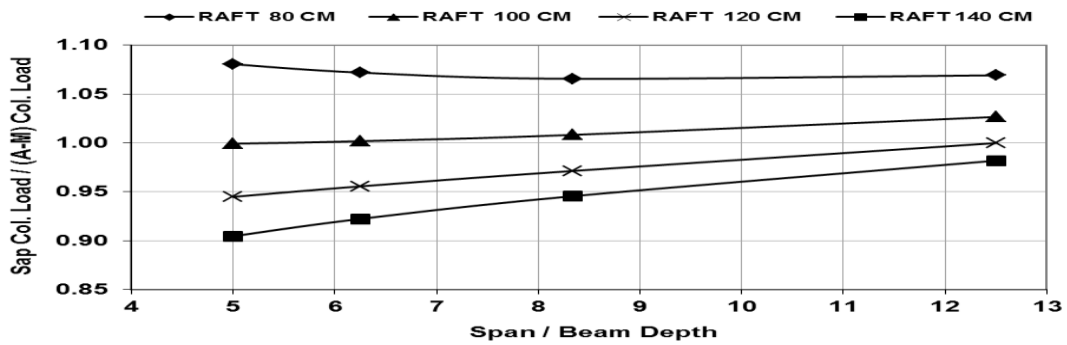
Fig. 13: Internal column load in models consist of 10 stories and soil type (1) -Ks=36000 KPa

4.3 Models Consist of 5 Stories with Soil Type (2) (Modulus of Sub-grade Reaction Ks=6000 KPa)

Fig. 14 indicates that corner column load decrease by 9% when beams depths increase from 40 cm to 100 cm in models with raft thickness 40 cm, decrease by 12% in models with raft thickness 60 cm, decrease by 10% in models with raft thickness 80 cm and decrease by 7% in models with raft thickness 100 cm. Corner column load increase by 14% at beams depth 40 cm when raft thickness increase from 40 cm to 100 cm and increase by 16% at beams depth 100 cm.

Fig. 15 indicates that there is an insignificant difference in edge column load when beams depths increase from 40 cm to 100 cm in all models. Edge column load increase by 2% at beams depth 40 cm when raft thickness increase from 40 cm to 100 cm and increase by 5% at beams depth 100 cm.

Fig. 16 indicates that there is no difference in internal column load when beams depths increase from 40 cm to 100 cm in models with raft thickness 100 cm. It also clears that internal column load increase by 13% when beams depths increase from 40 cm to 100 cm in models with raft thickness 40 cm, increase by 10% in models with raft thickness 60 cm and increase by 5% in models with raft thickness 80 cm. Internal column load decrease by 21% at beams depth 40 cm when raft thickness increase from 40 cm to 100 cm and decrease by 34% at beams depth 100 cm.
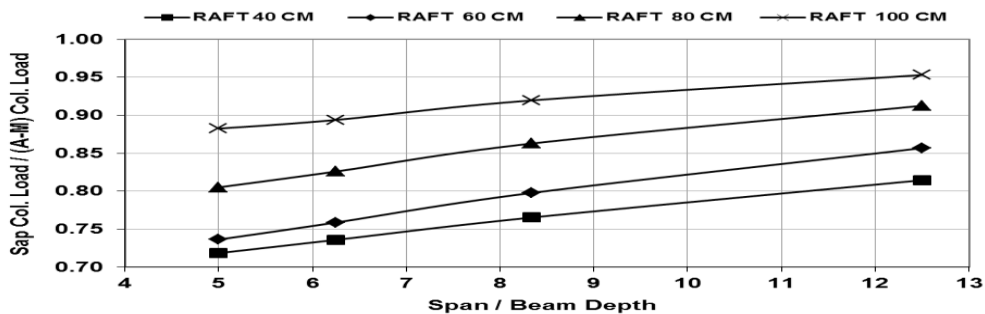

Fig. 14: Corner column load in models consist of 5 stories and soil type (2) -Ks=6000 KPa
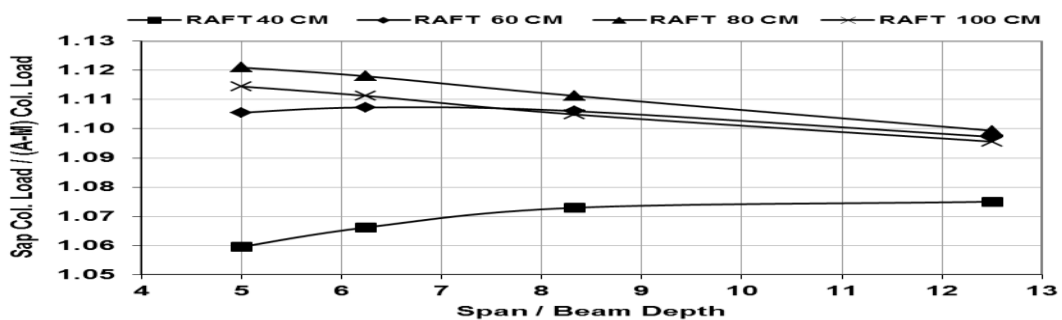

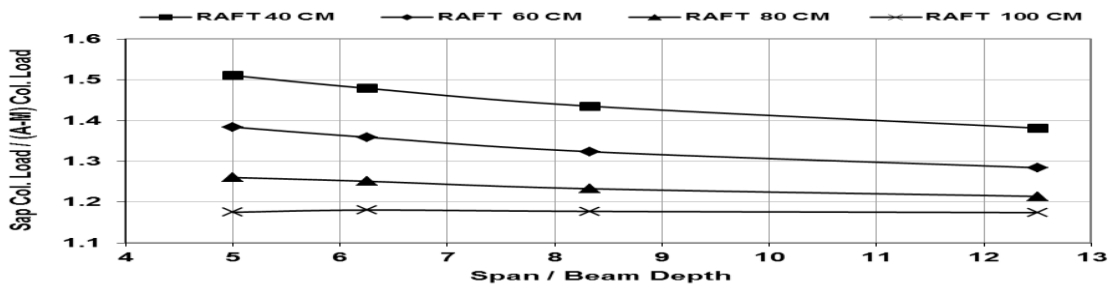**Fig. 15: Edge column load in models consist of 5 stories and soil type (2) -Ks=6000 KPa**

Fig. 16: Internal column load in models consist of 5 stories and soil type (2) -Ks=6000 KPa

4.4 Models Consist of 10 Stories with Soil Type (3) (Modulus of Sub-grade Reaction Ks=6000 KPa)

Fig. 17 indicates that corner column load decrease by 8% when beams depths increase from 40 cm to 100 cm in models with raft thickness 80 cm, decrease by 4% in models with raft thickness 100 cm and increase by 4% in models with raft thickness 140 cm. It also clears that there is an insignificant difference in corner column load when beams depths increase from 40 cm to 100 cm in models with raft thickness 120 cm. Corner column load increase by 15% at beams depth 40 cm when raft thickness increase from 80 cm to 140 cm and increase by 27% at beams depth 100 cm.

Fig. 18 indicates that there is an insignificant difference in edge column load when beams depths increase from 40 cm to 100 cm in all models. Edge column load decrease by 3% at beams depth 40 cm when raft thickness increase from 80 cm to 140 cm and decrease by 6% at beams depth 100 cm.

Fig. 19 indicates that there is an insignificant difference in internal column load when beams depths increase from 40 cm to 100 cm in models with raft thickness 100 cm. It also clears that internal column load increase by 3% when beams depths increase from 40 cm to 100 cm in models with raft thickness 80 cm, decrease by 5% in models with raft thickness 120 cm and decrease by 8% in models with raft thickness 140 cm. Internal column load decrease by 12% at beams depth 40 cm when raft thickness increase from 80 cm to 140 cm and decrease by 23% at beams depth 100 cm.
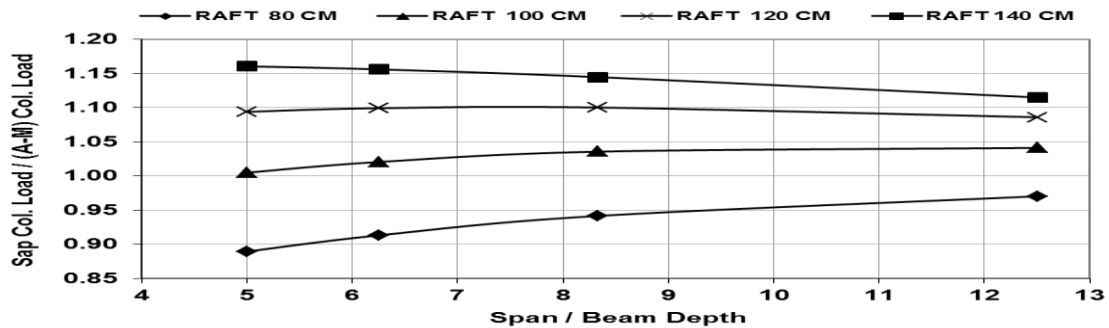

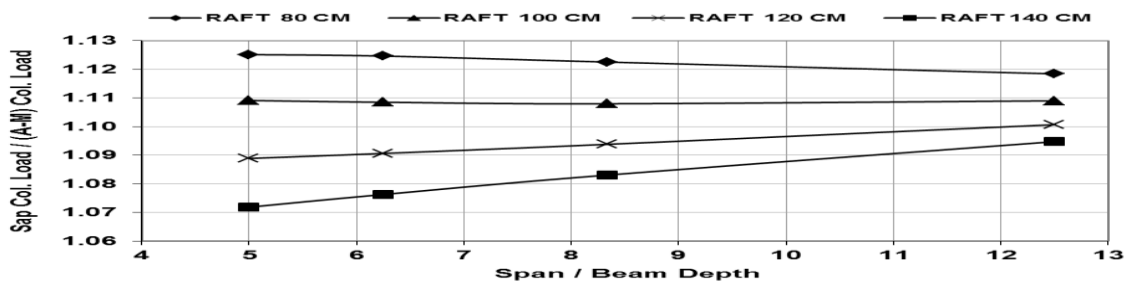**Fig. 17: Corner column load in models consist of 10 stories system and soil type (2) -Ks=6000 KPa**

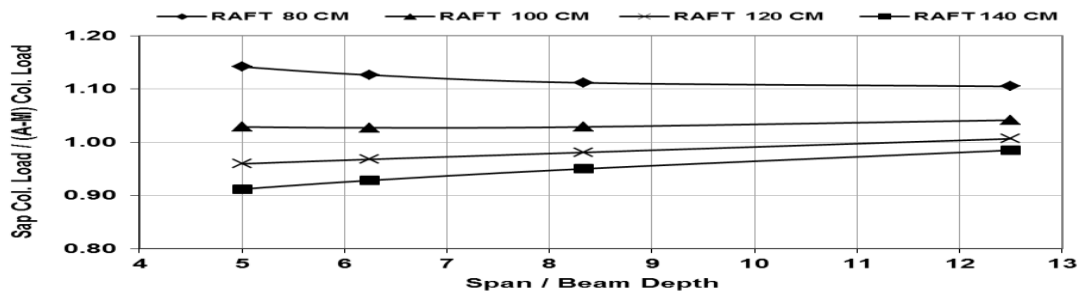**Fig. 18: Edge column load in models consist of 10 stories and soil type (2) -Ks=6000 KPa**

Fig. 19: Internal column load in models consist of 10 stories and soil type (2) -Ks=6000 KPa

4.5 Comparison between Models Consist of 5 Stories and Models Consist of 10 Stories at the Same Soil Type (1) -Ks=36000 KPa

Figures from 20 to 22 show the compare between columns loads in models consist of five stories and models consist of ten stories with solid slab system at the same soil type (1) whose modulus of sub grade reaction (Ks=36000 KPa) at raft thickness 80 cm and 100 cm and beam depth increase from 40 cm to 100 cm.

Fig. 20 indicates that corner column load increase by 7% when number of stories increase from 5 stories to 10 stories in models with raft thickness 80 cm at beam thickness 40 cm and increase by 10% at beam thickness 100 cm and increase by 10% in models with raft thickness 100 cm at beam thickness 40 cm and increase by 13% at beam thickness 100 cm. Fig. 21 indicate that there is an insignificant difference in edge column load when number of stories increase from 5 stories to 10 stories in models with raft thickness 80 cm and 100 cm when beam thickness increase from 40 cm to 100 cm. Fig. 22 indicate that internal column load decrease by 12% when number of stories increase from 5 stories to 10 stories in models with raft thickness 80 cm at beam thickness 40 cm and decrease by 14% at beam thickness 100 cm and decrease by 14% in models with raft thickness 100 cm at beam thickness 40 cm and decrease by 15% at beam thickness 100 cm.
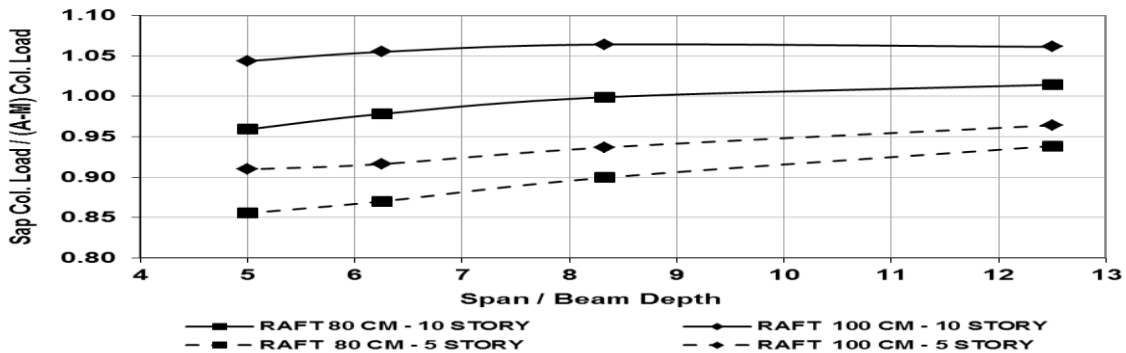

Fig. 20: Comparison between corner column load in models consist of 5 stories and models consist of 10 stories at the same soil type (1) -Ks=36000 KPa

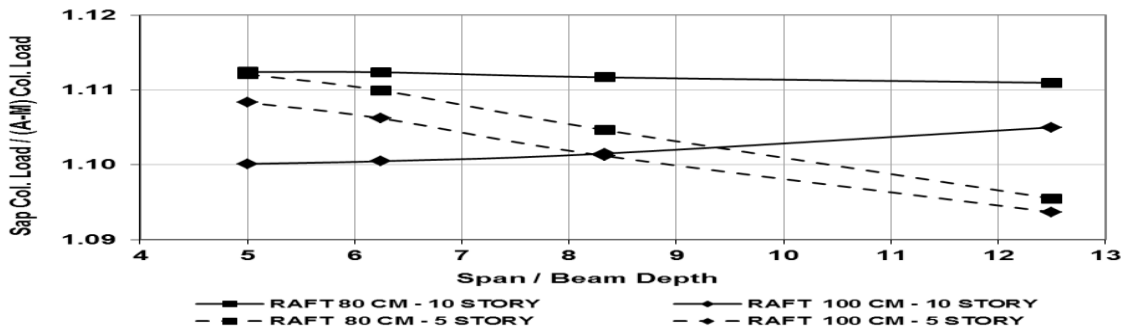**Fig. 21: Comparison between edge column load in models consist of 5 stories and models consist of 10 stories at the same soil type (1) -Ks=36000 KPa**
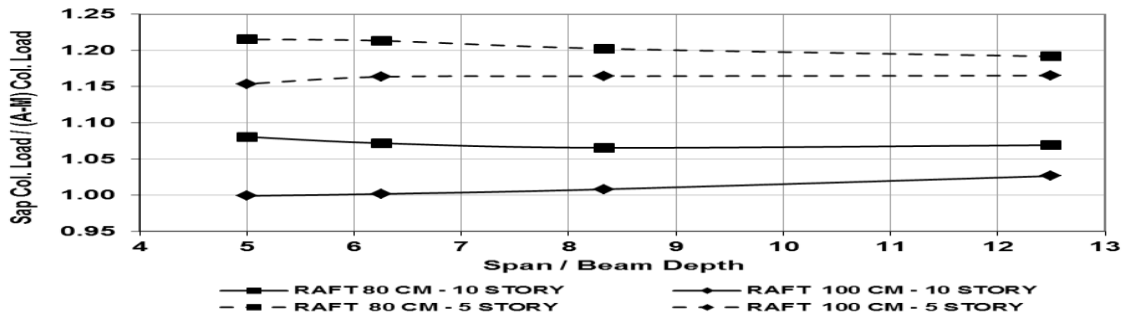

Fig. 22: Comparison between internal column load in models consist of 5 stories and models consist of 10 stories at the same soil type (1) -Ks=36000 KPa

4.6 Comparison between Models Consist of 5 Stories and Models Consist of 10 Stories at the Same Soil Type (2) -Ks=6000 KPa

Figures from 23 to 25 show the compare between columns loads in models consist of five stories and models consist of ten stories with solid slab system at the same soil type (3) whose modulus of sub grade reaction (Ks=6000 KPa) at raft thickness 80 cm and 100 cm and beam depth increase from 40 cm to 100 cm.

Fig. 23 indicates that corner column load increase by 6% when number of stories increase from 5 stories to 10 stories in models with raft thickness 80 cm at beam thickness 40 cm and increase by 8% at beam thickness 100 cm and increase by 9% in models with raft thickness 100 cm at beam thickness 40 cm and increase by 12% at beam thickness 100 cm. Fig. 24 indicates that there is an insignificant difference in edge column load when number of stories increase from 5 stories to 10 stories in models with raft thickness 80 cm and decrease by 6% when number of stories increase from 5 stories to 10 stories in models with raft thickness 100 cm at beam thickness 40 cm and decrease by 8% at beam thickness 100 cm. Fig. 25 indicate that internal column load decrease by 9% when number of stories increase from 5 stories to 10 stories in models with raft thickness 80 cm at beam thickness 40 cm and decrease by 13% at beam thickness 100 cm and decrease by 6% in models with raft thickness 100 cm at beam thickness 40 cm and 100 cm.
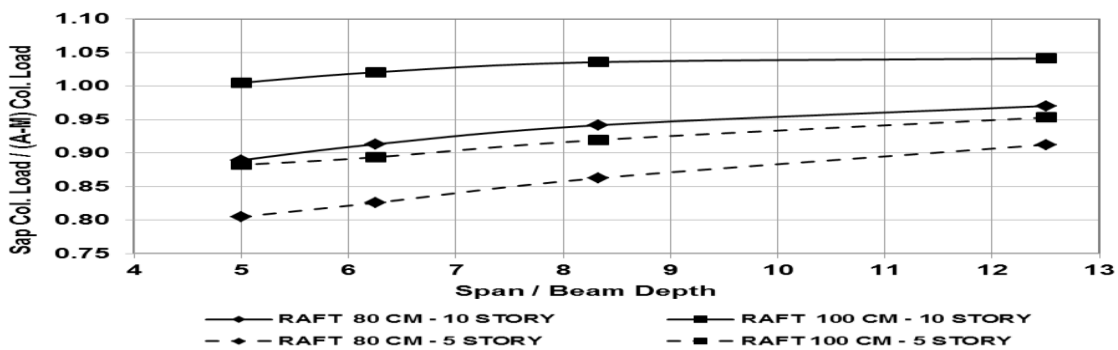

Fig. 23: Comparison between corner column load in models consist of 5 stories and models consist of 10 stories at the same soil type (2) - Ks=6000 KPa
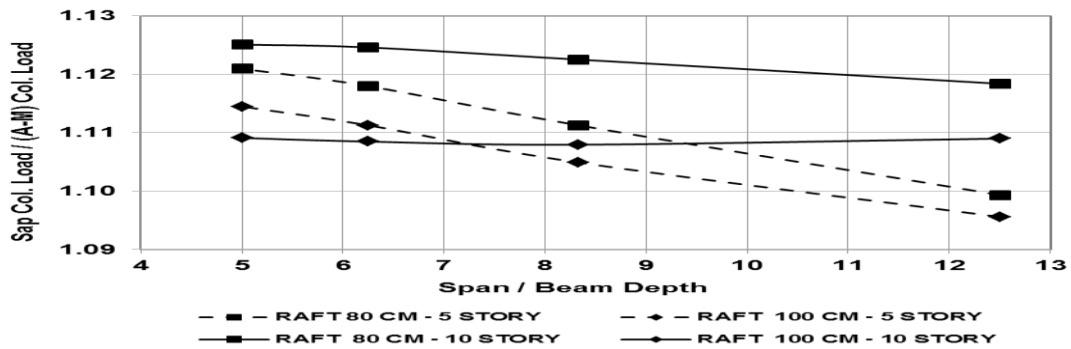
Fig. 24: Comparison between edge column load in models consist of 5 stories and models consist of 10 stories at the same soil type (2) -Ks=6000 KPa
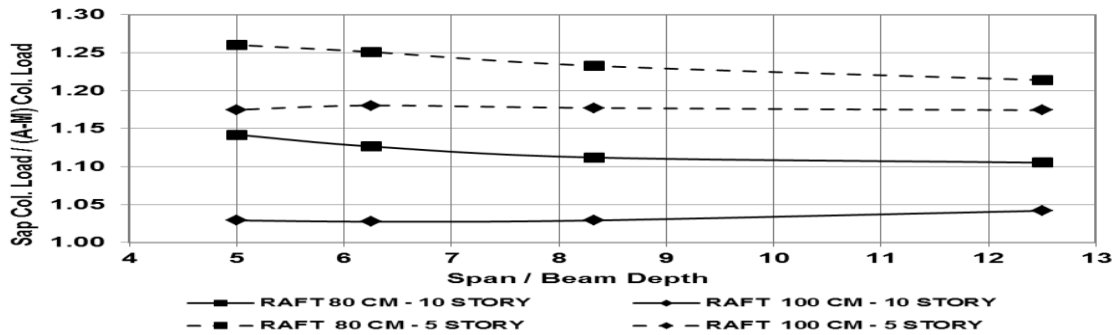

Fig. 25: Comparison between internal column load in models consist of 5 stories and models consist of 10 stories at the same soil type (2) -Ks=6000 KPa

5. CONCLUSIONS

This study investigates the effect of the structure stiffness on the stresses distribution under the foundation. Based on the current investigation, the main findings may be summarized as follow:

1- In case of building with average number of stories five stories:

A-When building lies on strong soil whose sub grade reaction K_s = 36000 kg/cm^2
- Increase beams depths from 40 cm to 100 cm leads to decrease in corner columns loads by (5%: 9%) and increase in internal column load by (1%: 10%) but it have no effect on edge columns loads.
- Increase raft thickness from 40 cm to 100 cm leads to increase in corner columns loads by (6%: 10%) and decrease in internal column load by (10%: 22%) but it have no effect on edge columns loads.

B- When building lies on weak soil whose sub grade reaction Ks = 6000 kg/cm2
  -Increase beams depths from 40 cm to 100 cm leads to decrease in corner columns loads by (7%: 12%) and increase in internal column load by (0%: 13%) but it have no effect on edge columns loads.
  -Increase raft thickness from 40 cm to 100 cm leads to increase in corner columns loads by (14%: 16%), increase in edge columns loads by (2%: 5%) and decrease in internal column load by (21%: 34%).

C- Beams depths must be small as it can be and according to structure requirements.

D- Raft thickness must be at least equal (span/6) and it is prefer to increase raft thickness to get uniform stresses distribution under the foundation.

2- In case of building with average number of stories ten stories:

 A- When building lies on strong soil whose sub grade reaction Ks = 36000 kg/cm2
   - Increase beams depths from 40 cm to 100 cm leads to change in corner columns loads from decrease by 5% to increase by 5% and decrease in internal column load by (1%: 8%) but it have no effect on edge columns loads.
   - Increase raft thickness from 80 cm to 140 cm leads to increase in corner columns loads by (11%: 21%), decrease in edge columns loads by (2%: 4%) and decrease in internal column load by (9%: 18%).

B-When building lies on weak soil whose sub grade reaction Ks = 6000 kg/cm2
- Increase beams depths from 40 cm to 100 cm leads to change in corner columns loads from decrease by 8% to increase by 4% and change in internal column load from increase by 3% to decrease by 8% but it have no effect on edge columns loads.
- Increase raft thickness from 40 cm to 100 cm leads to increase in corner columns loads by (15%: 27%), decrease in edge columns loads by (3%: 6%) and decrease in internal column load by (12%: 23%).

C-Beams depths must be small as it can be and according to structure requirements when raft thickness less than (span/5) but when raft thickness is bigger than that it is prefer to increase beams depths to get uniform stresses distribution under the foundation.

D-Raft thickness must be at least equal (span/4) and it is prefer to increase raft thickness to get uniform stresses distribution under the foundation.

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