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A parametric study on effect of non-uniformity of high rise building on mat foundation

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Abstract

The present study was carried out to investigate the effect of subgrade modulus and mat thickness on design of mat foundation. The mat of uniform thickness was analyzed with loads from 25 story reinforced concrete building with uniform and non-uniform height. The mat subjected to gravity load was modeled in SAFE 12. A comparative study has been made among some critical positions of the mat foundation in order to perceive the influence of soil subgrade modulus and mat thickness on mat design. Effect of Subgrade modulus was found as (i) The value of negative bending moments (midpoint of panel) decreases with soil subgrade modulus, and positive bending moments (beneath of columns) increases with soil subgrade modulus for all cases; (ii) Mat deflection decreases exponentially with increasing modulus of sub-grade reaction at all positions; and (iii) At positions beneath the columns, the contact pressure increases with increase of subgrade modulus. Effect of mat thickness was found as (i) The value of shear (both positive and negative) increases with the increase of mat thickness for all cases. But the change is not significant; (ii) The value of negative moment (mid panel) increases with the increase of mat thickness. The positive moments (under column) decreases with mat thickness; (iii) At all points deflection increases with the increase of mat thickness. However, differential settlement decreases with the increase of mat thickness; and (iv) The value of contact pressure increases with the increase of mat thickness for all cases.

Keywords: Mat foundation, subgrade modulus, finite element analysis.

1. Introduction

A mat or raft foundation is considered and designed as an inverted continuous flat slab supported without any upward deflection at the columns and walls. A raft foundation may be used where the base soil has a low bearing capacity and/or the column loads are so large that almost whole area is covered by conventional spread footings. There are several types of mat foundation, namely flat plate of uniform thickness, flat plate thickened under columns, Beam-slab system consists of up-stand or down-stand beams, slab with basement walls as a part of the mat (Figure 1). The present study is concerned with mat of uniform thickness. The uniform thickness mat is cast on a bed of blinding concrete and moisture-proof membrane to prevent damp rising through the slab (Barry 1966). This type of mat can be used in ground conditions where large settlements are not anticipated and hence a high degree of stiffness is not required. The slab is of uniform thickness and is reinforced at top and bottom to resist bending moment and shear (Rahman 1998).

The methods available for analysis of such rafts are rigid beam analysis (conventional method) and Non-rigid or Elastic method. Rigid beam analysis can be used when the settlements are small. This is the simplest approach. It assumes that mat is infinitely rigid with negligible flexural deflection and the soil is a linear elastic material. It also assumes the soil bearing pressure is uniform across the bottom of the footing if only concentric axial loads are present or it varies linearly across the footing if eccentric or moment loads are present. Although this type of analysis is appropriate for spread footing, it does not accurately model mat foundation. Non-rigid or Elastic method involves plates or beams on elastic foundations, plates or beams on elastic half space (elastic continuum), Readymade closed form solutions by elastic theory and, Discrete element methods, where the mat is divided into elements by grids. Discrete element method Includes Classical Method, Finite Difference Method (FDM), Finite Element Method (FEM) and Finite Grid Method (FGM). Finite element analysis is the most accurate way of analyzing the raft in which raft can be considered as plate resting on elastic foundation. The soil below the raft is treated as either Winkler foundation or elastic continuum (Rahman 2013). The present study analyzes the effect of subgrade modulus and mat thickness on shear, moment, deflection, contact pressure for uniform thickness mat system and represents these parametric changes for both uniform and non uniform height of building.

2. Brief review of literature

The earlier analysis on the raft foundation was mainly based on the conventional method in which the rigidity of the foundation and the superstructure were not included. Meyerhof (1947) was the first person to recognize the importance of rigidity of the superstructure and the foundation system. Rigorous analysis on the soil-raft frame interaction gained importance in the late 19th century, particularly after the advent of fast computers and numerical methods.

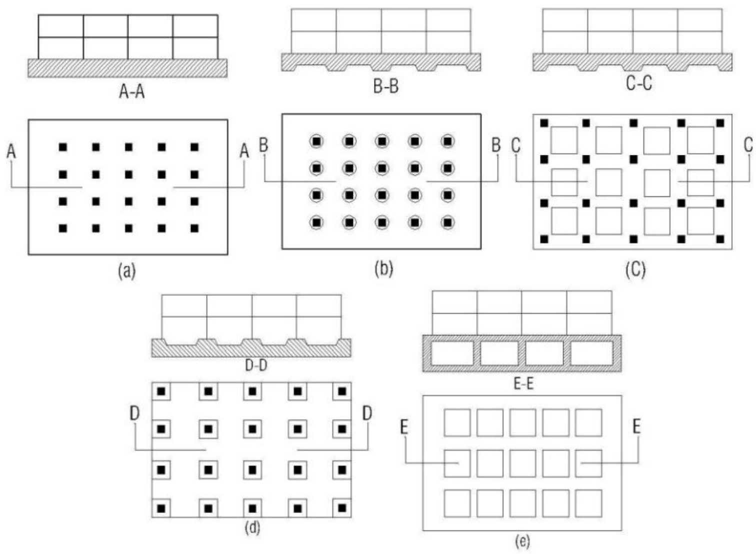

Fig. 1. Common types of mat foundation. (a) Flat plate; (b) plate thickened under columns; (c) and (d) beam-slab system; (e) basement walls as part of mat [4].

Grasshoff et al. 1957 analyzed a plane frame on a combined footing to bring out the effect of the rigidity of the superstructure and the condition of fixity of columns with the foundation on the bending moment and the contact pressure. (King and Chandrasekaran 1974) formulated a finite element procedure and analyzed a plane frame supported on a combined footing in which the frame and the combined footing were discredited into beam bending elements and the soil mass into plane rectangular elements. (Sommer 1957) studied the effect of the rigidity of the superstructure in the analysis of the foundation in the homogenous, isotropic and elastic half space.

Table 1
Variations of parameters of the models

Parameters	Reference Value	Ranges of variations
Modulus of subgrade Reaction	16 MN/m^3 (100 k/ft^3)	11, 16, 31, 63, 125 MN/m^3 (72, 100, 200, 400, 800 k/ft^3)
Mat thickness	254 cm (100 inches)	213, 244, 254, 274, 305 cm (84, 96, 100, 108, 120 inches)

Table 2
Moment variation due for uniform height and non-uniform height of building.

Grid	Maximum (-ve) moment		Status (Higher value of moment)	Variation	Maximum (+ve) moment		Status (Higher value of moment)	Variation (%)
	Uniform height (kN-m/m)	Non uniform height			Uniform height	Non uniform height		
GLY-6	3160	3572	NUH>UH	1.13	3216	3406	NUH>UH	1.06
GLY-56	303	755	NUH>UH	2.49	2308	3309	NUH>UH	1.43
GLX-5	3932	1843	UH>NUH	2.13	3880	5802	NUH>UH	1.50

NUH = Non Uniform Height of Building
UH = Uniform Height of Building

He concluded that the bending moment in the slab increases with an increase in the rigidity of the foundation (mat) and decreases with an increase in the rigidity of the superstructure. Such interaction studies have been carried out by Lee and Harrison (1970), Dejong and Morgenstern (1971), Hain and Lee (1974), Hooper (1984), Brown et al. (1986), Noorzaei et al. (1993 and 1995), Viladkar et al. (1994), Dasgupta et al. (1998), Stavridis (2002), Hora and Sharm (2007) etc. Noorzaei et al. (1991) described that the increase in the stiffness of raft overwhelming insignificantly leads to reduction in differential settlement, contact pressure, increase in moment in raft and further redistribution of moments in the superstructure member. Thangaraj et al. (2009) concluded that for the thicker raft and stiffer the soil (higher the modulus of elasticity), the interaction between the raft and the frame is not significant, which shows that the interaction behavior is tending towards the behavior of the frame on unyielding supports (condition of conventional analysis). Ukarande et al. (2008) stated that at lower soil modulus, deflections are increasing with raft thickness and at higher modulus trend is reverse. Positive bending moments are increasing and negative bending moments are reduced with increasing raft thickness. When effect of soil modulus is considered, it is found that positive bending moments are decreasing at higher value of subgrade modulus, and negative bending moments are increasing with subgrade modulus. Chore et al. (2014) described that Maximum deflections reduce with increase in raft thickness as well as increase in soil modulus. Maximum moments increase with increase in soil modulus in respect of piled raft whereas decrease with increase in soil modulus in respect of simply raft. Abdul Hussein (2011) concluded with that soil pressure distribution is far from being planar when the raft thickness is 0.4 m. However, as the thickness reaches 1.0 m, the pressure distribution approaches the planar profile. He also stated that by decreasing the raft thickness from 1.0 m to 0.4 m; the maximum deflection under columns was increased about 275%, a percentage which is near to that of the change in the thickness.

3. Numerical modeling and analysis

3.1 Description of the building

The structure consists of a 25 storied commercial building with shear walls and three underground basements. This model has eight bays in X- direction and six bays in Y-direction. In this model column center to center spacing is 7.62 m. Column size was varied with height of building. In case of uniform height the building covers total land area whereas the non-uniform height of building covers total land area from ground floor to 7 stories and after that it covers 75% of the total land area. Figure 3 and 4 shows the picture of the model of the structure.

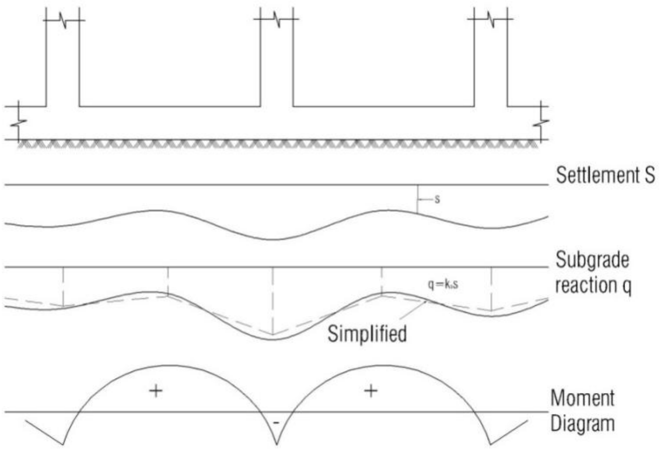

Fig. 2. sign convention of bending moment used in this paper.

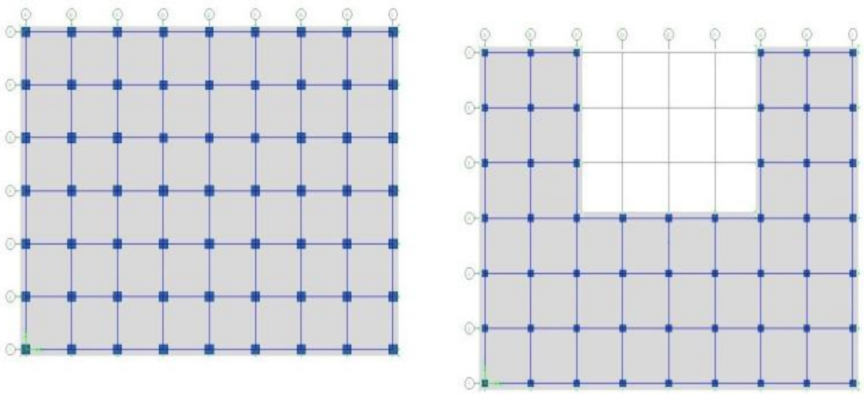

Fig. 3. Column, beam and slab of non-uniform structure (a) from story -3 to 7 (b) from Basement 8 to story 25

3.2 Structural idealization

The Mat of uniform thickness was analyzed with loads from 25 story reinforced concrete building with uniform and non-uniform height. While analyzing the mat effect of changing of the variable parameter was observed. The variations of parameters of these models were given in Table 1. The edges of mat were restrained by roller support. That means the mat was restrained in all edges horizontally. Vertically there was soil support under the mat. Soil support is directly given as subgrade modulus in the software.

The material properties of mat were taken as follows:
Poison's ratio, $\mu = 0.25$
Modulus of elasticity, E = 24.86 GPa (3604 ksi) and 27.78 GPa (4030 ksi)
Shear modulus, G = 10.36 GPa (1500 ksi) and 11.57 GPa (1680 ksi)
Concrete strength, $f'c$ = 27.6 MN/m^2 (4 ksi) for slab
Concrete strength, $f'c$ = 34.5 MN/m^2 (5 ksi) for column and beam
And steel yield strength, fy = 414 MN/m^2 (60 ksi).

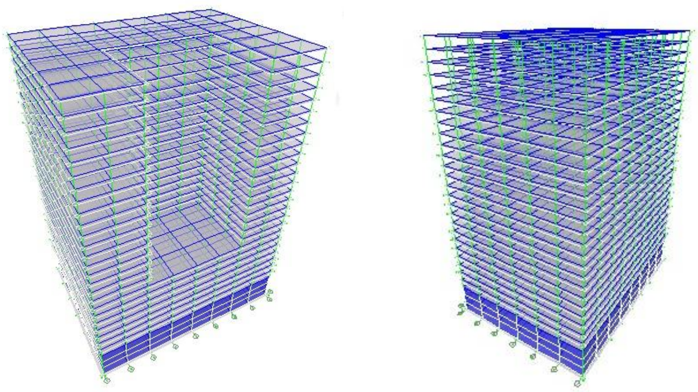

Fig. 4. 3D view of the finite element model of (a) non-uniform structure (b) uniform structure.

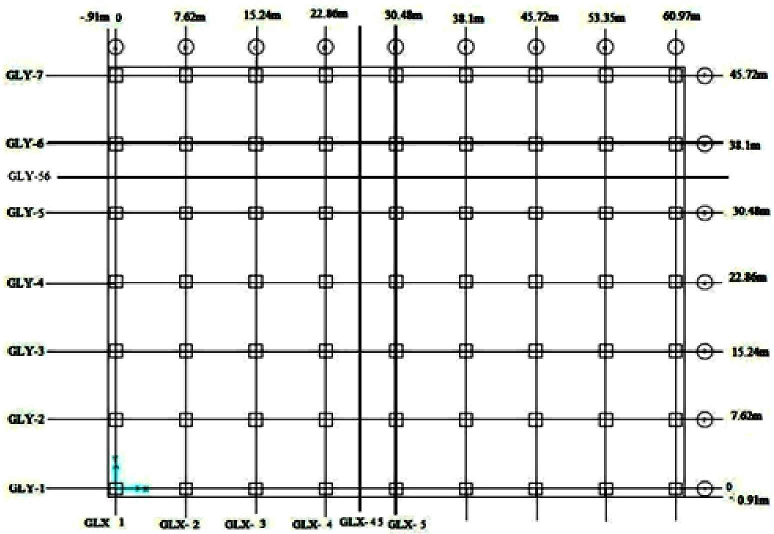

Fig. 5. Plan of Mat - Defining grid lines.

3.3 Analysis of mat foundation

The Mats were analyzed by the Finite Element Method (FEM) using the software SAFE. Maximum mesh size 1.20 m (4 ft) has been taken to get satisfactory accuracy of results.

3.4 Geometry of the mat foundation

A 63 m x 47 m (206 ft x 156 ft) mat foundation was used to carry the loads from a 25 storied building. Mat thickness was 254 cm (100 inches) for uniform thickness and 91 cm (36 inch).

Reference Modulus of sub grade reaction of soil is 15.71 MN/m^3 (100 k/ft^3). The Mat is extended by 91 cm (3 ft) from the centre of column. Column size is 137 x 137 cm^2 (54 x 54 in^2).

4. Results and discussion

4.1 General

To observe the "Effect of subgrade modulus" the mats were analyzed with different subgrade modulus (K_s) without changing the geometry and load condition. To observe the "Effect of mat thickness" the mats were analyzed with different mat thickness without changing the sub grade modulus, area and load condition. Modulus of sub grade reaction has been taken 15.71 MN/m^3 (100 k/ft^3). Shear, moment, deflected shape and contact pressure or soil pressure is observed to assess the effect of change for subgrade modulus and mat thickness. The variable parameters of sub grade modulus (Ks) and mat thickness (t) are given in Table 1.

Design parameters were observed for un-factored gravity load only. As the mats were asymmetric with geometry and load, so M11 and M22 were not similar. For same reason V13 and V23 were not similar. Where M11 and M22 are bending moments out of plane and V13 and V23 are transverse shear out of plane. Contact pressure and soil pressure are same. The mat must meet the punching shear criteria. For different sub grade modulus (K_s), the contour for shear, moment, deflected shape and contact pressure were obtained. In this study, the author follows the convention of moment sign described in Figure 2.

4.2 Defining observation points

From the contour diagram shear, moment, deflection and contact pressure/soil pressure were obtained at any point for different sub grade modulus. Some points were chosen for observation. Shear V13, moment M11, deflection and contact pressure/soil pressure were taken directly under interior columns line (GLY-6), (GLY-3), (GLX-5) and along middle of an interior panel (GLY-56), (GLY-45). The various observation points along column line for moment, shear, deflection and contact pressure/soil pressure are shown in Figure 5.

For an interior column line (GLY-6) and (GLX-5) and middle of an interior panel (GLY-56) of the mat, with various values of sub grade modulus, we obtained shear, moment, deflection and contact pressure from shear contour, moment contour, deflection contour, contact pressure contour respectively. These values were obtained from the finite element analysis by SAFE. Shears, moments, deflections and contact pressures are represented in graphically from Figure 6 to Figure 17 represent shear force, moment, deflection, contact pressure diagrams for column line (GLY-6) and (GLX-5) and middle of an interior panel (GLY-56) for uniform thickness mat and beam-slab mat of both uniform height and non-uniform height.

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4.4 Influence of subgrade modulus

4.4.1. Influence of subgrade modulus on shear

It is observed that the values of negative shear decrease and positive shear increase with the increase of subgrade modulus for all cases (Figure 6 and 7) but the change is not significant. Point of zero shears occurs between columns where maximum moment should occur. Again variation of shear in column line is not significant but in the middle of interior panel, this variation is significant. In Figure 10, maximum negative shear variation increase 5.82 times for almost same amount of increase in subgrade modulus in non uniform height of building. So shear variation is very small in column line and but significant shear variation occurs in interior panel (GLY-56).

Shear value (both positive and negative) of uniform height of building is higher than non-uniform height of building for column line (Figure 8). But for middle of an interior panel, shear value for non uniform height of building is higher up to uniform section and after that (when non-uniform section starts) shear value for uniform height of building is higher. (Figure 11 and 12). Non uniform section of section of building is induces low loading which causes lower value of shear in non uniform section.

4.4.2 Influence of subgrade modulus on moment

Positive moment is engendered in-between column where tension occurs at upper fiber and negative moments occur beneath column. Positive value of moment indicates hogging type and negative value indicates sagging type moment and this positive moment decreases and negative moment increase with the increase of subgrade modulus for Figure 14 & 15. For non-uniform height of building negative moment suddenly dropped and positive moment increases in non uniform section of building Non-uniform section of building causes lower self-weight of building which results lower negative value of moment in non uniform section. Shear variation due to increase in subgrade modulus also increases in non uniform section of building (Figure 15) and value of positive shear in non uniform section is higher for lower value of subgrade modulus. For Figure 18, for middle of an interior column line of non uniform height of building, lower value of subgrade modulus and higher value of subgrade modulus shows different characteristics. In middle of an interior column line of non-uniform height of building, variation of moment due to increment of subgrade modulus is insignificant up to uniform section but when the non-uniform section starts the variation is significant i.e. high value of positive moment and no negative moment is visible and the high the value of subgrade modulus, the low the value of positive moment. Only a minimum amount of reinforcement should be provided at top at non-uniform section and high percentage of reinforcement at the bottom of mat. On the contrary, middle of an interior panel of uniform height of building shows similar characteristics of column line (Figure 17).

For Figure 16, 19 and 21, it can be inferred from the Figure that negative moment is higher for non-uniform height of building while positive moment is higher for uniform height of building. This relation is true up to non-uniform section of building and beyond this distance this process is reverse due to the presence of this non-uniform section. So reinforcement should be provided based on these characteristics.

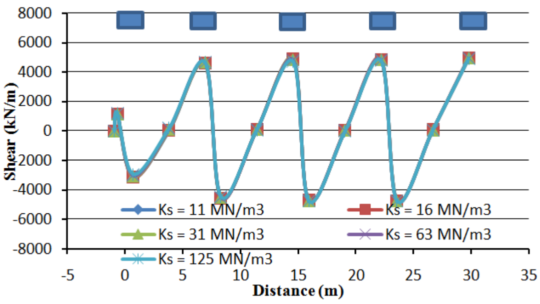

Fig. 6. Shear along column line (GLY-6) for uniform thickness of mat of uniform height of building at different subgrade modulus of foundation soil.

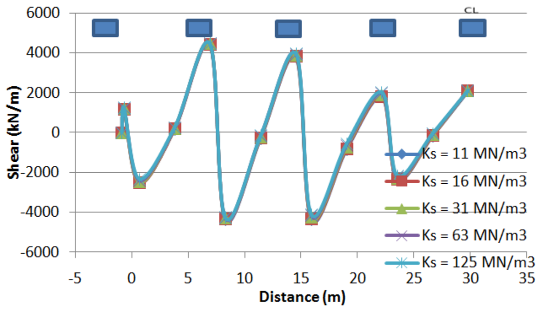

Fig. 7. Shear along column line (GLY-6) for uniform thickness of mat of non-uniform height of building at different subgrade modulus of foundation soil.

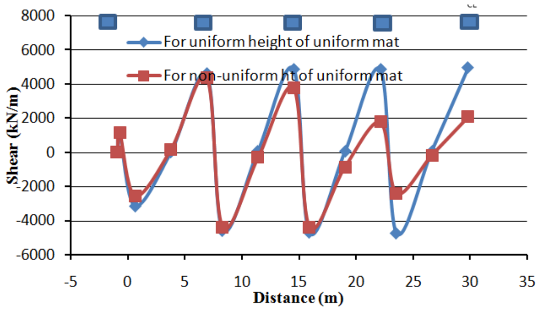

Fig. 8. Shear along column line (GLY-6) for uniform thickness of mat of uniform height and non-uniform height of building at constant subgrade modulus of foundation soil.

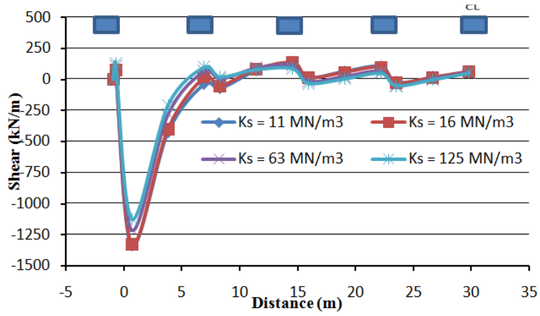

Fig. 9. Shear along middle of an interior panel (GLY-56) for uniform thickness of mat of uniform height of building at different subgrade modulus of foundation soil.

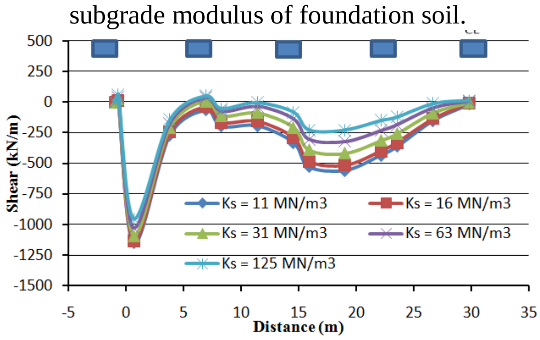

Fig. 10. Shear along middle of an interior panel (GLY-56) for uniform thickness of mat of non-uniform height of building at different subgrade modulus of foundation soil.

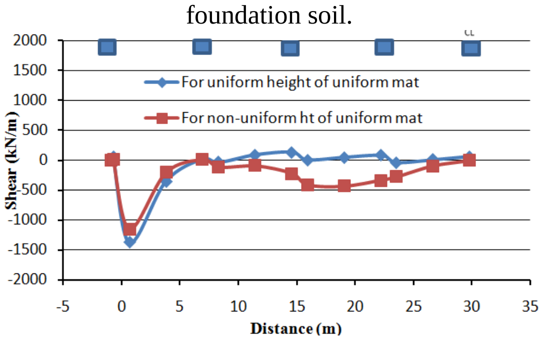

Fig. 11. Shear along middle of an interior panel (GLY-56) for uniform thickness of mat of uniform height and non-uniform height and constant subgrade modulus of foundation soil.

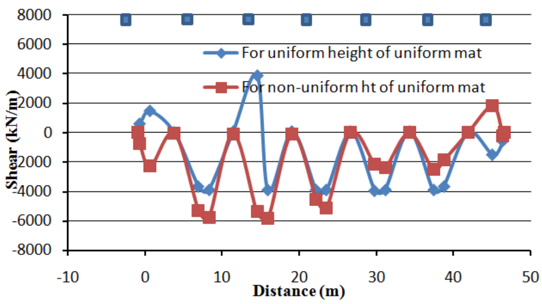

Fig. 12. Shear along column line (GLX-5) for uniform thickness of mat of uniform height and non-uniform height and of building at constant subgrade modulus of foundation soil.

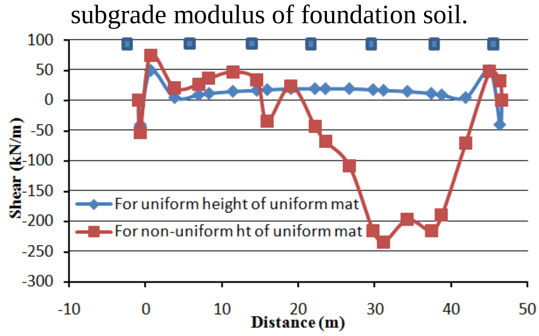

Fig. 13. Shear along middle of an interior panel (GLX-45) for uniform thickness of mat of uniform height and non-uniform height and of building at constant subgrade modulus of foundation soil.

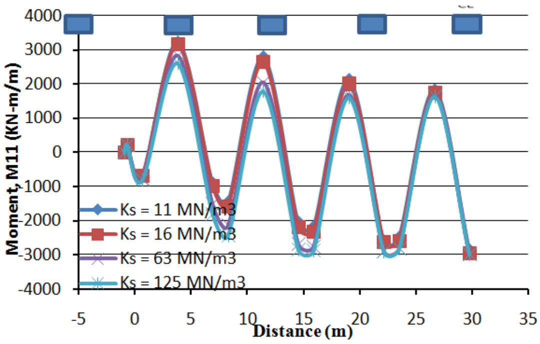

Fig. 14. Moment along column line (GLY-6) for uniform thickness of mat of uniform height of building at different subgrade modulus of foundation soil.

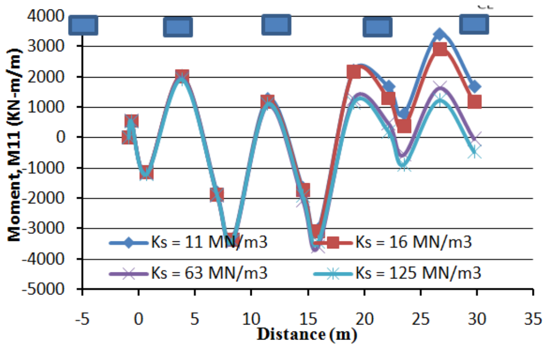

Fig. 15. Moment along column line (GLY-6) for uniform thickness of mat of non-uniform height of building at different subgrade modulus of foundation soil.

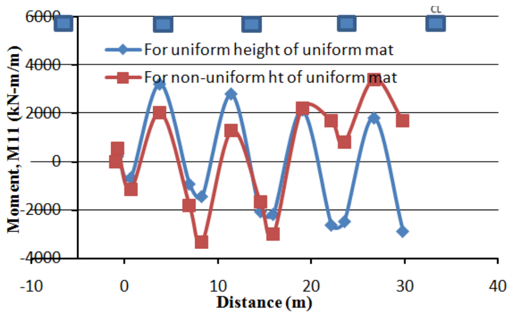

Fig. 16. Moment along column line (GLY-6) for uniform thickness of mat of uniform height and non-uniform height of building at constant subgrade modulus of foundation soil.

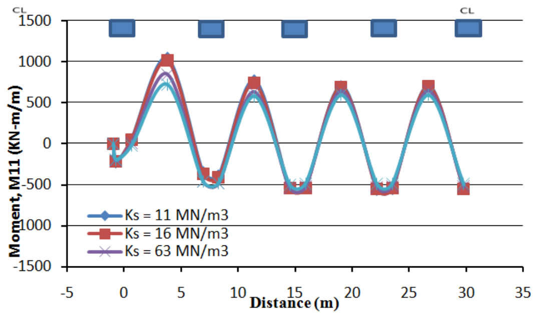

Fig. 17. Moment along middle of an interior panel (GLY-56) for uniform thickness of mat of uniform height of building at different subgrade modulus of foundation soil.

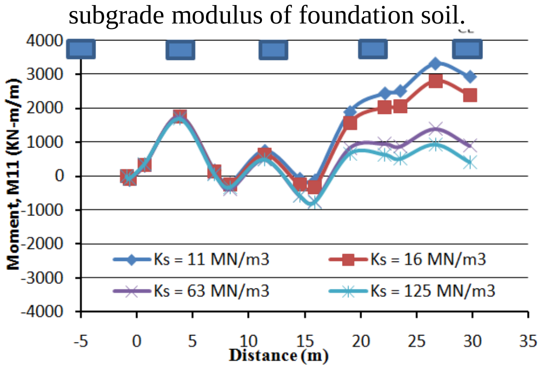

Fig. 18. Moment along middle of an interior panel (GLY-56) for uniform thickness of mat of non-uniform height of building at different subgrade modulus of foundation soil.

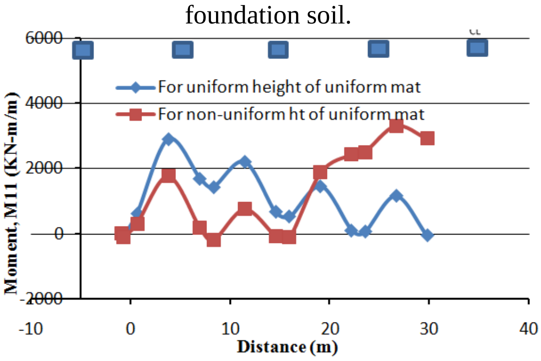

Fig. 19. Moment along middle of an interior panel (GLY-56) for uniform thickness of mat of uniform height and non-uniform height of building at constant subgrade modulus of foundation soil.

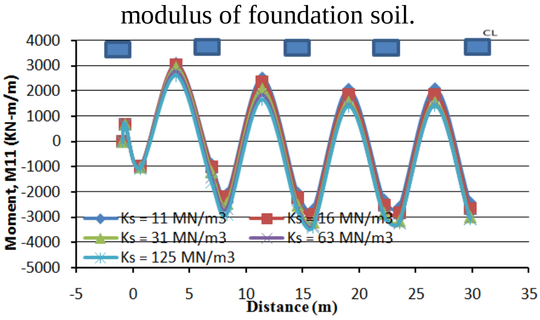

Fig. 20. Moment along column line (GLY-3) for uniform thickness of mat of non-uniform height of building at different subgrade modulus of foundation soil.

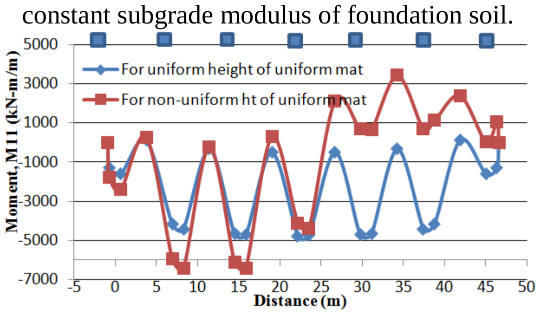

Fig. 21. Moment along column line (GLX-5) for uniform thickness of mat of uniform height and non-uniform height of building at constant subgrade modulus of foundation soil.

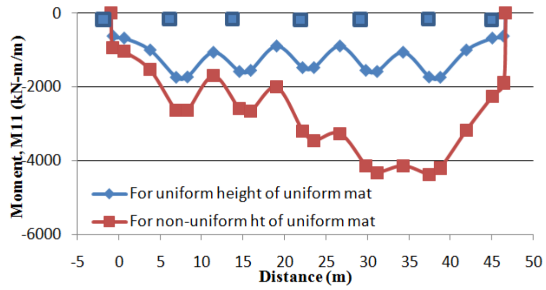

Fig. 22. Moment along middle of an interior panel (GLX-45) for uniform thickness of mat of uniform height and non-uniform height of building at constant sub grade modulus of foundation soil.

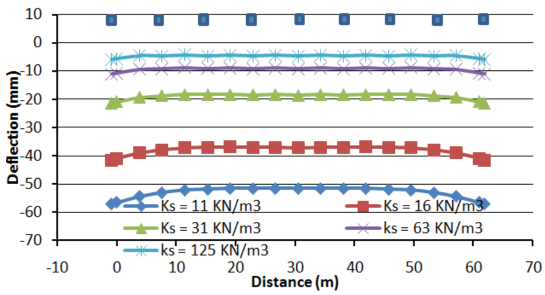

Fig. 23. Deflection along column line (GLY-6) for uniform thickness of mat of uniform height of building at different subgrade modulus of foundation soil.

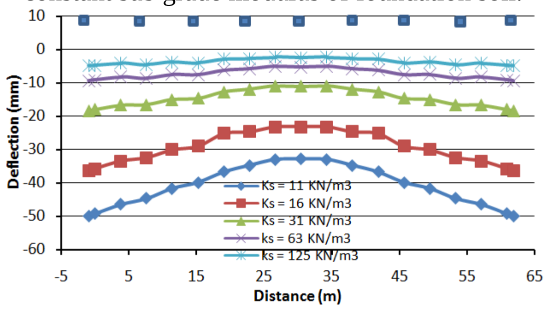

Fig. 24. Deflection along column line (GLY-6) for uniform thickness of mat of non-uniform height of building at different subgrade modulus of foundation soil.

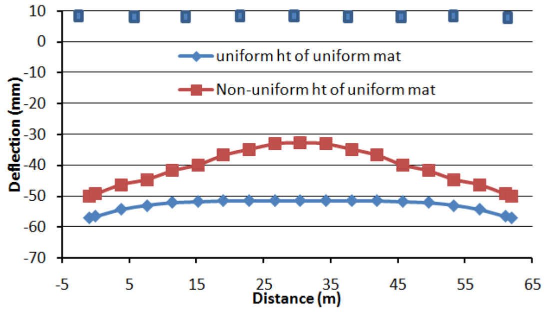

Fig. 25. Deflection along column line (GLY-6) for uniform thickness of mat of uniform height and non-uniform height and beam-slab mat of uniform height and non-uniform height of building at constant subgrade modulus of foundation soil.

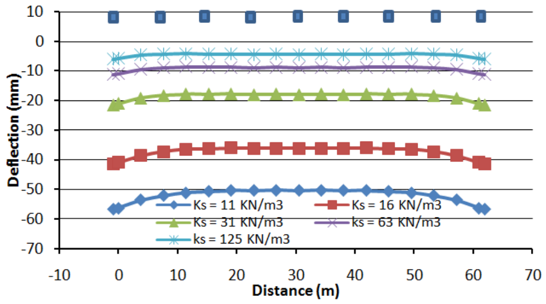

Fig. 26. Deflection along middle of an interior panel (GLY-56) for uniform thickness of mat of uniform height of building at different subgrade modulus of foundation soil.

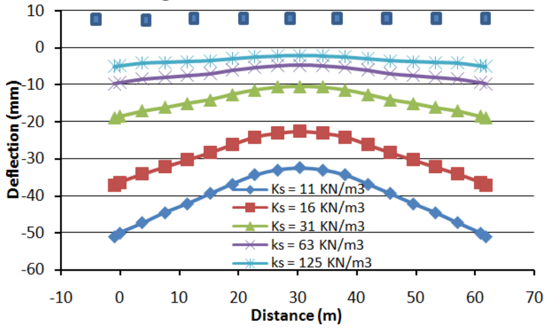

Fig. 27. Deflection along middle of an interior panel (GLY-56) for uniform thickness of mat of non-uniform height of building at different subgrade modulus of foundation soil.

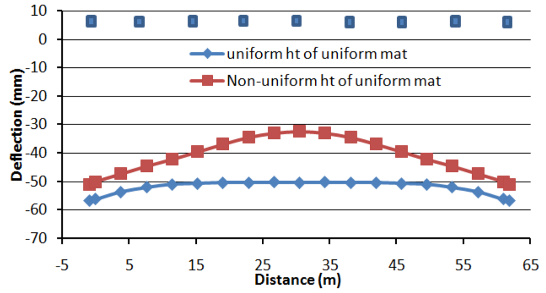

Fig. 28. Deflection along middle of an interior panel (GLY-56) for uniform thickness of mat of uniform height and non-uniform height of building at constant subgrade modulus of foundation soil.

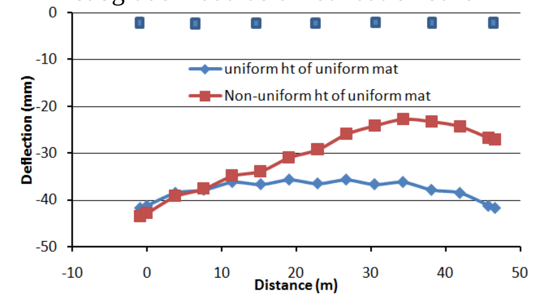

Fig. 29. Deflection along column line (GLX-5) for uniform thickness of mat of uniform height and non-uniform height of building at constant subgrade modulus of foundation soil.

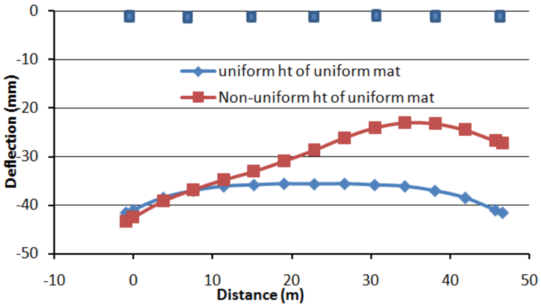

Fig. 30. Deflection along middle of an interior panel (GLX-45) for uniform thickness of mat of uniform height and non-uniform of building at constant subgrade modulus of foundation soil.

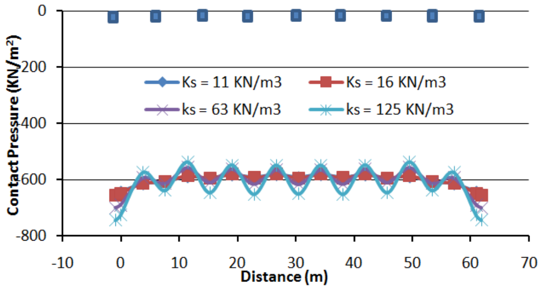

Fig. 31. Contact pressure along column line (GLY-6) for uniform thickness of mat of uniform height of building at different subgrade modulus of foundation soil.

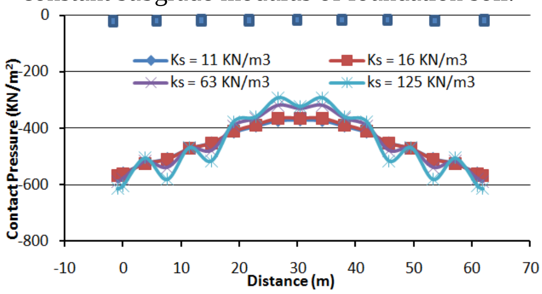

Fig. 32. Contact pressure along column line (GLY-6) for uniform thickness of mat of non-uniform height of building at different subgrade modulus of foundation soil.

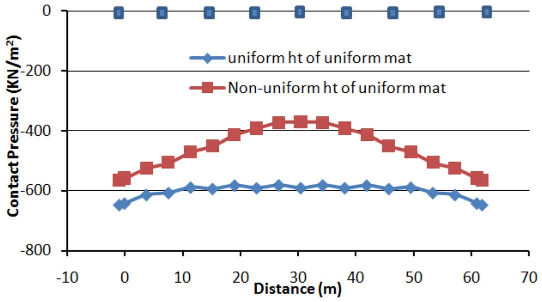

Fig. 33. Contact pressure along column line (GLY-6) for uniform thickness of mat of uniform height and non-uniform height at constant subgrade modulus of foundation soil.

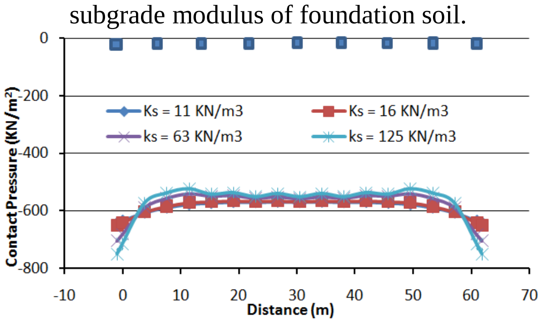

Fig. 34. Contact pressure along middle of an interior panel (GLY-56) for uniform thickness of mat of uniform height of building at different subgrade modulus of foundation soil.

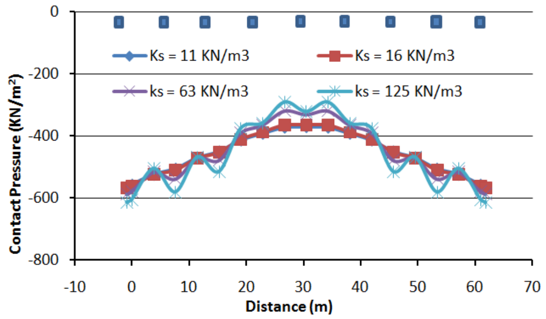

Fig. 35. Contact pressure along middle of an interior panel (GLY-56) for uniform thickness of mat of non-uniform height of building at different subgrade modulus of foundation soil.

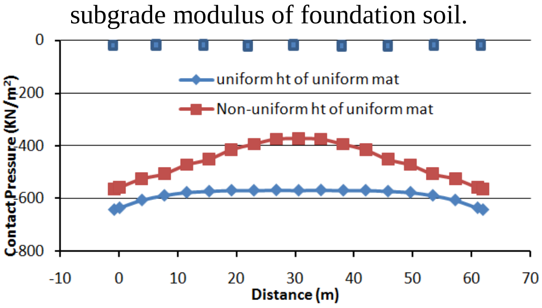

Fig. 36. Contact pressure along middle of an interior panel (GLY-56) for uniform thickness of mat of uniform height and non-uniform height of building at constant subgrade modulus of foundation soil.

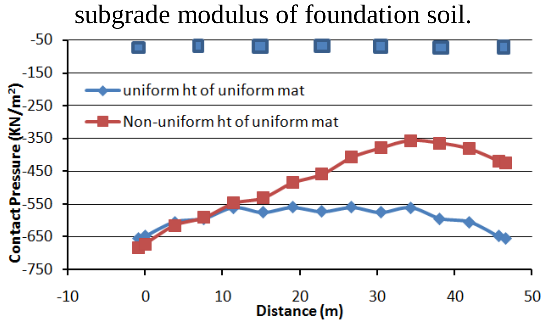

Fig. 37. Contact pressure along column line (GLX-5) for uniform thickness of mat of uniform height and non-uniform height of building at constant subgrade modulus of foundation soil.

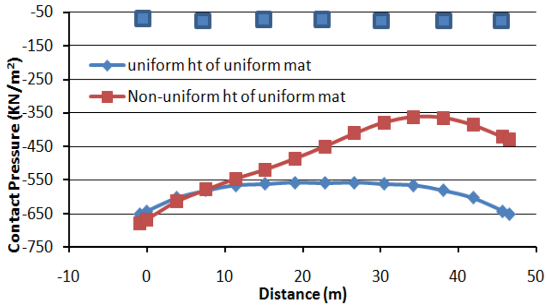

Fig. 38. Contact pressure along middle of an interior panel (GLX-45) for uniform thickness of mat of uniform height and non-uniform height of building at constant subgrade modulus of foundation soil.

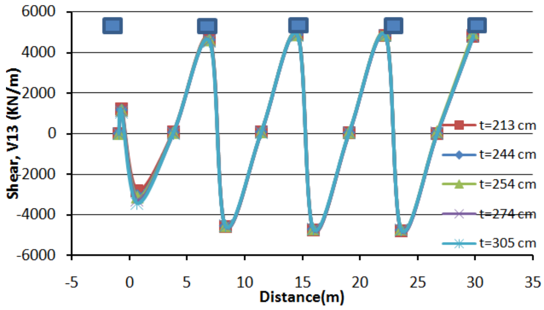

Fig. 39. Shear along column line (GLY-6) for uniform thickness of mat of uniform height of building at different thickness of mat.

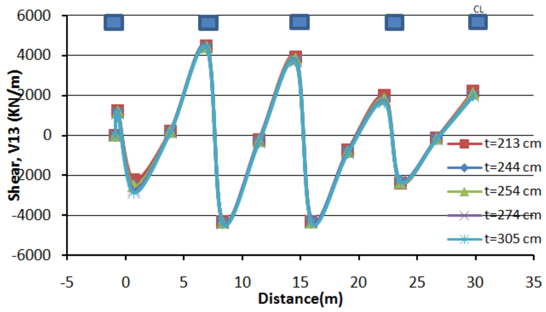

Fig. 40. Shear along column line (GLY-6) for uniform thickness mat of non-uniform height of building at different thickness of mat.

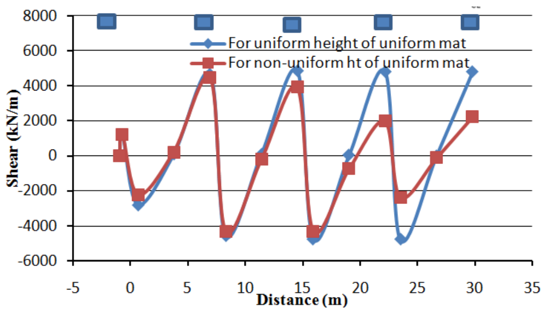

Fig. 41. Shear along column line (GLY-6) for uniform thickness of mat of uniform height and non-uniform height of building at same thickness of mat.

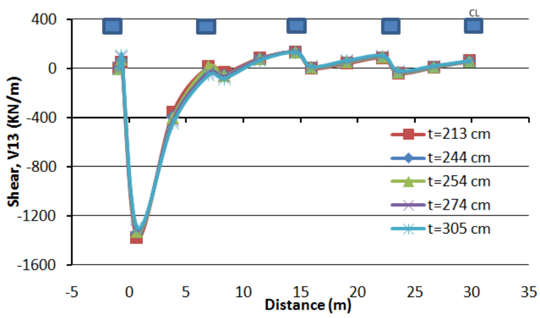

Fig. 42. Shear along middle of an interior panel (GLY-56) for uniform thickness of mat of uniform height of building at different thickness of mat.

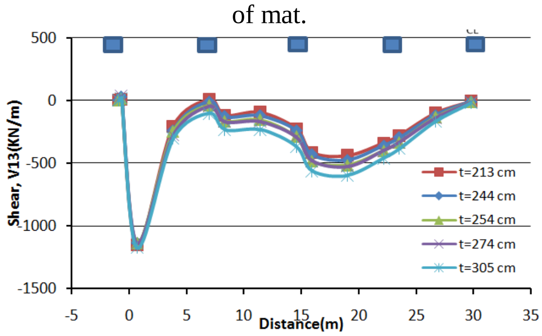

Fig. 43. Shear along middle of an interior panel (GLY-56) for uniform thickness of mat of non uniform height of building at different thickness of mat.

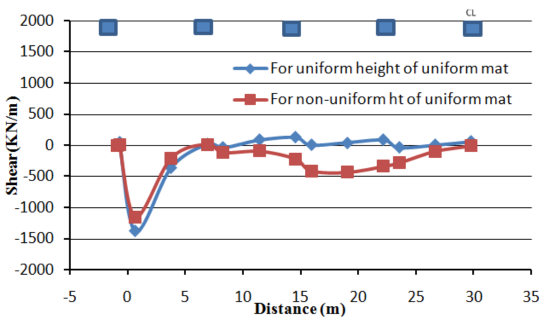

Fig. 44. Shear along middle of an interior panel (GLY-56) for uniform thickness of mat of uniform height and non-uniform height of building at same thickness of mat.

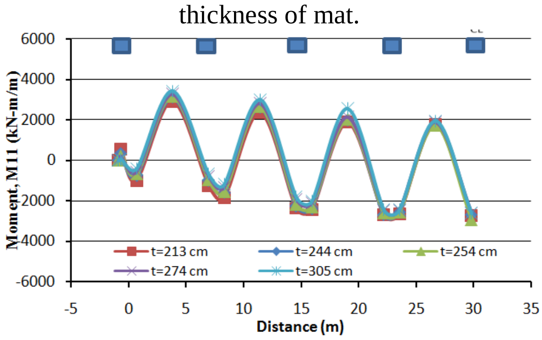

Fig. 45. Moment along column line (GLY-6) for uniform thickness of uniform height of building at different thickness of mat.

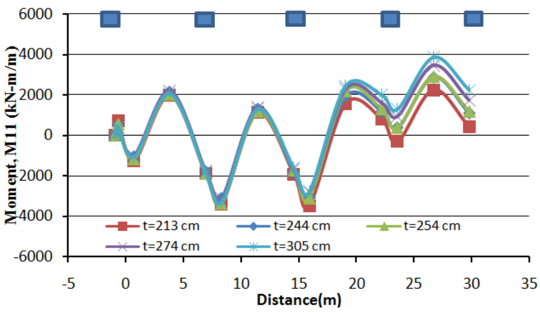

Fig. 46. Moment along column line (GLY-6) for uniform thicknesses of non-uniform height of building at different thickness of mat.

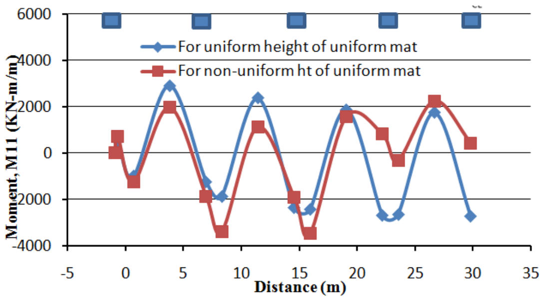

Fig. 47. Moment along column line (GLY-6) for uniform thickness of mat of uniform height and non-uniform height of building at same thickness of mat.

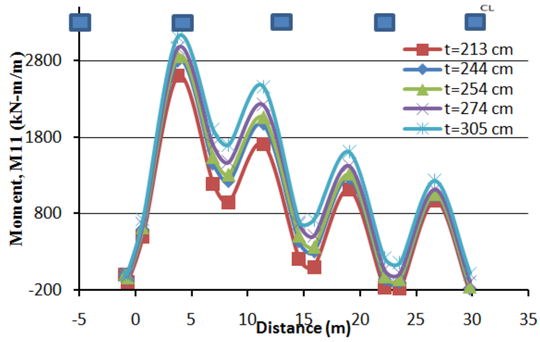

Fig. 48. Moment along middle of an interior panel (GLY-56) for uniform thicknesses of uniform height of building at different thickness of mat.

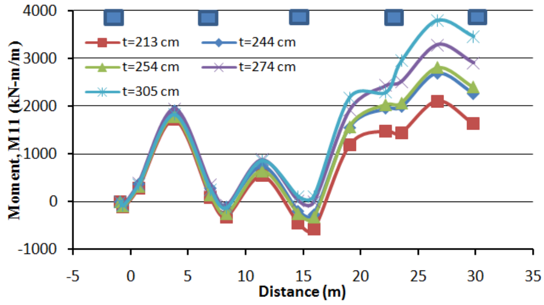

Fig. 49. Moment along middle of an interior panel (GLY-56) for uniform thicknesses of non-uniform height of building at different thickness of mat.

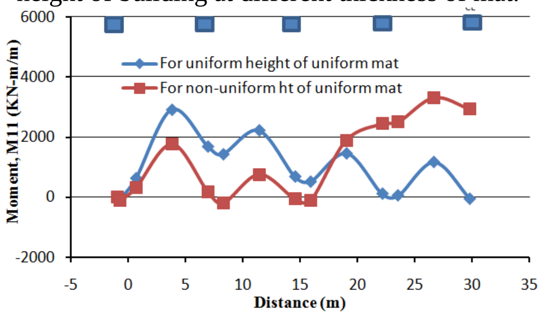

Fig. 50. Moment along middle of an interior panel (GLY-56) for uniform thickness of mat of uniform height and non-uniform height of building at same thickness of mat.

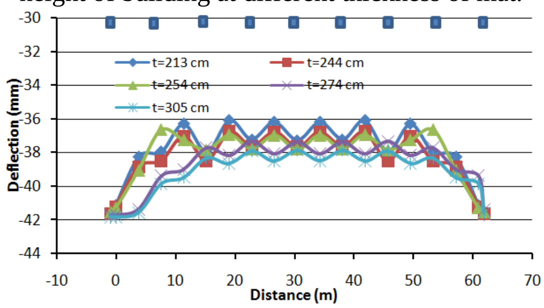

Fig. 51. Deflection along column line (GL-6) for uniform thicknesses mat of uniform height of building at different thickness of mat.

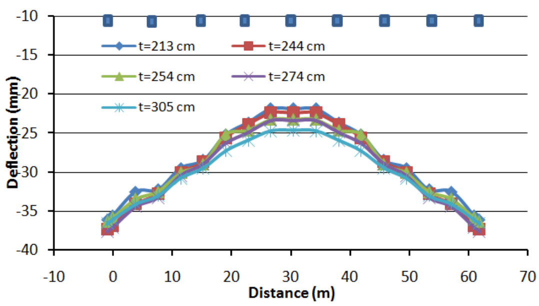

Fig. 52. Deflection along column line (GLY-6) for uniform thicknesses of non-uniform height of building at different thickness of mat.

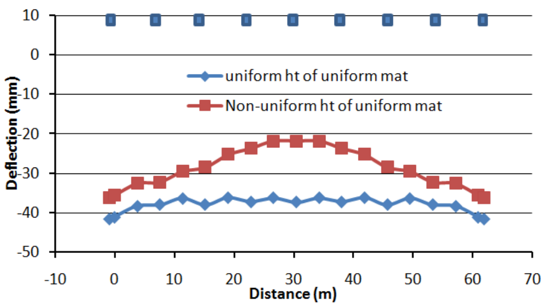

Fig. 53. Deflection along column line (GLY-6) for uniform thickness of mat of uniform height and non-uniform height of building at same thickness of mat.

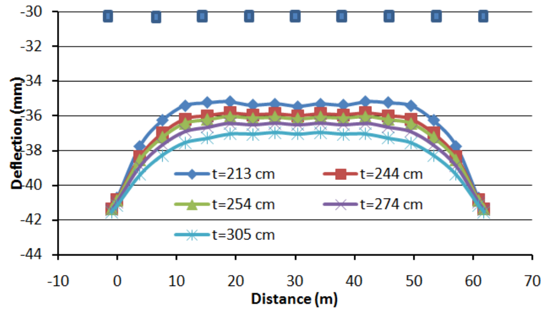

Fig. 54. Deflection along middle of an interior panel (GLY-56) for uniform thicknesses of uniform height of building at different thickness of mat.

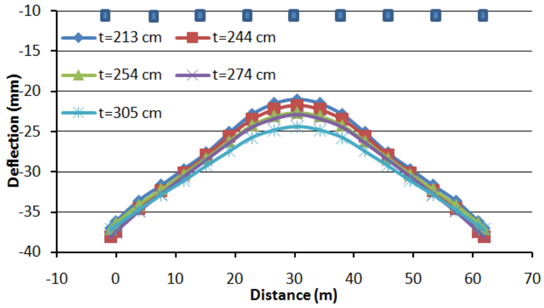

Fig. 55. Deflection along middle of an interior panel (GLY-56) for uniform thicknesses of non-uniform height of building at different thickness of mat.

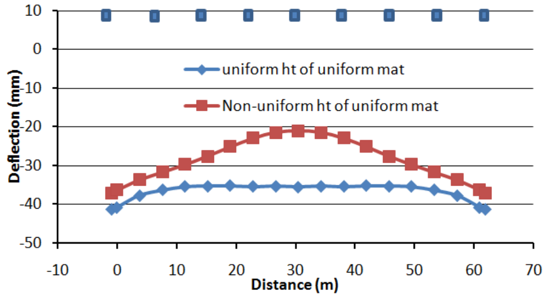

Fig. 56. Deflection along middle of an interior panel (GLY-56) for uniform thickness of mat of uniform height and non-uniform height of building at same thickness of mat.

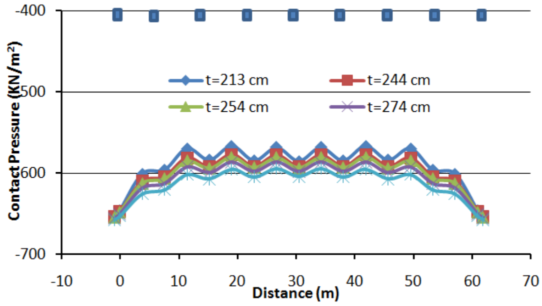

Fig. 57. Contact pressure along column line (GLY-6) for uniform thicknesses of uniform height of building at different thickness of mat.

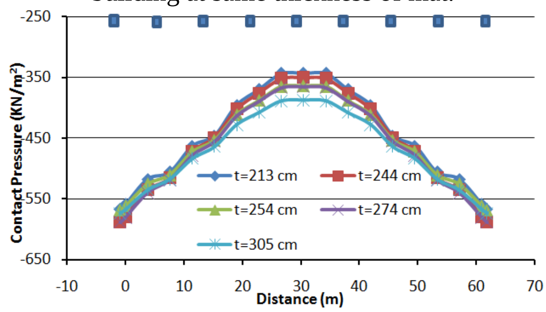

Fig. 58. Contact pressure along column line (GLY-6) for uniform thicknesses of non-uniform height of building at different thickness of mat.

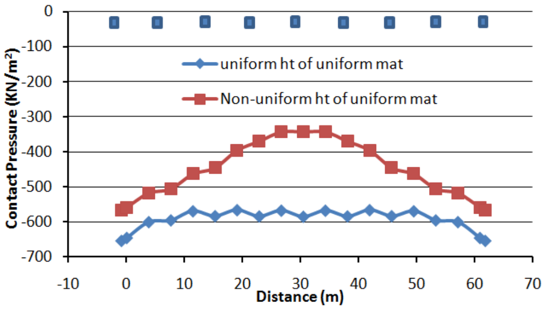

Fig. 59. Contact pressure along column line (GLY-6) for uniform thickness of mat of uniform height and non-uniform height of building at same thickness of mat.

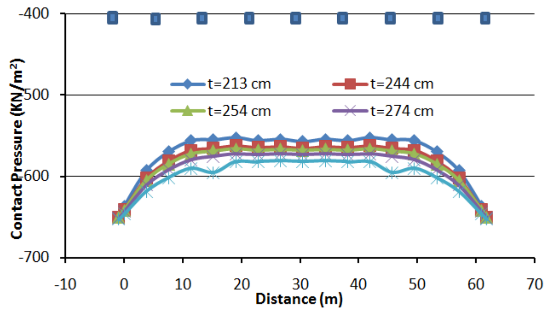

Fig. 60. Contact pressure along middle of an interior panel (GLY-56) for uniform thicknesses of uniform height of building at different thickness of mat.

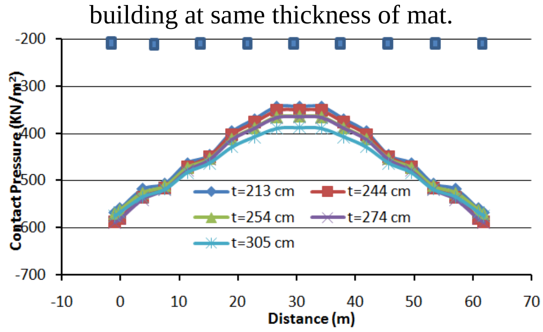

Fig. 61. Contact pressure along middle of an interior panel (GLY-56) for uniform thicknesses of non-uniform height of building at different thickness of mat.

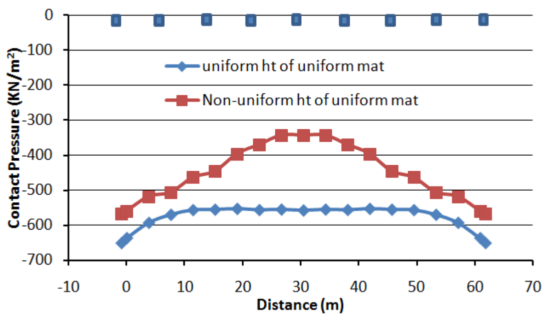

Fig. 62. Contact pressure along middle of an interior panel (GLY-56) for uniform thickness of mat of uniform height and non-uniform height of building at same thickness of mat.

In Table 2, in every aspect, both maximum negative and positive moment variation is higher for non-uniform height of building. Significant variation is observed for negative moment of GLY-56. Along GLY-56, maximum negative value for non-uniform height of building is 2.49 times of uniform height of building. So moment variation due to increase of subgrade modulus for non-uniform height of building is significant in interior panel and not in column line and maximum value of moment for different value of subgrade modulus is higher for non-uniform height of building. Figure 22 shows a different characteristic. There is no negative moment appears in the middle of an interior panel (GLX 45) and positive value increases suddenly where non-uniform section starts. So a high percentage of top reinforcement should be provided. Again, middle of an interior panel in X and Y direction has shown different characteristics i.e. no or very low negative moment in middle of an interior panel in x direction (Figure 17, 22).

4.4.3 Influence of sub grade modulus on deflection

If the foundation is relatively flexible and the column spacing is large, settlement (deflection) will no longer be uniform or linear. The more heavily loaded columns will cause larger settlements, and thereby larger subgrade reaction (bearing pressure), than the lighter ones. Also, since the continuous strip or slab midway column will deflect upward relative to the nearby columns, the soil settlement, and thereby the subgrade reaction, will be smaller midway between columns than directly at the columns. We know that, increasing subgrade modulus will decrease the deflection value for constant properties of soil. Due to 5.55 times increase in subgrade modulus, deflection value has decrease at almost same rate (5.82 times for positive deflection and 5.15 times for negative deflection) in GLY-6 (Figure 23). This variation is almost identical for both uniform and non-uniform height. For, interior panel (GLY-56), variation of deflection value is also identical to column line (GLY-6) but the deflection value of column line is little bit higher than the interior panel because of the presence of column.

In case of deflection curve for non-uniform height, a sudden hump shaped is observed between the distances of 22m and 46m approximately for GLY-6 (Figure 24) and GLY-56 (Figure 27) and for GLX-5 (Figure 29), GLX-45 (Figure 30), this shape is observed between distances of 15m and 45m approximately. This sudden change of curve is due to the presence of non-uniform section of building which causes low amount of load comparing to uniform section and creates low deflection on non-uniform portion. Furthermore, this variation of deflection for non-uniform height is not visible for high value of subgrade modulus (Figure 24 and 27). Especially for 125 MN/m^3, we observe less variation of deflection as we know this value of subgrade modulus is for dense sandy soil (Bowles 1997) which susceptible to negligible deflection. So, effect of non-uniform section is negligible for high modulus of subgrade value. Non-uniform height of building has low value of deflection comparing to uniform height of building and this difference increase in case of non-uniform section of building. Non uniform section building causes low self-weight of building which induces low value of deflection. In all deflection curves, deflection value is high at corner and it decreases slightly for uniform height of building and largely in mat center in case of non-uniform height of building for all the values of subgrade modulus.

4.4.4 Influence of sub grade modulus on contact pressure

The soil pressure under the column is always high and it is smaller between columns than directly at column. It can be inferred from Figure 31 to Figure 38 that contact pressure increases with the increase of subgrade modulus for all cases. For column line, it is noticed that contact pressure distribution is planar for low value of subgrade modulus and it’s getting sinuous (waiver) pattern with increasing value of subgrade modulus (Figure 32) for uniform height of building. Increasing subgrade modulus leads to increase in soil pressure and that’s why the soil is subjected to high pressure beneath the column and smaller between the columns which results a waiver pattern. So, pressure variation increases with increasing subgrade modulus for uniform height of building. In case of middle of an interior panel, insignificant pressure variation occurs with increasing value of subgrade modulus for uniform height of building (Figure 34) but for non uniform height building this pressure variation is significant. For uniform height of building there is less variation of pressure due to absence of column in interior panel. Although this it is true for non uniform height of building, pressure variation creates due to non uniform section with increasing subgrade modulus i.e. increasing soil pressure.

It is observed that contact pressure of uniform height of building is greater than that of non-uniform height of building (Figure 33, 36, 37 and 38). Non-uniform height of building is low self-weighted that imposed lower soil pressure comparing to the uniform height of building. Simulacrum curve of deflection is obtained for contact pressure for both uniform and non-uniform height of building because deflection value is proportional to soil pressure for constant property of soil.

The corner of the mat is subjected to high soil pressure and it decreases slightly for uniform height of building and largely in mat center in case of non-uniform height of building for all the values of subgrade modulus due to non-uniform section.

4.5 Influence of mat thickness

4.5.1 Influence of mat thickness on shear of mat

It can be inferred from Figure 39 to 43 that with the increasing value of mat thickness, shear value (both positive and negative) is also increasing but the change is not significant except for the shear along the middle of an interior panel (GLY-56) for non uniform height where the variation of negative shear is 2.70 times between t=213cm and t=274.32 (Figure 42). Normally, a point of zero shears occurs between two point load and this zero shear is seen between every two column of this mat (Figure 39 to 41). For Figure 41 and 43, it is found that shear value for uniform height is always higher than non-uniform height because of greater self weight in case of uniform height building. Due to presence of non uniform section of building, shear value is small in non uniform section in Figure 41.

4.5.2 Influence of mat thickness on moment

The total bending moment in a section of a mat is equal to the difference between positive negative moment (tension on the bottom of slab) due to the soil reaction and positive moment due to the column load (Teng 1992). Negative moment occurs beneath the column and between two column positive moments is engendered and simulacrum pattern of curve is observed in Figure 44 to 49. Positive value of moment indicates hogging type and negative value indicates sagging type moment. However, it can be inferred from the Figure 44 that positive bending moments are increasing with increment of raft thickness and negative bending moments are abating with raft thickness. Increasing of raft thickness causes high transmission of load compare to mat with small thickness which results gradual lowering of negative bending moment and increasing of positive moment. So, the positive bending moment (in-between columns, where tension occurs at the upper fiber) is more susceptible to changes in the raft rigidity (raft thickness) than the negative bending moment (at column). In column line, variation of positive moment is insignificant but in case of interior column line (GLY-56), this variation is 2.70 times for uniform height and almost 7 times for non-uniform height of building (Figure 47 and 48). Moment variation in non uniform segment of building is much more comparing to uniform section in middle of an interior panel of non uniform height of building. Lower value of load due to non uniform section causes no negative moment in non uniform zone of mat and higher the value of mat thickness lower the value of negative moment and higher the value of positive moment. High value of mat thickness induces low value of deflection under the column i.e. low value of moment. Negative moment varies 1.80 times in case of interior column line for non-uniform height of building (Figure 48).

For column line GLY-6 (Figure 46), positive moment is greater for uniform height of building and negative moment is higher for non uniform height of building but when the non-uniform section starts in non-uniform height of building this trend is reverse. In case of interior panel, similar pattern is achieved up to non-uniform section of building. Beyond this, only negative moment is seen for non-uniform height of building while uniform height of building's curve continues with its sinuous pattern (Figure 49). So a reasonable percentage of bottom reinforcement and minimum amount of top reinforcement should be provided in case of interior panel for non uniform section.

4.5.3 Influence of mat thickness on deflection

To increase mat thickness results in increase of self weight of mat. So deflection will also increases with the increase of mat thickness. Similar pattern of curve is observed in Figure 50,51, 53 and 54. At all point except at corner and edges, deflection increases with increase in mat thickness. It can be inferred from Figure 50 that thickness up to 254 cm, deflection values increase under column and increment of thickness of 0.5m and 0.92m than 254cm shows lower deflection value under column. In Figure 51 and 54, we get a hump shaped curve for column line and interior panel.

This hump shape pattern indicates presence of non uniform section of building which causes lower weight of the building comparing to uniform one. For both column line and middle of an interior panel, uniform height of building causes higher value of deflection compare to non-uniform height of building which is shown in Figure 52 and 55. But overall the variation of deflection due to increase in thickness is small especially in case of middle of an interior panel. From Figure 50 and 53, it is clear that differential settlement decreases with increasing thickness of mat.

4.5.4 Influence of mat thickness on contact pressure

From Figure 56, sinuous pattern of curve is the indicator of stiff soil (Wayne. C. Teng 1992). As increasing thickness will increase the self weight of building and soil pressure as well and in our figures of contact pressure (Figure 56 to 61), we observe similar phenomena. Again deflection is proportional to the soil pressure and that's why shape of the all the deflection and contact pressure curve is similar. In Figure 58 and 61, we get a hump shaped curve which is due to the low amount pressure induced by the non uniform section comparing to uniform one. Furthermore, pressure value is higher for uniform height of building than non uniform height of building due to less self weight shown in Figure 58 and 61.

The flexural rigidity (thickness) of the raft foundation has significant influence on the pressure distribution of the supporting soil especially at sections under column, and for the raft adopted in the present research; it was noticed that soil pressure distribution is far from being planar when raft thickness is 213cm.

However, as the thickness reaches 305 cm, pressure distribution approaches the planar profile.

5. Conclusion

The objective of the study was to understand the behavior of mat foundation with non-uniform height of the high-rise building. A thorough analytical and comparative study on mat foundation is conducted where the effect of subgrade modulus and mat thickness is worked out in this work.

Effect of subgrade modulus

On the basis of the results described in chapter four, the following conclusions may be drawn.

Shear

Shear variation is small in column line but significant variation occurs in case of middle of an interior panel. Shear value of uniform height of building is higher than non-uniform height of building for column line but for middle of an interior column line the relation in reverse.

Moment

The value of negative bending moments (midpoint of panel) decreases and positive bending moments (beneath of columns) increases with soil subgrade modulus for all cases. Positive moment is higher for non-uniform height of building while negative moment is higher for uniform height of building. This relation is true up to non-uniform section of building and beyond this distance this process is reverse. Moment variation due to non-uniform height of building is significant in interior panel. Maximum value of moment for different value of subgrade modulus is higher for non-uniform height of building.

Deflection

Mat deflection decreases exponentially with increasing modulus of sub-grade reaction at all positions. Deflection value of value of column line is little bit higher than the interior panel because of the presence of column. Effect of non-uniform section on deflection is negligible for high modulus of subgrade value. Non-uniform height of building has low value of deflection comparing to uniform height of building and this difference becomes significant in case of non-uniform section of building.

Contact pressure

At positions beneath the columns, the contact pressure increases with increase of subgrade modulus. Contact pressure of uniform height of building is greater than that of non-uniform height of building. The corner of the mat is subjected to high soil pressure and it decreases slightly for uniform height of building and largely in mat center in case of non-uniform height of building for all the values of subgrade modulus.

Effect of mat thickness

Shear

The value of shear (both positive and negative) increases with the increase of mat thickness for almost all cases. But the change is not significant. Significant variation of shear can occur in middle of an interior panel for non-uniform height of building.

Moment

Negative bending moments are increasing with raft thickness and positive bending moments decrease with raft thickness. The positive moments (under column) decreases with mat thickness. So, the negative bending moment (in-between columns, where tension occurs at the upper fiber) is more susceptible to changes in the raft rigidity (raft thickness) than the positive bending moment (at column). Positive moment is greater for non uniform height of building and negative moment is greater for uniform height of building but when the non-uniform section starts in non-uniform height of building this process is reverse. In case of interior panel, similar pattern is achieved up to non-uniform section of building. Beyond this, only negative moment is seen for non-uniform height of building while uniform height of building's curve continues with its sinuous pattern.

Deflection

At all points deflection increases with the increase of mat thickness. Differential settlement decreases with the increase of mat thickness. Deflection becomes very much low in non uniform section of building.

Contact pressure

The value of contact pressure increases with the increase of mat thickness for all cases. The flexural rigidity (thickness) of the raft foundation has significant influence on the pressure distribution of the supporting soil especially at sections under column.

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