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EFFECT OF SOIL NONLINEARITY ON ANALYSIS OF RAFT FOUNDATION

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Abstract

Soil supporting foundations behave in a nonlinear manner at loading close to its bearing capacity. This behavior affects soil pressure distribution and the corresponding stresses in the raft foundation, which differs significantly from considering the soil as elastic linear material. The present research uses the finite element method to study the effect of soil nonlinearity on the behavior of raft foundations subjected to concentrated loads. The analysis is based on the Winkler type of foundation. The analysis considered different values of the average soil pressure to its bearing capacity. The supporting soil was modeled as elastic perfectly plastic material. The effects of soil nonlinearity on the intensity and distribution of soil pressure, punching shear force, and bending moments in the raft are investigated. The effects of the foundation stiffness evaluation factor $L{\cdot}\lambda$ on the behavior of rectangular raft foundations were studied. This parameter combines the effects of the modulus of subgrade reaction, raft thickness, modulus of elasticity of concrete, and column spacing, as these parameters are interrelated. The results indicated that considering the subgrade soil as a linear elastic material underestimates punching shear and bending moments compared to modeling the soil as an elastoplastic material.

Keywords:

Raft foundation;
Soil nonlinearity;
Winkler's foundation;
Finite element.

1 Introduction

Raft foundation, sometimes referred to as mat foundation, is a combined footing that usually covers the entire area under a super-structure and carries its entire load and spreads it over the whole area beneath the building. Raft foundation is sometimes chosen for soils that have low load-bearing capacities but must support high column or wall loads [1]. Under some conditions, spread footings would have to cover more than half the building area, and raft foundations might be more economical [2], Commonly, the structural design of raft foundations can be performed by two conventional methods: the rigid method and the plate on elastic foundation method. In designing the raft by the rigid method, the raft is considered to be infinitely rigid with negligible flexural curvature and the soil reaction is constant or linearly varying and calculated on the basis of simple statics. In the plate on elastic foundation method, the supporting soil is represented by a half-space medium or an infinite number of springs. The latter method is sometimes referred to as the Winkler foundation method. In both methods, the supporting soil can be modeled as a linear or nonlinear material. In the Winkler foundation method, the reaction pressure sustained by the assumed soil springs under the raft per unit settlement is referred to as the modulus of subgrade reaction k. Winkler's foundation model has a shortcoming of disregarding the continuity of supporting media. This shortcoming can be overcome by incorporating a second parameter into the foundation model which takes into account the foundation shearing stiffness. However, there is yet no nonlinear two-parameter foundation model. Due to its simplicity, most commercial softwares use the Winkler model in the analysis of beams and plates on elastic foundations.

According to the ACI Committee Report 336 [3], Raft foundation can be considered rigid if the average length of two adjacent spans is less than $1.75/\lambda$ provided that the difference between

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adjacent loads and column spacing is less than 20 % of the higher value. The plate on elastic foundation method may be used if the average of span lengths as defined above is larger than 1.75/λ. The factor λ is

$$\lambda = \sqrt[4]{\frac{Bk}{4E_f I_f}}. \quad (1)$$

In the above equation, B is the width of the foundation strip between centerlines of two bays, k is the modulus of subgrade reaction, E_f is the modulus of elasticity of foundation material, and I_f is the moment of inertia of the cross-section of the footing strip. The rigid method yields overestimation of moments and shear forces in the raft, while the plate on elastic foundation method yields more accurate results [4-8]. According to section 13.3.4.3 of the ACI 318–19 code, soil pressure distribution under raft foundation shall be consistent with the soil properties, and with principles of soil mechanics [9]. The soil beneath raft foundations rarely behaves in a perfectly linear elastic manner based on Hooke's Law. It is well known that the stress-strain behavior of soils is not linearly elastic for the entire range of loading of practical interest [10]. Therefore, considering the soil nonlinearity is necessary, especially in cases of high ratios of average soil pressure with respect to the soil bearing capacity.

Since the raft foundation is usually used when the soil bearing capacity is weak so as to distribute the loads over the largest possible area, the average soil pressure will be close to the soil bearing capacity in zones of load concentrations such as column locations. Simulating the soil as linear springs in the analysis will produce locations where the soil reaction values exceed its bearing capacity. Neglecting that the pressure on the soil exceeds its bearing capacity in some locations is incorrect. According to section 13.3.11 of the ACI 318-19 [9], the allowable bearing pressure of soil shall not be exceeded when subjected to loading applied on the foundation. The decision to increase the raft thickness so as to distribute the soil reaction more uniformly is not economical. The alternative solution is to consider the soil nonlinearity in the analysis which will affect the distribution of soil reaction and the corresponding shear forces and bending moments in the raft.

Mehrotra et al. [11] used the stiffness method assuming linear subgrade reaction to analyze raft foundation supporting multi-bay superstructure. The maximum bending moment calculated by their method was about 25 % lower than that calculated by the traditional method of the rigid raft. Shukla [12] offered charts based on the Winkler hypothesis to calculate the bending moments, punching shear forces, and deflections in raft foundations. Tabsh and Al-Shawa [13] used the finite element method to study the influence of the stiffness of shallow foundations on the distribution of soil pressure, shear forces, and bending moments in the foundation. Their study indicated that bending moments in isolated footings are more affected by the flexibility of the structure than shear forces. They developed a rigidity factor that distinguishes between stiff and flexible footings.

Farouk and Farouk [14] conducted a geotechnical finite element analysis to study the influence of super-structure stiffness on soil pressure reaction and settlement for plane two-bay frames. They concluded that footing stiffness has little influence on the average soil reaction under the footing and on the maximum settlements. Analyses, charts and equations were presented to determine the average soil reaction and maximum settlement for interior and exterior footings for two-bay plane frames.

Jeong et al. [15] proposed an approximate computer-based analytical technique to investigate the performance of raft foundations supported by soil or piles. They investigated the effect of soil nonlinearity and raft flexibility on the behavior of substructure of high-rise buildings. They concluded that the results of the proposed method are in good agreement with field measurements. The precision of the proposed method is intermediate between 3-D finite element and linear elastic methods.

The objectives of the present study are:

1) to study the effect of soil nonlinearity on punching shear and bending moments in raft foundation compared to simulating the supporting soil as linear springs,

2) to determine the effect of the ratio of average soil pressure to its bearing capacity on the distribution of reaction soil pressure, shear forces and bending moments in the raft foundation, and 3) to evaluate the effect of the parameter $L \cdot \lambda$ on the structural behavior of the raft.

2 Approach

The analysis carried out in this study used program SAFE (CSI 2016) [16] which uses the finite element method to analyze the raft. The raft was modeled as thick plate elements based on the Mindlin-Reissner plate theory, in which the transverse shear deformation is considered in the analysis. Thick plate formulation is important when the ratio of raft thickness to its span is relatively high as in the case of raft foundation [17]. Mesh size of 0.5 by 0.5 m was used in this study. The mesh was refined under and around the column locations to track precisely soil pressure and stress variations in these locations. Fig. 1 shows the finite element mesh used in the study. Finer meshing of the raft resulted in negligible differences in the analysis output.

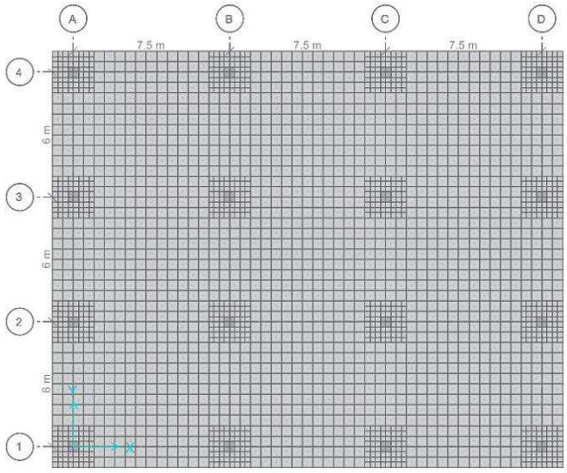


Fig. 1: Finite element mesh simulation of the raft.

Shear walls and openings were not included in this research. The self-weight of the raft was considered in the analysis because it affects the distribution of soil pressure in the nonlinear type of analysis. Live load on raft surface was neglected because it usually has a low value compared to the dead load. Since moments and shear forces at the supports of high-rise buildings are usually small when analyzed under gravity loads [18], only gravity dead and live loads were applied on column locations. The total axial loading on the central columns was taken as 5400 kN. The loads on the corner columns and edge columns were taken as 25 % and 50 % of loads of the interior columns respectively. This assumption is relatively realistic because the load is assumed proportional to the tributary area of slabs supported by each column. The boundary conditions of the nodes were set as supported by soil springs in vertical direction without restraining in lateral directions. Column loads were modeled as uniformly distributed over their cress- sectional area. The average soil pressure was taken between 50 % and 90 % of its bearing capacity. The average soil pressure is calculated by dividing the sum of all column gravity loads plus the raft weight by the total area of the raft. The raft considered in this study is rectangular and supports four rows of 0.5 x 0.5 m columns in each direction. The column spacing is uniform with 6 m in the short direction and 7.5 m in the long direction, Fig. 1. The raft thickness is kept constant as 0.85 m in all analysis cases so as not to affect the dead load and perimeter of the critical section for punching shear calculations.

The soil was modeled as elastic perfectly plastic material, Fig. 2. The modulus of subgrade reaction has a unit of kN/m^3, and its value depends on soil properties as well as other factors, such as the length and width of the foundation as well as the embedment depth of the foundation [19, 20]**.** Nonlinear static analysis allowing uplift with zero tensile stiffness was adopted in this study and compared to the linear analysis of the same raft.

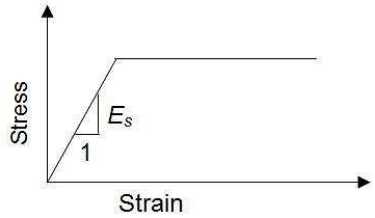


Fig. 2: Elasto-plastic idealization of subgrade soil.

3 Parametric study

The effects on soil pressure distribution, punching shear, and bending moments on raft foundations are considered in this study. For constant loading, the parameters that highly affect these actions and considered in this study are:

1) Ratio of average soil pressure to the soil bearing capacity. Three values were used corresponding to 50 %, 70 % and 90 % of soil bearing capacity respectively, Table 1.

2) The value of foundation stiffness evaluation factor $L \cdot \lambda$ where L is the spacing between columns in the long direction 7.5 m and λ as defined in Eq. (1) above; four values of Winkler's modulus were used corresponding to $L \cdot \lambda$ values of 1.75, 2.75, 3.75 and 4.75 respectively.

Table 1: Material properties of concrete and soil.

Parameter	Value
Concrete young's modulus [MPa]	26667.3
Concrete Poisson's ratio	0.2
Concrete density [kN/m^3]	23.56
Bearing capacity [kN/m^2]	132, 170.83, 239
Winkler's modulus of soil [kN/m^3]	$1.62 \cdot 10^4$, $9.87 \cdot 10^4$, $34.2 \cdot 10^4$, $87.8 \cdot 10^4$

The effects of the modulus of subgrade reaction, concrete modulus of elasticity, raft thickness, and column spacing are considered implicitly in the second parameter as they are interrelated. Comparison is made between modeling the supporting soil as linear elastic springs and elastic-plastic springs. Poison's ratio of concrete was taken as 0.2 and unchanged in all analysis cases because it is of secondary importance in comparison to the previous parameters [18]. The flexural rigidity of the raft is based on the gross concrete section properties.

4 Results

Fig. 3 shows the effect of the parameter $L \cdot \lambda$ on maximum soil pressure for different bearing capacity values. The results show that the maximum soil pressure is only 23 % higher than the average soil pressure 119.6 kN/m^2 for $L \cdot \lambda$ equals to 1.75, which indicates almost uniform soil pressure distribution under the raft for $L \cdot \lambda$ equal to 1.75, which is the limit between the rigid method and the plate on elastic foundation method. Whereas, for higher values of $L \cdot \lambda$ the maximum soil pressure increased significantly in the linear analysis of the raft. For the nonlinear analysis, the pressure reached the bearing capacity values of the soil at higher values of $L \cdot \lambda$.

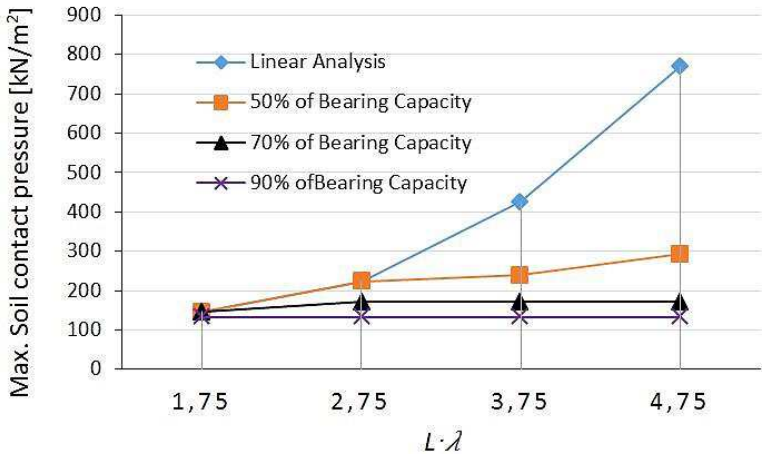


Fig. 3: Effect of the parameter $L \cdot \lambda$ on maximum soil pressure under the raft.

Figure 4 shows that the minimum soil pressure is inversely affected with the parameter $L \cdot \lambda$. The minimum soil pressure for $L \cdot \lambda$ equal to 1.75 is almost constant for different bearing capacity values and is about 86 % of the average soil pressure.

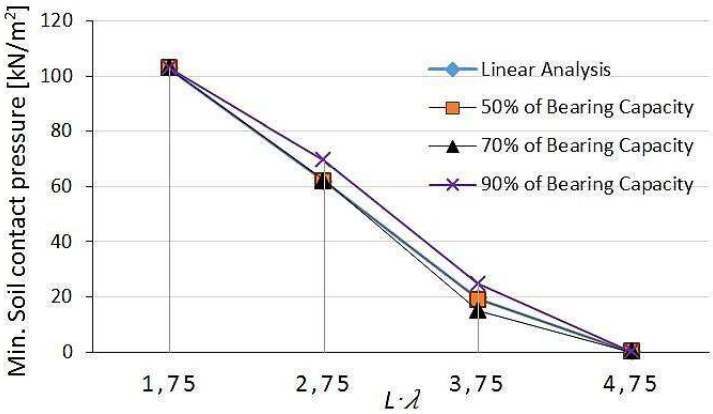


Fig. 4: Effect of the parameter $L \cdot \lambda$ on the minimum soil pressure under the raft.

The value of soil pressure can diminish at some zones for a value of $L \cdot \lambda$ equal to 4.75 or higher indicating that separation of the raft from the soil occurs in these areas. The bearing capacity has little effect on minimum soil reaction. Fig. 5 shows the soil pressure distribution for linear analysis with a value of $L \cdot \lambda$ equal to 3.75. Figure 6 shows the soil pressure distribution for nonlinear analysis with average soil pressure equal to 70 % of the soil bearing capacity and $L \cdot \lambda$ value of 3.75. It is clear from the figure that in a large proportion of the raft, the soil pressure has reached its bearing capacity, and obviously, this area increases as the average soil approach its bearing capacity. Therefore, the analysis results are expected to approach those obtained by the rigid method in such cases.

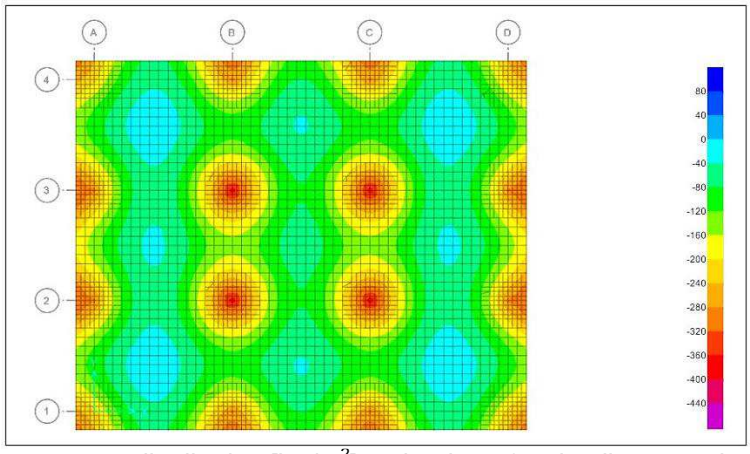


Fig. 5: Soil contact pressure distribution [kN/m^2] under the raft using linear analysis for $L \cdot \lambda$ equal to 3.75.

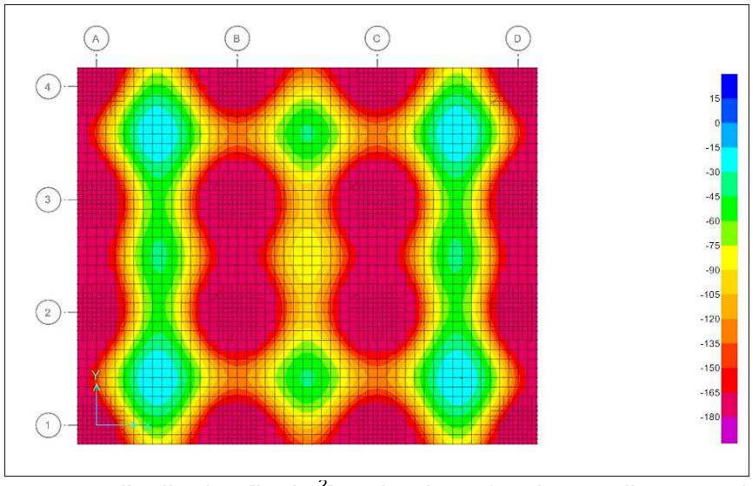


Fig. 6: Soil contact pressure distribution [kN/m^2] under the raft using nonlinear analysis for $L \cdot \lambda$ equal to 3.75.

Fig. 7 shows the relation between punching shear forces and the parameter $L \cdot \lambda$ for the interior columns for different bearing capacity values. Since the axial load is constant in all analysis cases, the punching shear force is reduced by different amounts according to the soil reaction under the column in the zone of critical section for punching shear [21]. The figure shows that the punching shear is affected by the value of $L \cdot \lambda$ in the linear analysis and the punching shear is decreased by 11 % when the value of $L \cdot \lambda$ increases from 1.75 to 4.75. However, in the nonlinear analysis, the punching shear is not highly affected by the $L \cdot \lambda$ values. Furthermore, the punching shear is slightly decreased by increasing the bearing capacity values.

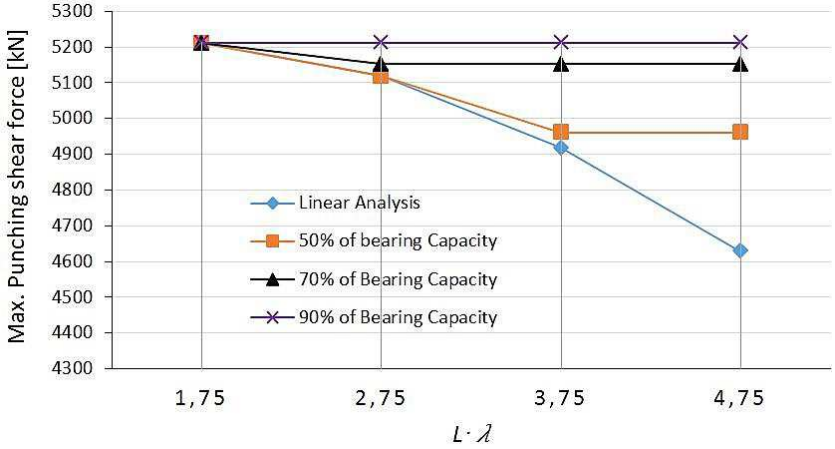


Fig. 7: Effect of parameter $L \cdot \lambda$ on maximum punching shear force.

These results indicate that the linear analysis for high $L \cdot \lambda$ values underestimates the punching shear forces due to very high soil reaction pressure under column locations, which can exceed the bearing capacity of the soil. Fig. 8 shows the impact of the parameter $L \cdot \lambda$ on the maximum middle strip positive moment in the long direction for different bearing capacity values. The maximum positive moment is less affected by the ratio of average soil pressure to its bearing capacity value for low $L \cdot \lambda$ values and the difference between linear and nonlinear analysis is very low. However, for higher values of the parameter $L \cdot \lambda$, the maximum positive moment is highly affected and decreases by about 33 % when the value of $L \cdot \lambda$ increases from 1.75 to 4.75. For a constant ratio of soil pressure to its bearing capacity value, the maximum positive bending moment decreased with an increase of the parameter $L \cdot \lambda$, especially in the linear analysis.

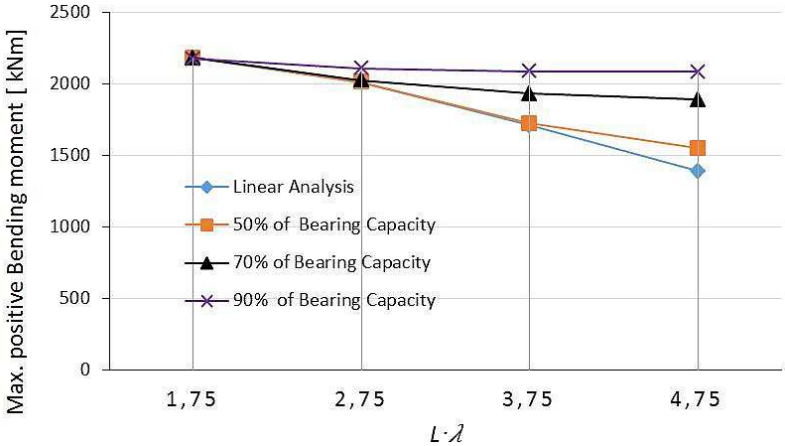


Fig. 8: Effect of parameter $L \cdot \lambda$ on maximum middle strip positive moment.

This figure indicates that the linear analysis also underestimates the maximum positive moments due to concentrations of soil reaction pressure under columns, with lower contact pressure in midspans.

Fig. 9 shows the bending moment diagram in the long direction of the raft for $L \cdot \lambda$ of 3.75 using linear analysis. The figure shows the column strip and middle strip moments for the upper half of the raft.

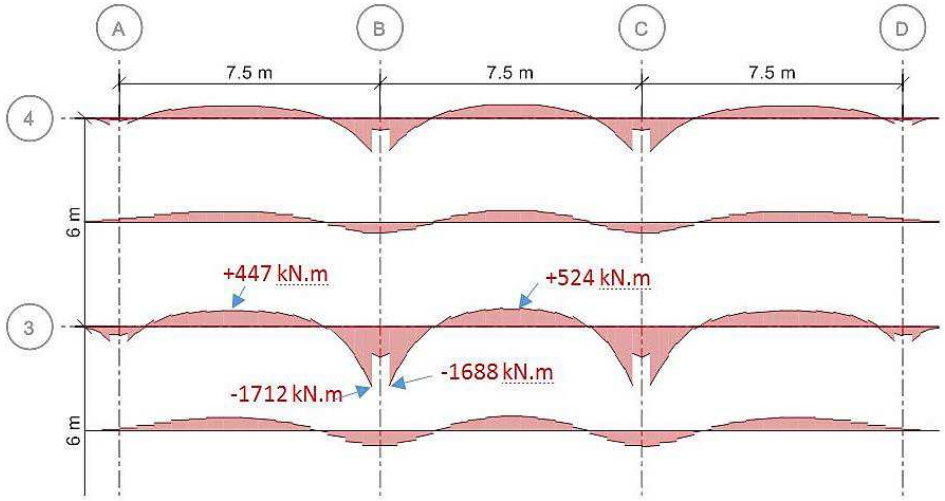


Fig. 9: Column strip and middle strip moments for linear analysis with $L \cdot \lambda$ of 3.75.

Fig. 10 and 11 show the bending moments of the corresponding nonlinear analysis of the raft with average soil pressure equal to 70 % and 90 % of the soil bearing capacity, respectively.

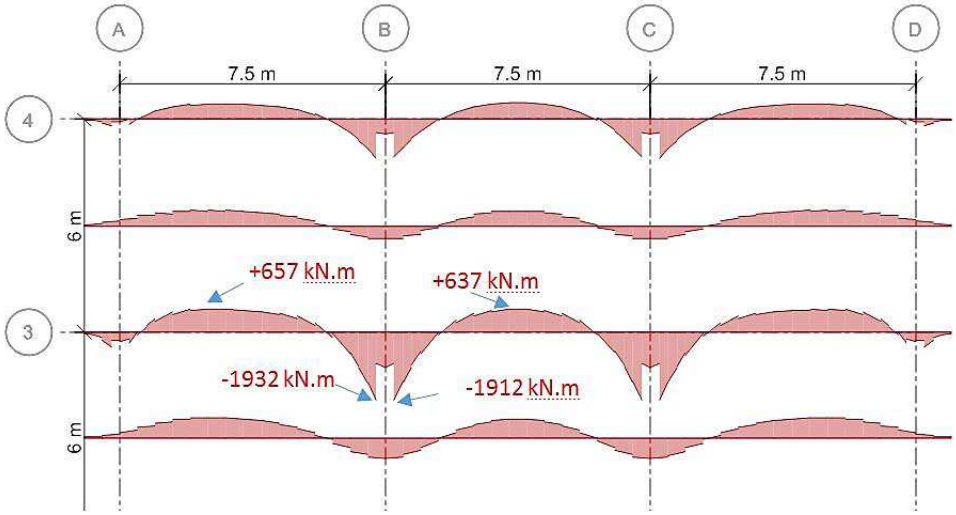


Fig. 10: Column strip and middle strip moments for nonlinear analysis with $L \cdot \lambda$ of 3.75 with average soil pressure 70 % of bearing capacity.

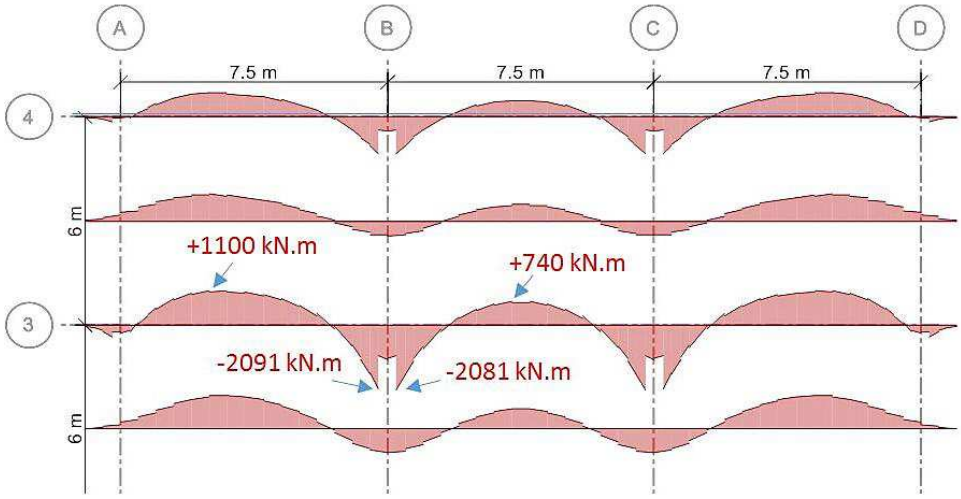


Fig. 11: Column strip and middle strip moments for nonlinear analysis with $L \cdot \lambda$ of 3.75 with average soil pressure 90 % of bearing capacity.

Fig. 12 shows the effect of the parameter $L \cdot \lambda$ on maximum middle strip negative bending moments in the long direction for different bearing capacity values. The negative bending moment is highly affected by the parameter $L \cdot \lambda$ in the linear and nonlinear types of analysis. In the linear analysis, when the value of $L \cdot \lambda$ increases from 1.75 to 4.75, the maximum negative moment decreases from 1183 kN·m to 325 kN·m. Furthermore, in the nonlinear analysis, the ratio of average soil pressure to its bearing capacity has a high impact on the negative bending moment, especially for higher values of the parameter $L \cdot \lambda$. When the soil pressure approaches its bearing capacity, almost uniform soil reaction will be induced under the raft and therefore, the negative and positive moments are increased correspondingly.

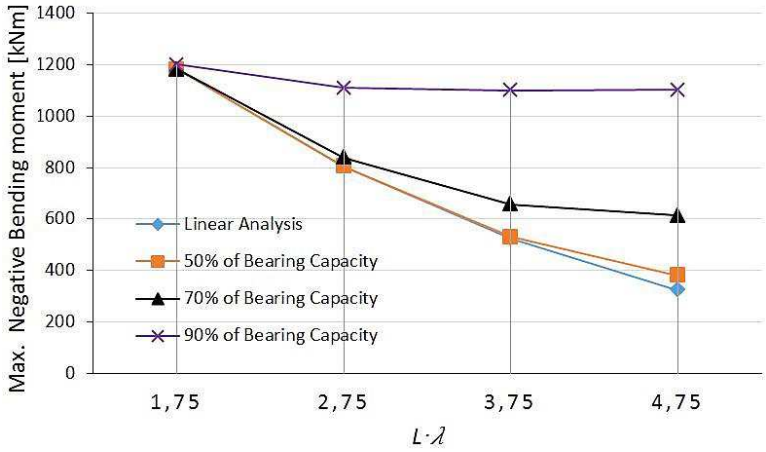


Fig. 12: Effect of parameter $L \cdot \lambda$ on maximum middle strip negative moment.

5 Conclusions

1) Despite the shortcoming of Winkler's model of neglecting soil continuity beneath the foundation. Its capability to take account of soil nonlinearity makes it an efficient model for design purposes.

2) The soil reaction pressure may exceed the soil bearing capacity in flexible raft foundations (high $L \cdot \lambda$ values) in the linear analysis method, and may therefore yield unrealistic results.

3) For a given modulus of subgrade reaction, a lower ratio of average soil pressure to its bearing capacity yields lower maximum bending moments and punching shear forces and a more economical design of raft foundation.

4) Analysis of raft foundation based on assuming linear subgrade yields underestimation of the punching shear forces and bending moments, especially for high ratios of average soil pressure to soil bearing capacity and for high $L \cdot \lambda$ values. Therefore, it is recommended to use the nonlinear analysis method in such cases.

5) The maximum negative bending moments in raft foundations are highly affected by the ratio of average soil pressure to the bearing capacity, especially for high $L \cdot \lambda$ values.

6) When the average soil pressure approaches its bearing capacity, an almost uniform soil reaction is induced under the raft. Therefore, the nonlinear analysis results will approach the results of the rigid raft analysis method, and the linear analysis underestimates the negative and positive moments.

7) The punching shear force is less affected by the analysis type, $L \cdot \lambda$ value, and by the ratio of average soil pressure to its bearing capacity.

8) As a next research idea, it is proposed to study the effect of foundation material nonlinearity on the analysis and design of raft foundation, since such nonlinearity will change the stiffness of the foundation and the corresponding reaction pressure distribution, shear forces and moments.

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