

Effects of Flexural Rigidity and Soil Modulus on the Linear Static Analysis of Raft Foundations

Haider M. Abdul Hussein

Dept. of Civil Eng., College of Eng., University of Babylon

Abstract

It is a common practice to assume infinite rigidity when analyzing and designing mat foundations, using the conventional "rigid" method, a case in which the effects of the mat flexural rigidity and the modulus of subgrade reaction of the supporting soil are ignored. The intent of this research is to investigate the effect of the flexural rigidity, modulus of subgrade reaction and the corresponding variations of the pressure of the soil under the foundation in the linear static analysis results (bending moment, shear forces, and deflection) in a typical raft. The soil is considered to be homogeneous elastic materials and the linear finite element analysis is carried out by using the rectangular four-node thick plate element, in which the shear deformation is taken into account. It was concluded that the flexural rigidity considerably affects the analysis more than the soil modulus.

Key Words: Raft Foundation, Static Analysis, Soil Modulus, Flexural Rigidity.

الخلاصة

من الشائع أن تفرض جساءة لانهائية عند تحليل وتصميم الأسس الحصىرية، وذلك باستخدام الطريقة "الجاسئة" المعروفة، وبالتالي يتم إهمال تأثير كل من الجساءة الانثنائية للأساس الحصىري ومعامل رد الفعل الأرضي للتربة الساندة. الهدف من هذا البحث هو تقصي مدى تأثير الجساءة الانثنائية ومعامل رد الفعل الأرضي وما يرافق ذلك من تغيرات في ضغط التربة تحت الأساس على نتائج التحليل الخطي (عزم الانحناء، قوى القص والتشوهات) في أساس حصىري مثالي. تم تمثيل التربة كمادة مرنة و متجانسة، كما تم إجراء تحليل خطي بواسطة طريقة العناصر المحددة وباستخدام العنصر الصفائحي السميك المستطيل ذو الأربع عقد، والذي تؤخذ فيه التشوهات القصية بنظر الاعتبار. وقد تم الاستنتاج بأن جساءة الأساس تؤثر بشكل كبير على التحليل وبشكل أكبر من تأثير معامل رد الفعل الأرضي.

1. Introduction

The type of foundation and its design for any structure is based on magnitude of the loads on it and the type of founding strata which support it. Conventional methods used so far had to be simple because of limitations of computing devices. With the major advances of micro computer technology and especially the silicon chip, extensive computer capabilities have become available and affordable to most, thus making complex and otherwise laborious calculations possible with comparatively lesser effort and minimizes the chances of errors in the manual computations (Subramanian, 2005).

A "raft" or "mat" foundation is a large concrete slab used to interface columns in several lines with the base soil. It may occupy the entire foundation area or only a part of it. A raft foundation may be used where the base soil has a low bearing capacity and/or the column loads are so large that more than 50 percent of the area is covered by conventional spread footings (Kame, 2008).

A raft foundation is usually continuous in two directions and covers an area equal to or greater than the base area of the structure. A raft foundation is suitable when large differential settlements are anticipated. It is also suitable for ground containing pockets of loose and soft soils. In some instances, the raft foundation is designed as a cellular structure where deep hollow boxes are formed in the concrete slab.

Raft foundations are relatively large in size. Hence, the bearing capacity is not the only controlling factor in the design. Differential and total settlements also control the design (Pun, 2006).

2. Rigidity of Mat Foundations

Mat foundations are generally used with uniform thickness all over. Economy can be attained by reconfiguring the mat in different ways. One type of such reconfiguration is by thickening the mat below the columns. Case studies reveal that mat thickness away from the column faces can be reduced by about 40% (Ahmad, 2003).

In the present work; the raft foundation has a uniform thickness. By varying this thickness and fixing all other factors; the effect of the raft rigidity on the analysis will be investigated.

The raft thickness affects differential settlement and bending moments, but has little effect on load sharing or maximum settlement. Increasing the raft thickness, was approved to have a greater effect on the maximum bending moment. However, there is little effect on the maximum bending moment when the raft thickness is increased beyond 1.5 m (Noh, 2008).

The positive bending moments are increasing with raft thickness and negative bending moments are reduced with raft thickness (Kame, 2008).

Except for thin rafts, the maximum settlement is not greatly affected by raft thickness, whereas the differential settlement decreases significantly with increasing raft thickness. Conversely, the maximum moment in the raft increases with increasing raft thickness (Poulos, 2001).

3. Analysis of Raft Foundations

Extensive research work about rafts and piled rafts has been carried out and published in the last decades, and different analysis methods have been developed that can be classified into several categories: empirical, analytical and numerical methods (Helen, 2007).

The methods available for analysis of 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 foundations. Mats are not truly rigid, so the settlement beneath the columns will be greater than that beneath unloaded areas. These differential settlements will cause variations in the soil bearing pressure and corresponding changes in the flexural stresses in the mat. 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. The Discrete element method includes, Finite Difference Method, 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 (Kame, 2008).

The present work aims to estimate the accuracy of the conventional rigid method by comparing its analysis results to the more accurate finite element analysis.

4. Finite Element Procedure

The Slab Analysis by the Finite Element method software “SAFE” is used in the present work for its simplicity. In the analysis, SAFE converts the object-based model created by the user into a finite element model, called the analysis model. The finite element mesh used in the analysis is a rectangular mesh based on a maximum acceptable element size.

Usually, the computer software transforms the problem of plates on elastic foundation into a computer-oriented procedure of structural analysis (Kame, 2008). The plate (raft) is idealized as a mesh of finite elements interconnected only at the nodes (corners), and the soil may be modeled as a set of isolated springs (Winkler foundation). The Finite element analysis adopted for raft is based on the classical theory of thick plates resting on Winkler foundation that accounts for the transverse shear deformation of the plate, as shown in figure (1). The formulation is based on the assumptions that deflections are small compared with the thickness of plate, and that a normal to the middle surface of the undeformed plate remains straight, but not necessarily normal to the middle surface of deformed plate. The stresses normal to the middle surface are considered negligible.

Four noded, isoparametric rectangular elements with three degree of freedom per node (the transverse displacement w , rotation about x-axis θ_x , and rotation about y-axis θ_y) are considered in the development of finite element formulation, as shown in figure (2). Independent bilinear shape functions are assumed for displacement and rotational degrees of freedom. By equating first variation of total strain energy of the plate foundation system to zero, the force-deflection equation for plate-foundation element can be obtained.

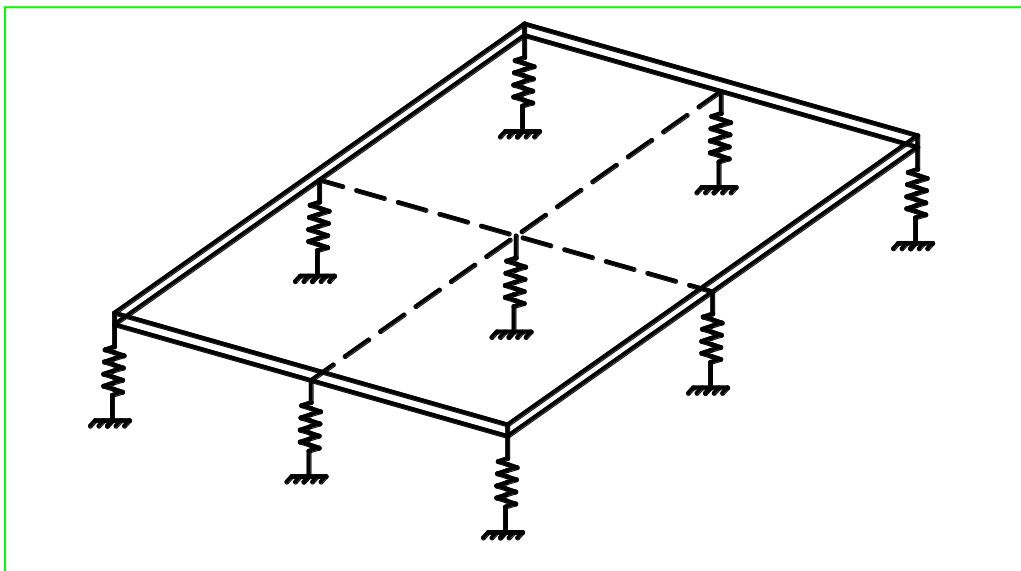


Figure (1): Structural idealization of raft and supporting soil (Kame, 2008)

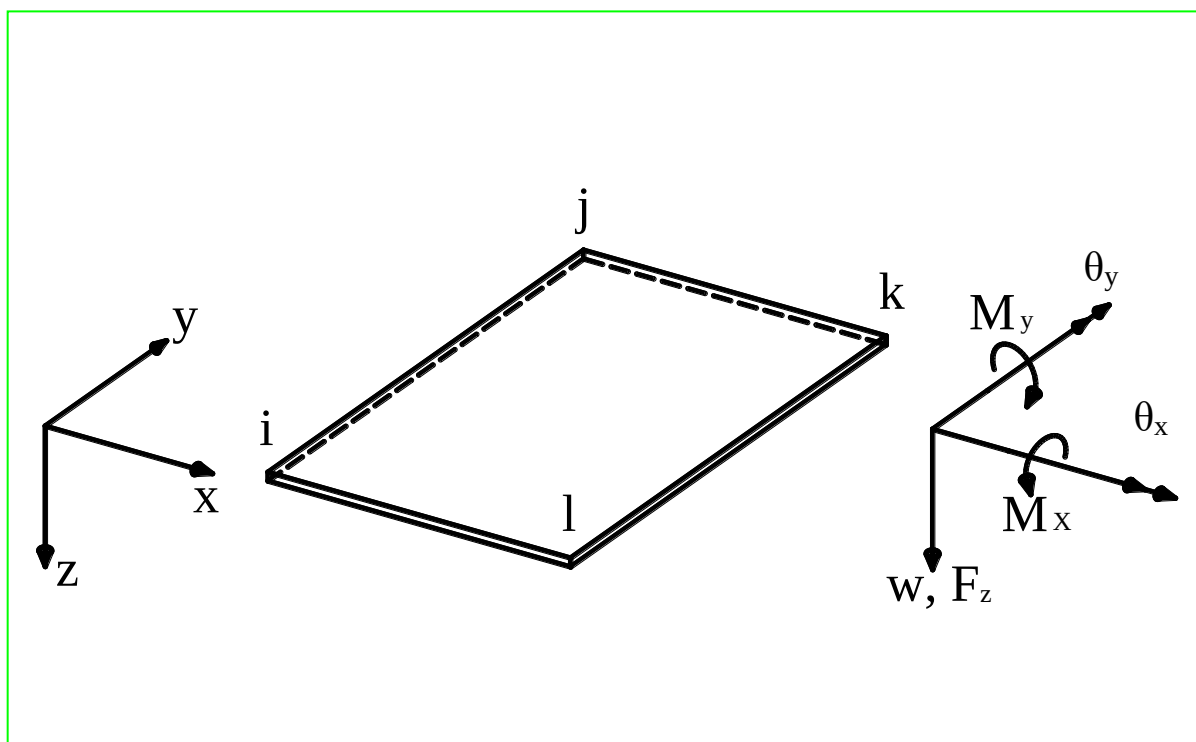


Figure (2): Coordinate system, forces and corresponding displacements in the rectangular plate element

5. Effect of the Raft Foundation Rigidity

For the typical and symmetric raft foundation shown in figure (3), a parametric study is carried out in order to investigate the effect of the flexural rigidity (thickness) on the analysis. The following values are used:

$L = 6.0$ m, $d = 0.5$ m, column dimensions: 0.4 m $\times$ 0.4 m, column load = 1.0 MN, modulus of elasticity for the raft material = 21 GPa, modulus of subgrade reaction for the supporting soil (k) = 80 MN/m³ and the thickness (t) is variable.

In figures (4), (5), (6) and (7), the adopted thicknesses were 0.4 m, 0.6 m, 0.8 m and 1.0 m respectively. In each case, the reaction of the soil is drawn against the distance along the raft for both an interior column strip and a central middle strip of the raft, and the finite element pressure is compared to the uniform pressure, which is calculated by the conventional rigid method (i.e.: total load / total area).

Figure (8) represents the deflected shape of a section under an interior columns line with various values of the raft thickness (t), while figures (9) and (10) show the bending moments and shear forces respectively, drawn for an interior column strip.

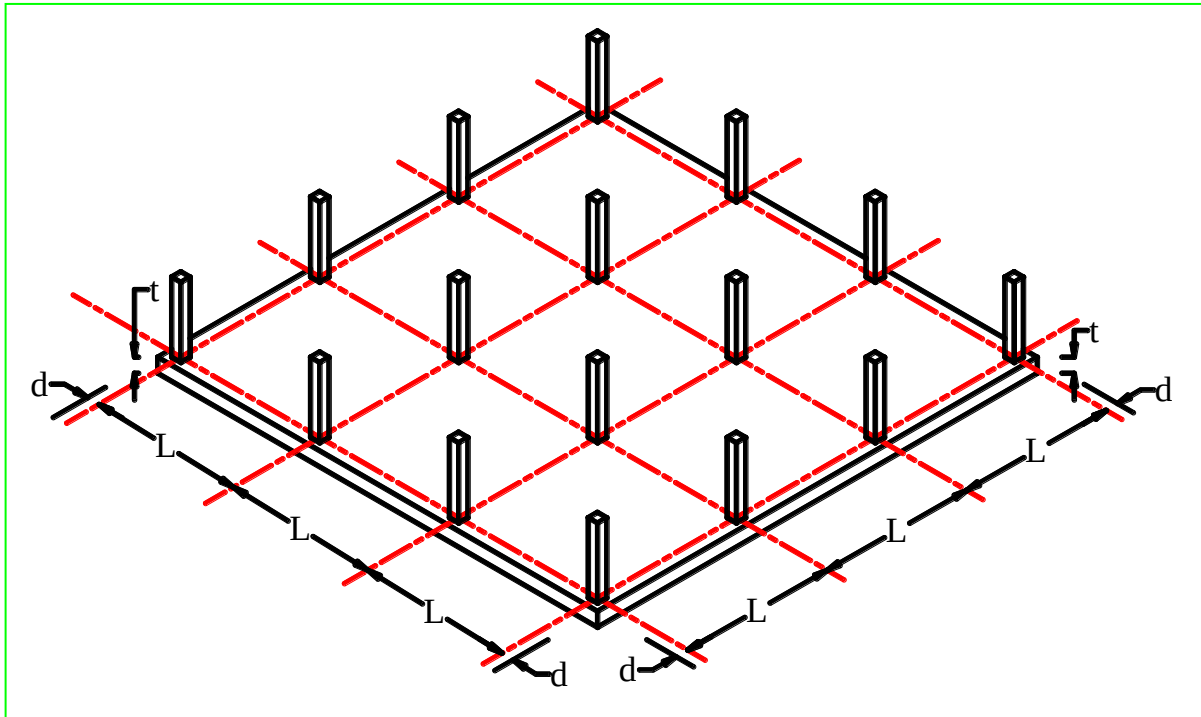


Figure (3): Typical Raft Foundation

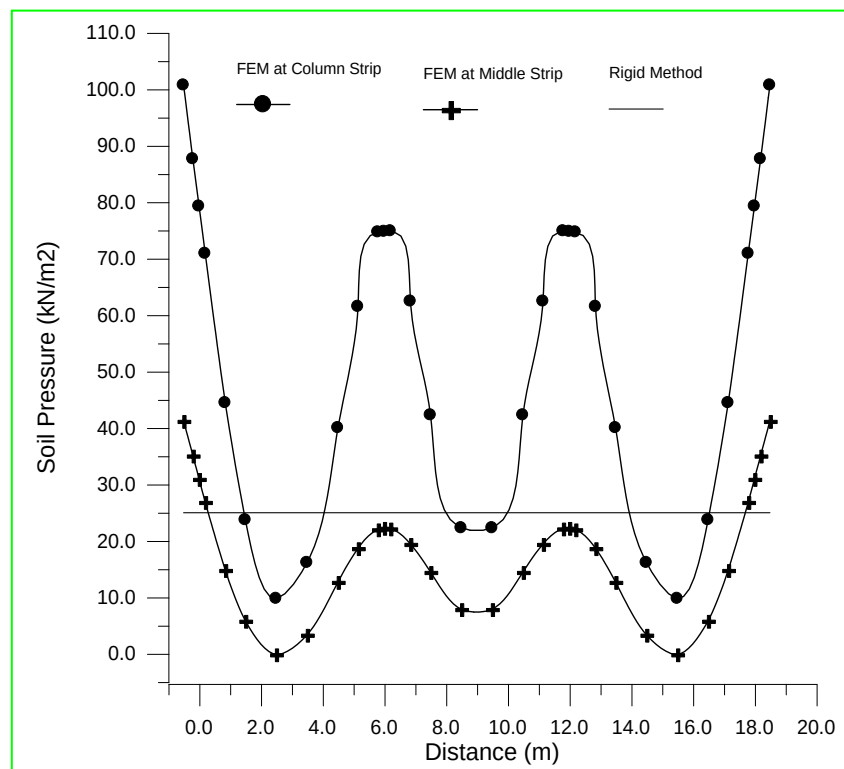


Figure (4): Distribution of soil pressure when $t = 0.4$ m

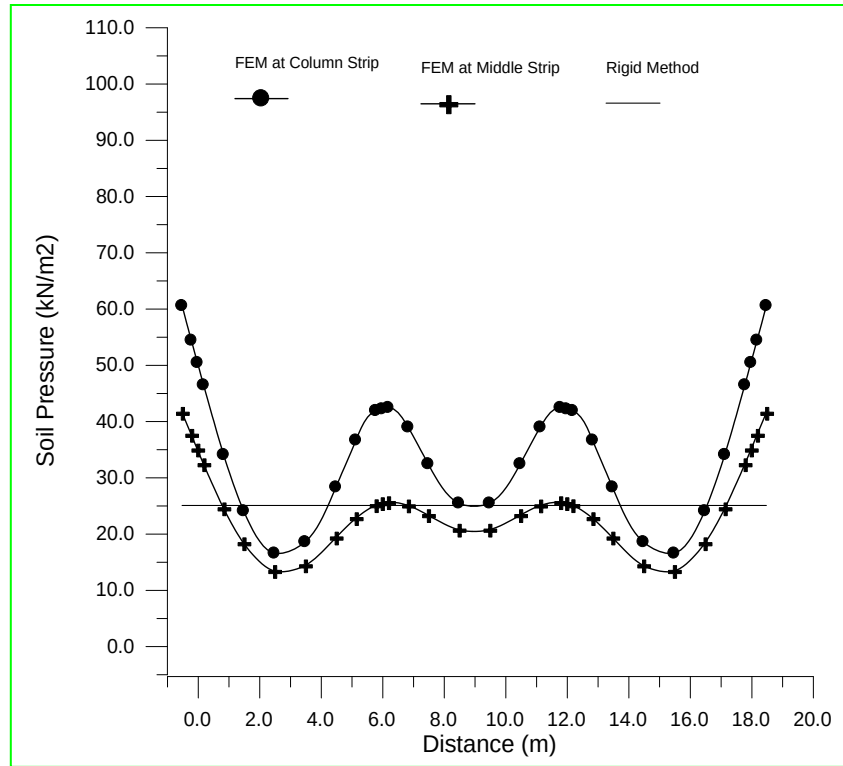


Figure (5): Distribution of soil pressure when $t = 0.6$ m

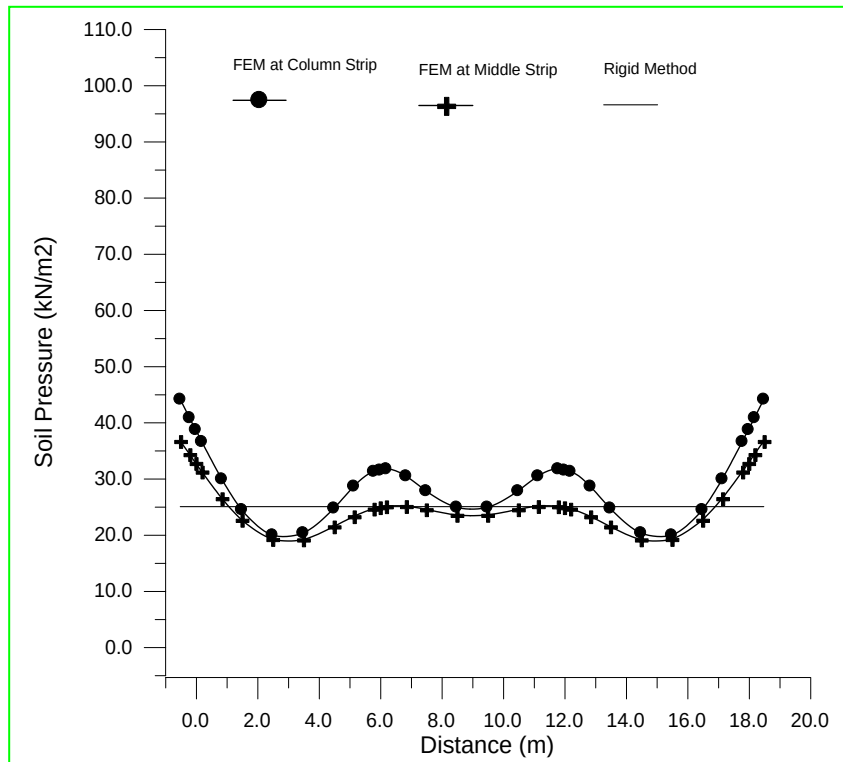


Figure (6): Distribution of soil pressure when $t = 0.8$ m

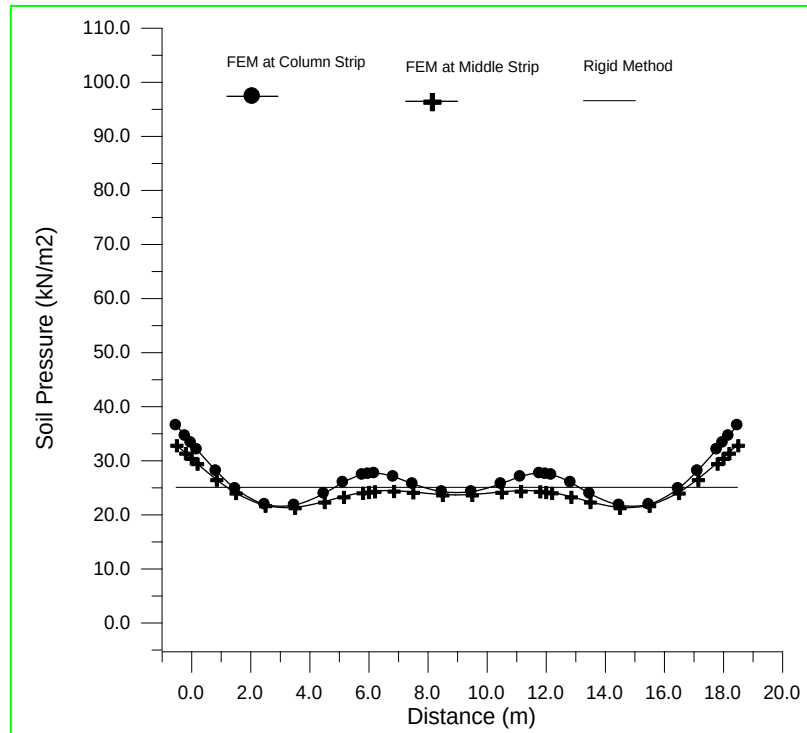


Figure (7): Distribution of soil pressure when $t = 1.0$ m

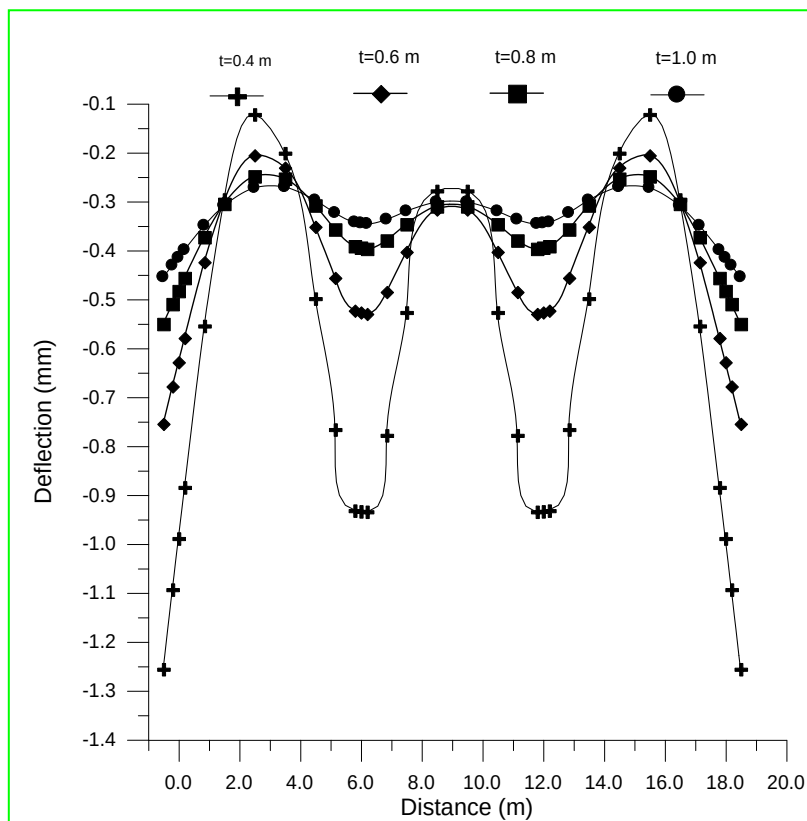


Figure (8): Deflection vs. distance with t variable

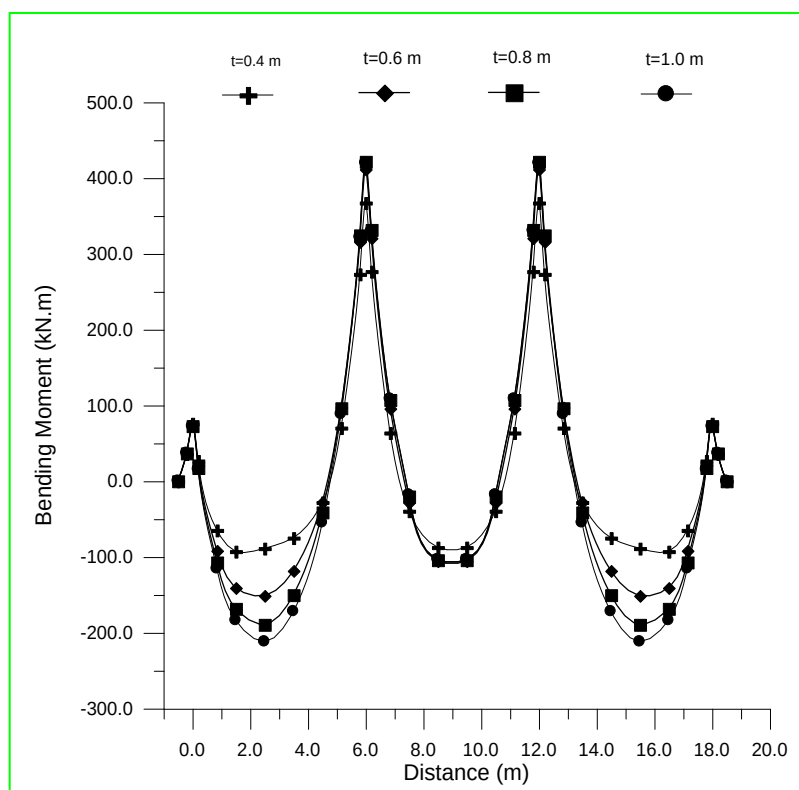


Figure (9): Bending moment vs. distance with t variable

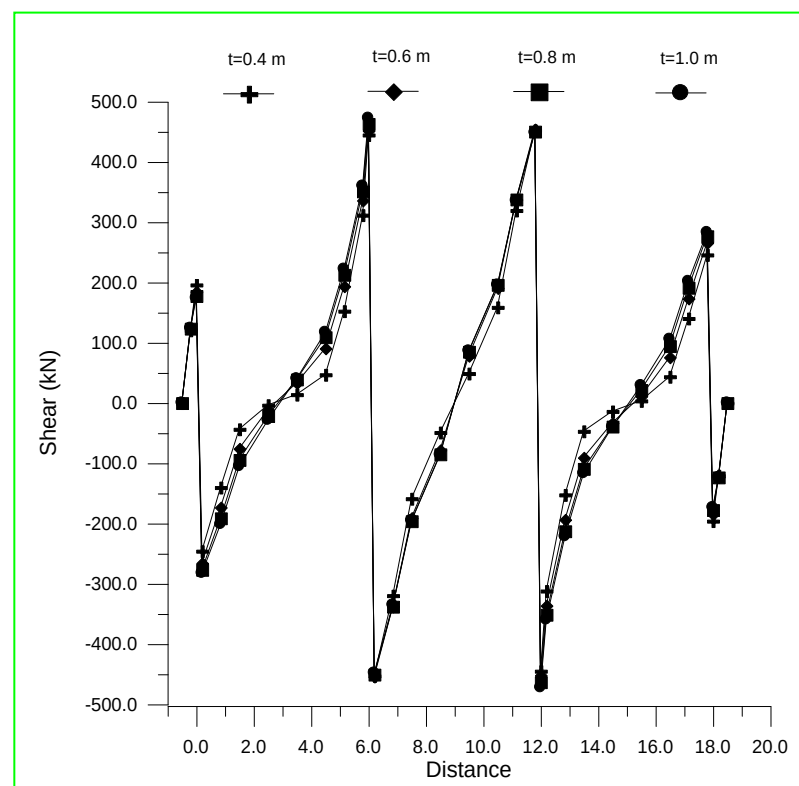


Figure (10): Shear force vs. distance with t variable

6. Modulus of Subgrade Reaction

The term subgrade reaction refers to the pressure distribution which is the result or 'reaction' of the 'subgrade' to a load imposed upon the top of a foundation structure. In practice, the foundation structure is commonly a reinforced concrete slab or mat, and the subgrade usually refers to the soil or rock upon which the structure is constructed (Liao, 1995).

The selection of the coefficient of subgrade reaction "k" for the design of rafts, beams, and rigid pavements is not satisfactory because of the wide range of values recommended in the literature for each soil type and density. A simple relationship was found between k and the standard penetration test values that takes into account the effect of the footing size or the width of the loaded area. Test results are compared with other plate load tests on granular soils in different areas around the world, to establish confidence in the derived correlation and to explain the causes of variation in different granular deposits (Ismael, 1987).

7. Determination of the Modulus of Subgrade Reaction

The modulus of subgrade reaction and its probabilistic characteristics can be determined directly by field test. As an alternative to the determination of the modulus of subgrade reaction, regular soil properties may be used (Gagin & Ivanilov, 2008).

In 1955, Karl Terzaghi (Liao, 1995) published a classic paper titled 'Evaluation of coefficients of subgrade reaction', in which he presented recommendations for estimating the spring constants which have come to be commonly used to model the foundation subgrade in the analysis of mat foundations and other similar problems

One of the most popular models in determining the modulus of subgrade reaction is Winkler model. In this model the subgrade soil assumes to behave like infinite number of linear elastic springs that the stiffness of the spring is named as the modulus of subgrade reaction. This modulus is dependant to some parameters like soil type, size, shape, depth and type of foundation and etc. The direct method to estimate the modulus of subgrade reaction is plate load test that it is done with 30-100 cm diameter circular plate or equivalent rectangular plate (Reza & Janbaz, 2008).

Because of the limitation of available data and the uncertainty of soil condition, it was also proposed to use the empirical equations. The following empirical equations (Widjaja, 2008) were suggested to estimate k value both in clay and sand:

Clay : $k = 40 - 50 s_u \text{ (t/m}^3\text{)}$

Sand : $k = 70 - 100 N_{SPT} \text{ (t/m}^3\text{)}$

where s_u is an undrained shear strength (t/m^2) and N_{SPT} is a value of Standard Penetration Test.

8. Effect of the Modulus of Subgrade Reaction

In the present work, the effect of soil modulus is investigated by fixing all the other parameters and varying the modulus of subgrade reaction from 60 MN/m^3 to 120 MN/m^3 for the same typical and symmetric raft foundation shown in figure (3).

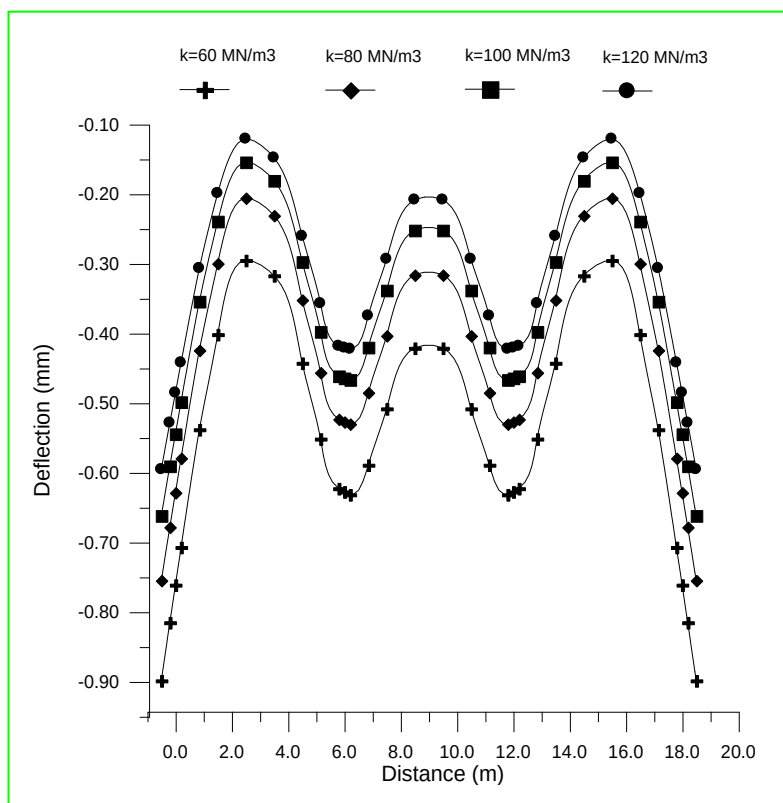


Figure (11): Deflection vs. distance with k variable

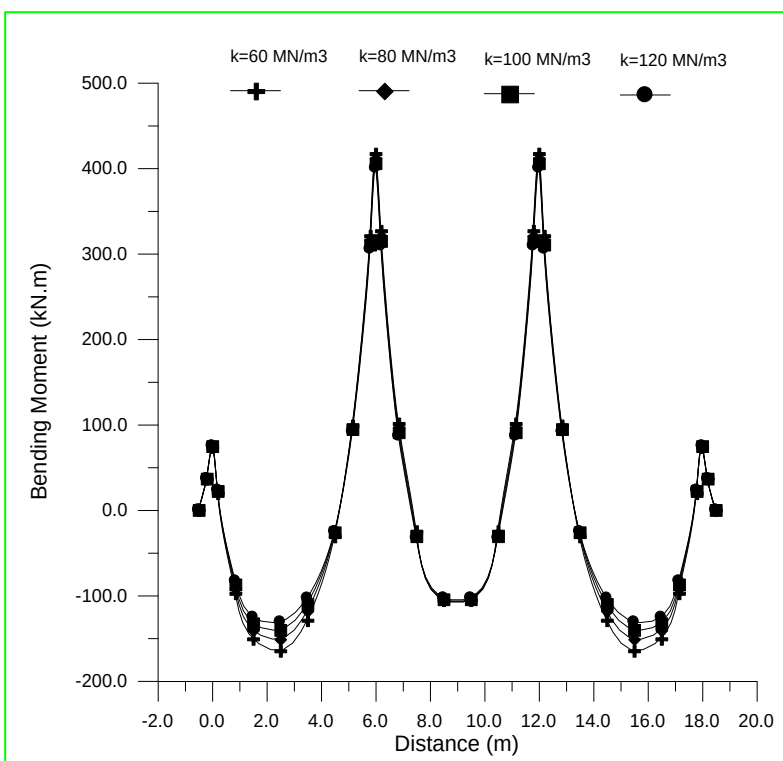
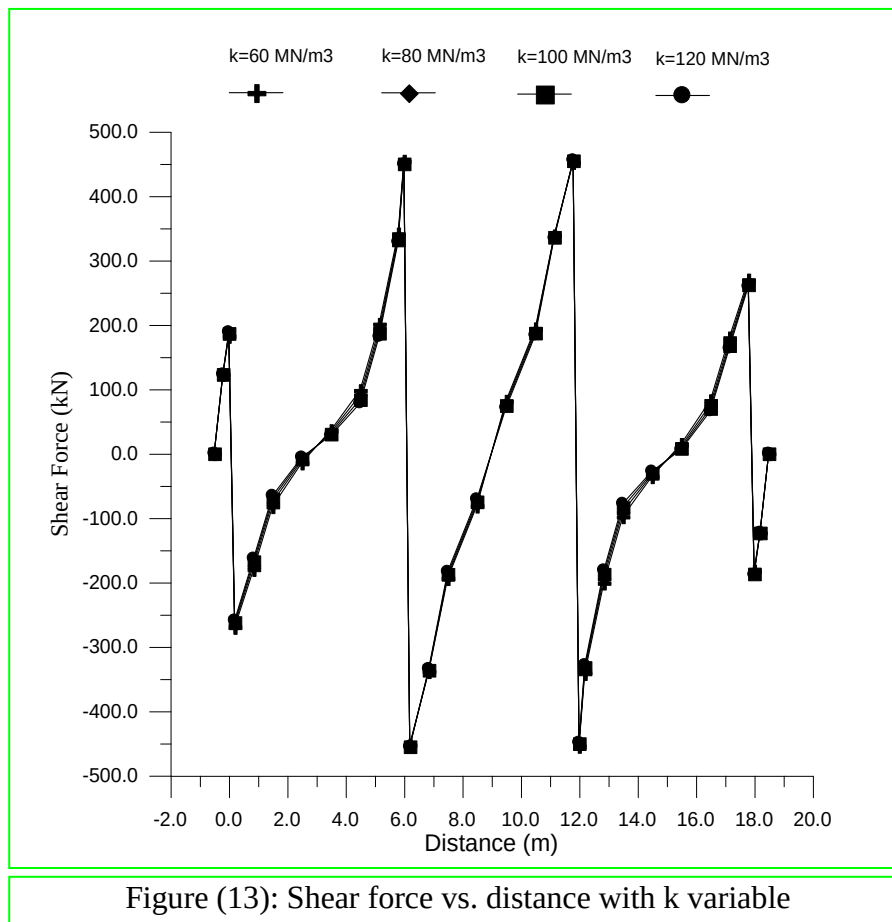


Figure (12): Shear force vs. distance with k variable

When studying the effects of the soil modulus the, following values are used:

$L = 6.0$ m, $d = 0.5$ m, column dimensions: 0.4 m x 0.4 m, column load = 1.0 MN, modulus of elasticity for the raft material = 21 GPa, thickness (t) = 0.6 m and the modulus of subgrade reaction for the supporting soil (k) is variable.

Figure (11) represents the deflected shape of the raft for a section directly under an interior columns line, while figures (12) and (13) show the bending moment and shear force diagrams respectively, for an interior columns strip of the raft, with various values of (k).



9. Conclusions

In the present work, parametric studies on raft foundations are worked out wherein effect of raft rigidity and soil modulus are considered, and it was concluded that:

1. The flexural rigidity (thickness) of the raft foundation has a significant influence on the pressure distribution of the supporting soil, especially at sections under columns, and for the raft adopted in the present research; it was noticed 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 assumed in the conventional rigid method.

2. 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. On the other hand, the deflected surface of the raft was shifted either upward or downward when increasing or decreasing the soil modulus respectively, without changes in curvature.

3. The negative bending moment (in-between columns, where tension occurs at the upper fiber) is more susceptible to changes in the raft rigidity (thickness) than the positive bending moment (at columns). On the other hand, the negative and positive bending moments are less susceptible to changes in the modulus of subgrade reaction.

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